MMC All Aluminum Cylinder Block for High Power SI Engines

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ABSTRACT

An all aluminum cylinder block with a Metal Matrix Composite (MMC) cylinder bore was developed which made it possible to re-design the base engine for high performance with a bore-to-bore distance as narrow as 5.5mm. The cylinder block is an open deck type and the MMC preform consists of alumina-silica fibers and mulite particles. A laminar flow die cast process was selected to ensure defect-free MMC bore quality. To insure good lubrication, electrochemical machining was applied to the bore surface.

By use of radioisotope (RI) measurements, MMC reinforcement was optimized for wear characteristics. Particular attention was paid to use of fuels with high sulfur levels.

1. FOREWORD

The 2ZZ-GE engine, a 1.8 Liter in-line 4 cylinder, was developed and introduced to the market for the 2000 model year Celica sports car. The engine was based on the 1.8 Liter 1ZZ-FE \(^{(1)}\) which has a longer piston stroke and cast iron cylinder liners. The specifications of the 1ZZ-FE and 2ZZ-GE engines are shown in Table 1. The new all aluminum cylinder block made it possible to shorten the bore-to-bore distance from 8.5mm with cast iron liners to 5.5 mm. A shorter piston stroke embodies the high speed attributes of a performance engine.

Fig. 1 illustrates a cross sectional view of 2ZZ-GE type engine and Fig. 2 shows an external appearance of the MMC cylinder block.

Table 1. Engine Specifications

<table>
<thead>
<tr>
<th></th>
<th>1ZZ-FE</th>
<th>2ZZ-GE</th>
</tr>
</thead>
<tbody>
<tr>
<td>Displacement (cc)</td>
<td>1794</td>
<td>1796</td>
</tr>
<tr>
<td>Bore x stroke (mm)</td>
<td>Φ79×91.5</td>
<td>Φ82×85</td>
</tr>
<tr>
<td>Bore-to-bore distance (mm)</td>
<td>8.5</td>
<td>5.5</td>
</tr>
<tr>
<td>Bore material</td>
<td>Cast iron</td>
<td>MMC</td>
</tr>
<tr>
<td>Valve train configuration</td>
<td>VVT-i</td>
<td>VVT-i</td>
</tr>
<tr>
<td>Compression ratio</td>
<td>10.0 : 1</td>
<td>11.5 : 1</td>
</tr>
<tr>
<td>Maximum power (kW/rpm)</td>
<td>107/6400</td>
<td>135/7600</td>
</tr>
<tr>
<td>Maximum torque (Nm/rpm)</td>
<td>172/4400</td>
<td>180/6800</td>
</tr>
<tr>
<td>Dry weight (kg)</td>
<td>102</td>
<td>115</td>
</tr>
</tbody>
</table>
2. ADVANTAGE OF MMC BORE

Fig. 3 shows the sealing design of a multi-layer steel cylinder-head gasket. The distance of about 5mm between the bores is the narrowest limit to ensure good sealing performance. Therefore, we chose a bore-to-bore distance of 5.5mm. Table 2 shows the results of a comparative study on various kinds of cylinder bores which have the potential to reduce the bore-to-bore distance.

In the case of cast iron liner designs, the maximum temperature between the bores will exceed the allowable limit. Focusing on high-temperature strength of the sealing area between the bores, we concluded that the MMC bore design has an advantage for shorter bore-to-bore distances considering all aluminum block designs. The advantages are as follows:

- High Young's modulus (shown in Fig. 4)
- High tensile strength at elevated temperature (shown in Fig. 5)
- High compressive strength (shown in Fig. 6)

Fig. 7 shows a photograph of the area between bores of the MMC block. The correlation between the bore-to-bore distance of an open deck aluminum block and specific engine output (series production engines) is shown in Fig. 8. This illustrates the superiority of the MMC bore design.
3. SPECIFICATION OF MMC CYLINDER BLOCK

Fig. 9 shows the final specification for the MMC cylinder block and the microstructure of the bore material. (MMC composition is shown in Table 5 ; page 5) For this application, Fe-P plating was developed and adopted as surface treatment for the piston skirt. It has higher hardness and good manufacturability. The amount of the P additive was optimized in order to achieve a film that is the rigid and flexible. The mean Vicker’s hardness of Fe-P plating is HV550 compared to Fe plating at HV350.

