Mechanical Properties of Spheroidal Graphite Cast Iron Made by Reduced Pressure Frozen Mold Casting Process

Kazumichi Shimizu¹, Yaer Xinba¹, Masahito Tanaka² and Hideki Shudai³

¹Department of Material Science and Engineering, Muroran Institute of Technology, Muroran 050-8585, Japan
²Sankyo Co. Ltd, Osaka 555-0001, Japan
³Mayekawa MFG. Co., Ltd, Tokyo 135-8482, Japan

The reduced pressure frozen mold casting process has been known as a recycling-based casting method with several advantages, such as improvement of the work environment, reduction of industrial waste and significant improvement of product yield. In this method, only water and silica sand were used to make mold, which was rapidly frozen at —40 °C, then molten metal was poured into it. In the present investigation, samples were made by the reduced pressure frozen mold casting process and previous processes, and comparisons of their mechanical properties, especially the fatigue strength, were reported.

As a result, it was clarified that cast iron made by the reduced pressure frozen mold casting process has a sufficient strength; therefore the reduced pressure frozen mold casting process was expected to be applicable to other castings that have been made by previous casting processes. [doi:10.2320/matertrans.MRA2008357]

(Received October 8, 2008; Accepted February 23, 2009; Published April 8, 2009)

Keywords: reduced pressure, frozen mold, casting, mechanical property, fatigue strength

1. Introduction

Recently, establishing a recycling-based society with a small environmental load has produced a strong demand. In the casting industry, where cast recycling is possible, acting on improving the working environment and environmental problems are being regarded as more and more important.

One of the previous casting processes was producing a cast part by forming a mold from a sand mixture and pouring molten liquid metal into the cavity of the mold. However, the working environments of the casting process was very poor due to the noise, dust, vibration, stench, etc., and even worse, a large quantity of industrial waste, such as large amounts of sand, was produced. In addition, in the recycling and regenerating process of these sands, the sand and hardener were finely ground and floated into air, which also polluted the surrounding environment of the factory, the cost of the environmental protection, such as a dust collector, increased.

The domestic production cost of these casting processes rose because of the expense of the hardener and disposal costs of these industrial wastes. Accordingly, in the present day, Japan’s casting industry could not compete with the importing of cheap overseas castings and tried to overcome the difficulties of new technology studies. Also again the typical [dirty], [hard] and [dangerous] workshops were also difficult to ensure the health of young laborers.

As one of the solutions, the frozen mold casting process was developed. It was a technology that involved freezing the moisture content in the sand that replaced the sand hardening process in previous casting processes.

At the beginning of the 1970s, W.H. Booth Co. in England designed a molding method that used “Green sand”, a mixture of silica sand, clay, moisture and some other additives that was frozen by liquid nitrogen to serve as the cast mold, and this method was practically used for frozen mold casting.1,2) In our country, since the 1970s, aimed at energy savings, non-environmental pollution casting technology and application of LNG (Liquefied Natural Gas) low temperature industrial technology, many research institutions and enterprises have been studied for the practical use of this method.1,3–10) This former type frozen mold was called the F-set mold, which was a mold making method that froze the moisture in green sand using dry ice or liquid nitrogen to strengthen the mold. Compared to this, the reduced pressure frozen mold (RPFM) casting process aimed at the establishment of an energy saving/non-environmental pollution casting technology, and was developed as part of a new regional consortium R&D enterprise supported by METI (Ministry of Economy, Trade and Industry).

The RPFM casting system basically consists of a molding workshop, freezing equipment, a teeming workshop, and sand disposal equipment. Since the sand can be directly reused, the sand recycling equipment and the large-scale environmental purifier equipment are not needed. This RPFM casting process has the following superior features when compared to the conventional processes:

1. Only water is used as a binder in the sand mixing/molding process to obtain a sufficient mold compressive strength. No organic binder/curing agents, which cause gas generation and the large environmental load during teeming, are needed.
2. During the shake-out process, the binder (the frozen water) becomes fluid due to the high temperature metal when the casting is finished. As a result, the bonding force of the sand will disappear and the sand mold can be naturally collapsed. Accordingly no large sand disposal equipment is needed.
3. The RPFM casting process can reduce the significant amount of generated dust, noise, and vibration when compared to the conventional casting processes.
4. The metal fluidity is very fine. Even if the amounts and sizes of the risers are significantly reduced, casting defects are controlled to a minimum and the production yield can be much improved.
It has adaptability to make a core of the casting.

The RPFM can rapidly and effectively freeze the mold when compared to the mold just placed in a freezing room. However, there was little information about the mechanical properties of the casting obtained by the RPFM casting process, especially when compared to the conventional casting methods. In addition, there has been a concern about the possibility of forming an unexpected chilled structure caused by the rapid solidification by the frozen mold used in the RPFM casting process. In the view of these points, the mechanical properties of the casting produced by this new molding method using reduced freezing technology was investigated and a comparison with those from the conventional methods were reported in this paper.