4. MMC MATERIAL SELECTION

Cylinder bore materials require the following characteristics:

- Good wear resistance
- High scuffing resistance
- High compression strength
- High tensile strength
- Low oil consumption

To meet these requirements, we decided to modify the piston MMC which is reinforced by ceramic fiber (alumina fiber or alumina-silica fiber). Piston MMC has been used for the ring grooves of diesel pistons. (2)

4.1 SCREENING TEST – Initial screening was conducted by focusing on the types, sizes and volume fractions of reinforcements.

4.1.1. Wear Properties

(1) Method – For wear tests, we used an LFW-1 tester to perform a comparative evaluation of the wear depth under the test conditions given in Table 3. A correlation has been obtained with on-engine testing.
(2) Results – [1] Fig. 10 shows the test results of various MMC materials reinforced by alumina fibers and particles. As for the ring material wear, smaller particle size and lower particle hardness show less the ring material wear. We selected the 12µm mullite for the MMC bore material, because the tensile strength of the MMC reinforced by a 3µm mullite is lower than that of the MMC reinforced by a 12µm mullite. The reason is that the 3µm mullite tends to introduce micro porosities into the MMC.

[2] Fig. 11 shows the relationship between the volume fraction of a 12µm mullite particle and wear properties for each type of fiber. The ring material wear was less than the other types in the MMC reinforced by the alumina-silica fiber because of its low hardness. In the case of MMC reinforced by alumina-silica fiber, the wear of MMC bore material and ring material are well balanced when the volume fraction of mullite particle is 5% or higher. Fig. 12 shows the relationship between total volume fraction of reinforcements (fiber and particle) and MMC tensile strength. The degradation of tensile strength is observed when the total volume fraction is 20% or higher. This is caused by the increase of micro porosity in the MMC.

4.1.2. Scuffing Resistance – The oil retention ability of bore surface is highly related to scuffing. Honing marks on the bore surface work as oil depositories to avoid scuffing. In case of the cast iron bore, honing marks are very uniform. However in case of the MMC bore, the honing marks could disappear by plastic deformation of aluminum matrix during engine operation and scuffing could occur.

(1) Method – A reciprocal movement friction tester was used. Table 4 shows the test conditions in which the data correlation was confirmed with on-engine tests. The time period from test start until the µ drastically increased was defined as the scuffing time. The scuffing times for various MMC materials were studied.
(2) Results – Fig. 13 shows the relationship between volume fraction of mullite particle and scuffing time for each particle size. As the particle size decreases from 25µm to 3µm and volume fraction of particles increases from 10% to 20%, the scuffing time also increases. This is caused by increasing in the particle dispersion density, resulting in shorter distances between the particles and limiting the growth of the adhesion nucleus. However, as discussed in section 4.1.1, it is necessary to limit the volume fraction of reinforcements, due to the degradation in the tensile strength. Therefore, an ECM process described below was adopted to ensure good scuffing resistance.

![Figure 13. Relation Between Scuffing Time and Reinforcement (crystallized alumina silica fiber Vf5%)](image)

(3) Quantification of ECM process for bore surface – The ECM process in which depressions are created in the matrix aluminum portion of the bore surface is known as a good method to control the lubricating properties. Quantification of ECM-processed surface characteristics was studied to ensure mass production quality control. Fig. 14 shows the relationship between $V_o$ and scuffing time. $V_o$, calculated by equation (*)1), represents the maximum oil volume which can be retained by the bore surface. Based on Fig. 14, the lower limit of $V_o$ was determined. The upper limit of $V_o$ was determined from the relationship between $V_o$ and the oil consumption.

![Figure 14. Relation Between $V_o$ and Anti-Scuffing Time](image)

ENGINE TESTS

4.2.1 Sulfur Concentration in Fuel – It is known that wear is promoted when acid adheres to the cylinder bore during engine warm up as a result of sulfur in the fuel.**3** The sulfur concentration in the fuel for some regions of the world is shown in Fig. 15. It turns out that the sulfur concentration in the fuel in North America and Europe may exceed maximum of 1000 ppm. The aggressive nature of MMC material wear due to sulfur concentration was investigated. The RI tracer techniques were used to assess the wear.**4**

![Figure 15. Sulfur concentration in unleaded](image)

4.2.2 Radioisotope Wear Analyses

(1) Specimens – [1] Specimen engine:
V6, 3.0-liter aluminum block with MMC liners (MMC1 and MMC2 shown in Table 5 were tested.)

<table>
<thead>
<tr>
<th>Table 4. Scuffing test conditions</th>
</tr>
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<tbody>
<tr>
<td><strong>Speed</strong></td>
</tr>
<tr>
<td><strong>Reciprocating stroke</strong></td>
</tr>
<tr>
<td><strong>Load</strong></td>
</tr>
<tr>
<td><strong>Time</strong></td>
</tr>
<tr>
<td><strong>Oil</strong></td>
</tr>
<tr>
<td><strong>Lubrication method</strong></td>
</tr>
<tr>
<td><strong>Mating material</strong></td>
</tr>
</tbody>
</table>

![Table 4. Scuffing test conditions](image)
[2] Specimen fuels:

Three kinds of gasoline currently sold in the U.S. and the Japanese market were evaluated. Sulfur was added in order to see the influence of sulfur concentration.

- Japan: regular gasoline (Sulfur concentration: 50 ppm)
- USA: regular gasoline (Sulfur concentration: 920 ppm)
- USA: premium gasoline (Sulfur concentration: 170 ppm)

Sulfur additive agent: Di-tert-butyl disulfide (DBDS)

[3] Specimen piston rings:

Nitrided top ring (activation part)

(2) RING wear Measurement method – A thin-layer activation RI tracer method, was used as shown in Fig. 16 to measure the ring wear. The specimen engine with radioactivated rings was ran and the ring wear was monitored (in a short period) by measuring the RI concentration in lubricant oil. The amount of the ring wear was then calculated from the increasing of the RI in lubricant oil. Table 6 shows the ring conditions, including radioactivity. As shown in the results in Fig.17, this method is capable of measuring the wear on a real-time basis.

Figure 17. Example of measurement results

(3) Results – First, the relationship between sulfur concentration and the ring wear of using U.S. fuel and DBDS-additive fuel was studied. The DBDS was added to Japanese regular gasoline. Fig.18 shows the results of the ring wear measurements. As it is shown in Fig.18, no significant differences were found in the ring wear between the U.S. fuel and the DBDS additives fuels for a given sulfur level.

Figure 18. Comparison between U.S. Fuel and DBDS Added Japanese Fuel

Using the MMC1, the influence of sulfur concentration and cooling water temperature were studied, and aggressive nature of attack on mating materials between MMC1 and MMC2 was compared.

[1] Influence of Sulfur Concentration
Fig. 19 shows the results of the ring wear measurements of using the DBDS-additive fuel with different sulfur concentrations. It was clear that the higher the sulfur concentration, the greater the ring wear at low cooling temperature.

![Figure 19. Influence on Sulfur Concentration in Fuel on Ring Wear Rate](image)

[2] Influence of Cooling Water Temperature

Fig. 20 shows the results of ring wear measurements by varying the inlet cooling temperature. The lower the coolant temperature, the greater the wear. This tendency become more pronounced when the coolant temperature is 40 degree celsius and below. Furthermore, even in the case of high-sulfur fuel, ring wear is small when the water temperature is 80 degree celsius and above. As can be seen in Fig. 17, change in coolant temperature manifests the change in wear rather quickly.

This mechanism is as follows:

- Acids in the bore increase when coolant temperature is low.
- The acids eliminate oil film between the bore and piston rings.
- Abrasive wear between the bore and piston rings increase.