2. Casting Process Using Reduced Pressure Frozen Mold Casting Method

In the present study, silica sand with an average diameter of 408 μm was used. Table 1 shows its composition.

The mold making process, shown as Fig. 1, began with filling the sand mixed with a suitable moisture content into a flask (Fig. 1(b)) that was placed on a wooden mold with vent holes (Fig. 1(a)). The mold filled with the sand was rapidly frozen using a reduced pressure aspirator with a freezing equipment. Figure 2 is a schematic diagram of the reduced pressure aspirator. The mold freezing technology makes good use of the certain permeability extent of the sand and lets low temperature air in the freezing room pass through the sand by force, this enables to freeze the moisture rapidly and uniformly. According to a previous study, the RPFM method has 10 times freezing effect when compared to a mold just placed in freezing room.9) The pattern was then removed from the flask. After the surface of mold cavity coated with a heat resistant coating (Fig. 1(c)), the drag and cope were mated and the pouring cup set to complete the frozen mold (Fig. 1(d)). The mold cavity was filled with the molten metal (Fig. 1(e)). The frozen mold was heated by the high temperature metal to naturally collapse. After removal of the parts (Fig. 1(f)), the sand would be returned in to the sand treatment system. These working contents are almost the same as the conventional sand molding casting process except that the mold cavity is manufactured by the freezing equipment.

It is considered that the strength of the frozen mold differs with the size of the sand, moisture content, and even the mold captivity when freezing. In this system, the compressive strength of the frozen mold has a tendency to increase with the moisture content and reduction of the freezing temperature. Therefore the strength of the mold when the moisture content is 4.0~5.0 mass%, and the freezing temperature is −5~−10°C is considered to be the most acceptable. However, it takes a long time to uniformly freeze the mold from its surface to center at −10°C or higher, and it is inefficient from the view point of manufacturing. Using the reduced pressure freezing technology for optimizing the mold process, the entire mold can be rapidly and uniformly frozen at −40°C to obtain the desired strength. The method also improves the availability of the equipment.

3. Experimental Procedure

3.1 Specimens

The specimens investigated in this study were spheroidal...
Graphite cast irons (FCD) made by various castings using “RPFM” which used only silica sand and water, a “Green sand mold” which used green sand that was a mixture of silica sand, clay, moisture, and other additives, and the “CO₂ process mold” which employed a mixture of sand and a liquid silicate binder.

These specimens are manufactured by using the Y-shaped block pattern. The Y-shaped block pattern’s shape and size are shown in Fig. 3. Molten metal is poured under the same conditions (pouring temperature is 1530−1540°C, pouring time is approximately 20 s) for all the molds.

The specimens cut into two parts from the Y-shaped block, and labeled RPFMs 1 and 2, Green sand molds 1 and 2, and CO₂ process molds 1 and 2. Their chemical compositions are shown in Table 2. It can be clearly seen that their chemical compositions were approximately the same. Each specimen’s microstructure, spheroidal graphite ratio and pearlite area ratio were also shown in Fig. 4. Spheroidal graphite ratio and pearlite area ratio were calculated using the microstructure of the specimens according to JIS G 5502.

### 3.2 Static tests

The specimens for tensile test were prepared by machining. The tensile test is performed using an Instron universal testing machine (AG-50kNE) at the constant cross head speed of 1 mm per minute. The test piece had 6 mm diameter and 42 mm parallel portion according to the JIS 14 standard. The shape is shown in Fig. 5.

For the hardness test, the Brunel hardness test and Rockwell hardness test were preformed. The test piece was a 30 × 30 × 15 mm plate. For the Brunel hardness test, the diameter of the indenter was 10 mm, the load was 29400N with the loading time of 30 seconds, and the number of measurement points was 5. For the Rockwell hardness test, the B scale was used, the loading time was 30 seconds, and the number of measurement points was 7.

### 3.3 Impact test

An instrumented Charpy impact tester was used. The pendulum hammer has a load of 243N and the swing arm length is 0.6385 m. The standard test piece for the Charpy impact test was a V-notched specimen with a size of 10 mm × 10 mm × 55 mm according to JIS Z 2242, shown as in Fig. 6.

### 3.4 Fatigue test

The fatigue tests were performed using a plane bending fatigue tester (made by TKS Group). For this testing machine, the allowable average bending moment was 0−15 Nm, the repeat rate limit was 300−1500 c.p.m, and the repeat time can reach 999999 × 100 times. The cutting position of the plate test piece from the Y-block is shown in Fig. 7, and the shape and size of the test piece is shown in Fig. 8. The test piece’s minimum width is 20 mm, 3 mm thick, with a minimum cross-section area of 60 mm². A regular sinusoidal stress with the stress ratio of R = −1 at the loading frequency of 20Hz was applied. The maximum number of cycles was N = 10⁷ cycles.