![Figure 20. Influence of Coolant Temperature on Ring Wear Rate](image)

[3] Influence of the MMC Material

Fig. 21 shows the comparison of ring wear in MMC1 and MMC2 liners at 1,400 rpm with full load condition. It turns out that ring wear of MMC2 was as little as one-third of MMC1.

The reason is that the hardness of MMC2’s reinforcement is lower than that of MMC1 and the mullite particle size of MMC2 is smaller than that of MMC1.

![Figure 21. Improvement of MMC2 from MMC1](image)

4.2.3. Engine Durability Test – To verify the RI wear analyses, a composite pattern engine durability test was carried out. Test conditions included the 30 degree selsius of inlet coolant temperature condition in consideration of low temperature corrosive wear. Total testing duration was 74 hours and 60% of the testing time was under the low coolant temperature condition. Fig. 22 shows the results. As expected from the RI wear analyses, ring wear with MMC2 was much less than that of MMC1. In addition, bore wears in MMC1 and MMC2 was almost the same. Based on these results, the MMC2 which is reinforced by 5% crystallized alumina-silica fiber and 10% mullite particle was finally selected as the MMC bore material. With this level of volume fraction of reinforcements, preforms can be produced by the conventional suction process which offers a cost advantage. Furthermore, regarding the bore and piston wear, we obtained a good correlation between vehicle long distance driving tests and bench engine tests using high sulfur concentration fuel. Therefore, it was concluded that there would be no reliability problems associated with the bore and ring wear in the field.

![Figure 22. Wear Durability Tests](image)
5. HEAD GASKET SEALING

It is important to control the wall temperature between the bores to ensure the reliability of head gasket sealing performance. Especially in high power engine blocks, the water jacket extends into the region between the bores to control the wall temperature. In this MMC block, the reliability of head gasket sealing performance was verified without water jacket between the bores because of its high thermal conductivity and high compression strength at elevated temperatures. (Fig. 6) Fig. 23 shows an indentation on the upper surface of the bore after engine durability test. The indentation level between the bores, the region of high temperatures, was acceptable to ensure the gasket sealing performance.

6. PRODUCTION ENGINEERING

6.1. CASTING

6.1.1. Quality Requirements – In ordinary aluminum die-casting processes, solidification shrinkage is compensated as a result of the molten melt replenishment. With this technique, it is still impossible to fully eliminate the microporosity formation which results in inferior material strength. On the other hand due to their short inter-bore distance and the absence of the higher strength cast iron liners, MMC blocks require a higher material strength than the conventional blocks. Fig. 24 shows the relationship between the defect size and the tensile strength. It has been specified as a casting quality requirement that a near zero defect level had to be secured in and around the bore areas.

![Figure 24. Relation between aluminium matrix strength and casting defect size (at 293K)](image)

6.1.2 Major Problems

1) Die release – (a) (Table 7) – Fig. 25 shows the die release performance comparison of a block with cast-iron liner inserts and the MMC block. It shows that the die releasability of an MMC block is less than using the black with cast-iron liners. This is due to the fact that the cast-iron liners alleviate the effect of aluminum solidification shrinkage in the bore area. If the preform is cast into the block in the same manner as conventional inserts, the direct contact between the die and the MMC material which has a high friction coefficient, will cause difficulty in die release.

![Figure 25. Material Mold Releasing Performance](image)

2) Casting defects – If a preheated preform is cast in the same manner as a cast-iron liner insert, the risk of the following defects will increase due to the characteristics of MMC

   • Inadequate aluminum fill –-(b)

Even if the molten aluminum is filled at high pressure when entering the preheated preform, inadequate fill will result in the areas near the bore surface which are in contact with the die. This results in the formation of minute voids around the bore.

   • Microporosity –-(c)

Solidification progresses slowly in the MMC section which contains inorganic materials with a high thermal
insulation effect. As a result, the molten aluminum remains in this area will be absorbed by the surrounding metal, leaving micropores.

- Cracks ---(d)

As the preform is composed of inflexible inorganic materials, MMC's elongation-to-fracture value is smaller than that of ADC12. Due to this and slower solidification speed of the MMC, minute cracks may occur as a result of the stress between the MMC and the surrounding aluminum (ADC12) during the solidification. Fig. 26 shows the conventional die-casting process and its casting quality.

![Photograph of inadequate aluminum fill and Microporosity](image1)

![Photograph of Cracks](image2)

Figure 26. Conventional System

6.1.3. System Development – Table 7 shows major problems and system developments and Fig. 27 shows the system development.

Table 7. Plan for Ensuring MMC Quality

<table>
<thead>
<tr>
<th>Problem</th>
<th>Plan</th>
<th>Patent</th>
</tr>
</thead>
<tbody>
<tr>
<td>(a) Die Release</td>
<td>Filling the inner circumference of the MMC with aluminum</td>
<td>○</td>
</tr>
<tr>
<td>(b) Aluminum infiltration</td>
<td>Pouring molten metal through the laminar-flow process and improving the release of the gas from the mold</td>
<td>-</td>
</tr>
<tr>
<td>(c) Microporosity</td>
<td>Thinner material adjacent to the MMC</td>
<td>○</td>
</tr>
<tr>
<td>(d) Cracking</td>
<td>Squeeze pin control in accordance with solidification</td>
<td>○</td>
</tr>
<tr>
<td></td>
<td>Precise mold temperature control by internally cooling the mold (without external cooling)</td>
<td>○</td>
</tr>
<tr>
<td></td>
<td>Determining the proper texture</td>
<td>○</td>
</tr>
</tbody>
</table>

Figure 27. Developed System

(a) Die release – A special method of filling the melt into the inner preform surfaces and a new preform setting technique, were developed in order to achieve non-contact condition between the highly frictional MMC and the die. In addition, the solidification control achieved by die temperature control during the period preceding die release, will be implemented for reducing shrinkage.

(b) Infiltration – Preform setting

In order to prevent the molten aluminum from solidifying before preform infiltration, the preform will be preheated to the required temperature before being set into the die.

- Melt filling

Laminar flow of the melt will be achieved in order to eliminate air into the preform.

- Adoption of vertical die configuration

- Improvement of die degassing to reduce air content within the preform.

- Aluminum penetration

The melt will be filled into the inner preform surface areas as well. With this, the required preform penetration depth can be reduced by half.

The size of the cavities within the preform can be made more consistent to minimize the residual air within the MMC.

(c) Microporosity – The draft configuration around the MMC area has been designed to provide an uniform wall thickness which reduces the potential solidification shrinkage. In addition, die temperature control will be implemented to assist the directional solidification toward the squeeze pin. The melt replenishment will also be controlled by mean of squeeze pin control to effectively compensate for solidification shrinkage.

(d) Cracks

- Preform composition

The composition ranges which provide the maximum elongation-to-fracture value and the smallest possible air content without affecting the engine's wear properties, has been selected.
Solidification control

The solidification speed of the surrounding aluminum will be matched to that of the MMC, which solidifies slowly to reduce stress in and around the MMC area during solidification shrinkage.

6.1.4. Development Keypoints — Development of preform and general die element have been carried out for MMC block casting quality assurance.

(1) Preform — In order to enable the melt to fill into the inner preform surface areas, the preform must be supported only from the top and the bottom of the die. A high-strength preform has been developed to prevent damage during the melt fill. As shown in Fig. 28, a special binder has been added to the preform to achieve proper strength at loads exceeding 18 N in the JIS Ring Crushing test.

Figure 28. Preform Strength

(2) Die Temperature Control

[1] Unique Technology Development

Previously, due to die cracking concerns, a die wall thickness of 10 to 15mm had always been secured between the internal die cooling holes and the die cavity surface. As a result, the internal cooling effect was not very good and it was impossible to have internal cooling holes in the areas with a complicated draft configuration. This drawback used to be compensated for controlling the die temperature through water and die-lubricant spraying after removing casting parts from the die. However, this technique allowed unpredictable die temperature variations and not possible to control precisely.

To address this difficulty, a stress-analysis based on die life prediction technique has been developed. This enables the internal cooling holes to be close to the die surface and therefore of allows effective control of the die temperature through internal cooling flow. By this method, a dependable solidification control that is required to ensure the MMC casting quality, can be achieved.

[2] MMC Quality Assurance

• Weight reduction and internal quality

To achieve laminar flow in melt filling, the injection speed has been lowered to one tenth of that of a horizontal die configuration. Fig. 29 shows the relationship between the injection speed and the general block wall thickness which indicates that with this speed, an increase in the product wall thickness would normally be necessary to assure good melt filling throughout the cavity. By discontinuing water spraying the die, the die temperature can be maintained at a high level during melt filling so that satisfactory melt filling can be assured even with the conventional wall thicknesses. By this method, weight reduction and internal quality assurance have been achieved simultaneously.

Figure 29. Injection Speed and General Thickness of Block

• Die release and infiltration

In order to assure sufficient aluminum infiltration to the preform, the bore part of the die should be maintained at a high temperature during the melt injection. However, during the period preceding the die release step, this part of the die should be cooled heavily by internal cooling to assure die releasability while solidification of the areas around the bore must be slowed down to suppress shrinkage. In order to satisfy all these requirements at the same time, the internal cooling flow will be automatically changed throughout a single cycle in order to control the die temperature and the solidification conditions.

• Directional solidification

Directional solidification toward the squeeze pin through which the melt is replenished, has been achieved through product geometry design and die temperature control. This will prevent the melt absorption by the MMC area where the solidification is slower. At the same time, the solidification shrinkage within the MMC area will be compensated by the melt replenishment. Through the aforementioned steps, even the minute defects in and around the MMC area can now be successfully controlled.
(3) Squeeze Pin Control – The aluminum solidification varies with time, so it is difficult to replenish the molten metal with a squeeze pin which moves at constant speed. Therefore, a new control system in which the squeeze pin speed varies in accordance with the solidification conditions was developed.

6.2 BORE FLAW INSPECTION – In terms of the bore flaws, in addition to the approaches taken in the casting process, flaw inspections are performed to ensure proper quality.

6.2.1 Internal Flaws – We perform ultrasonic inspections to check the internal flaws that are caused by air pockets. Due to the presence of the blind areas and because this method is not affected by the raw material surface conditions, this inspection is performed in the raw material stage. The entire bore is inspected through the spiral scanning of the bore interior. The results of this inspection are image-processed in order to inspect only the portion that is made into the finished product, excluding the material which will be removed during machinery.

6.2.2 Surface Flaws – The surface flaws are divided into 2 types; cracks and exposed aluminum. Cracking is caused by improperly balanced solidification and exposed aluminum is caused by the gap in the forming body which originate from the lack of local replenishment of molten aluminum. These types of flaws are inspected with the eddy current inspection. Because this is a flaw detection process that excels in finding the surface flaws, it is performed after the bore has been honed. Similar to the ultrasonic method, the entire bore is inspected through the spiral scanning of the bore interior. The two types of flaws are distinguished by image-processing looking into the differences in the shape and area of occurrence depending on the casting mechanism.

7. SUMMARY

1. Developing an MMC all aluminum block for a new high power sports type engine, 2ZZ-GE, for mass production was realized.
2. Crystallized alumina-silica fiber and mullite particle were selected as MMC reinforcements. The Strength, rigidity between the bores and the wear properties of the MMC cylinder block were ensured by optimizing the volume fraction and size of reinforcements.
3. The influences of sulfur concentration in fuel and coolant temperature on piston ring wear were clarified by the RI tracer analysis.
4. A casting technology to produce an almost defect-free MMC block was established by adopting a laminar-flow die-cast filing and by developing control techniques for mold temperature, squeeze pin and gas discharge.

8. ACKNOWLEDGEMENT

We would like to express our profound gratitude to the numerous people within and outside the company without whose cooperation this project could not have materialized.

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