All tests including tensile test, hardness test, Charpy impact test, and fatigue test were conducted at atmospheric pressure and room temperature.
4. Experimental Results and Discussion

4.1 Mechanical properties of specimens

Table 3 shows the results of the tensile test, hardness test and impact test of the FCD made by the various casting methods. From the table, it can be seen that elongation of some specimens manufactured in this study tended to show low values below 10%. In general, the strength of FCD is dependent on the base matrix and spheroidal graphite ratio, that is to say, with the decreasing spheroidal graphite ratio, the tensile strength and elongation decrease. In general, the elongation of the FCD with a spheroidal graphite ratio of less than 80% is less than 10%; accordingly, its specific...
deformation energy will be lost. The results of this study well agree with the common characteristics of the FCD. Therefore, the effects of the base matrix and spheroidal graphite ratio of the FCD on mechanical properties are considered in the present investigation.

From Table 3, it can also be seen that the tensile strength is approximately 3 times its Brunel hardness for each material, therefore, having a good correlation of \( \sigma_B = 3 \cdot \text{HB} \). In general, there has a correlation between the hardness and tensile strength for the cast iron. In the case of the FCD, the relationship of \( \sigma_B = 3 \cdot \text{HB} \) for the tensile strength \( \sigma_B \) and Brunel hardness \( \text{HB} \) was reported. Since the hardness is determined by the base matrix, not or slightly affected by the spheroidal graphite ratio, the Brunel hardness values as shown in Table 3 were almost the same independently of the mold-making methods.

According to a previous study, the Charpy impact property of the FCD dramatically differed with the base matrix. The Charpy impact value decreased when the pearlite area ratio increased. In the present investigation, the pearlite area ratios of the specimens made by the various molds including RPFM were approximately the same as shown in Fig. 4. Therefore, there were not clear differences in the Charpy impact values among them.

From the results mentioned above, it can be understood that the FCD specimens made by various methods including the RPFM casting process have almost the same mechanical properties from the view points of the tensile strength, hardness, and Charpy impact value.

### 4.2 Fatigue strength

The S-N curves obtained from the fatigue tests of the FCD specimens made by various molds such as the RPFM, Green sand mold, and CO\(_2\) process mold are shown in Fig. 9. As a consequence, the fatigue limit of the FCD made by the RPFM, Green sand mold, and CO\(_2\) process mold were \( \sigma_{w} = 195 \text{ MPa} \), \( \sigma_{w} = 200 \text{ MPa} \), and \( \sigma_{w} = 135 \text{ MPa} \), respectively. The fatigue strength of the FCD made by the RPFM was approximately the same value as that made by the Green sand mold, and showed a slightly higher value than that made by the CO\(_2\) process mold.

In order to discuss the results, the microstructures of the fractured FCD specimens after the highest-cycle fatigue tests were observed using an optical microscope. The results are shown in Fig. 10. It can be clearly seen that there were no significant differences between the FCD made by the RPFM and by the Green sand mold. Since the pearlite area ratios of these two FCD specimens were approximately the same as shown in Fig. 4, they showed almost the same fatigue properties.

### Table 3 Mechanical properties and spheroidal graphite ratio of FCD manufactured by different molds.

<table>
<thead>
<tr>
<th></th>
<th>Tensile strength ( \sigma_B ) (MPa)</th>
<th>0.2% proof stress ( \sigma_{0.2} ) (MPa)</th>
<th>Elongation ( \phi ) (%)</th>
<th>Brunell hardness ( \text{HB} )</th>
<th>Rockwell hardness ( \text{HRB} )</th>
<th>Charpy impact value ( C(kJ/m^2) )</th>
<th>( \sigma_B / \text{HB} )</th>
<th>Spheroidal graphite ratio (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>RPFM</td>
<td>1</td>
<td>599</td>
<td>330</td>
<td>10.8</td>
<td>168</td>
<td>86.4</td>
<td>87.4</td>
<td>3.57</td>
</tr>
<tr>
<td></td>
<td>2</td>
<td>519</td>
<td>307</td>
<td>7.5</td>
<td>163</td>
<td>89.0</td>
<td>71.8</td>
<td>3.18</td>
</tr>
<tr>
<td>Green sand mold</td>
<td>1</td>
<td>629</td>
<td>345</td>
<td>9.3</td>
<td>171</td>
<td>91.0</td>
<td>75.1</td>
<td>3.68</td>
</tr>
<tr>
<td></td>
<td>2</td>
<td>515</td>
<td>315</td>
<td>6.2</td>
<td>171</td>
<td>86.6</td>
<td>71.8</td>
<td>3.01</td>
</tr>
<tr>
<td>CO(_2) process mold</td>
<td>1</td>
<td>574</td>
<td>321</td>
<td>6.2</td>
<td>172</td>
<td>84.7</td>
<td>61.6</td>
<td>3.34</td>
</tr>
<tr>
<td></td>
<td>2</td>
<td>—</td>
<td>—</td>
<td>—</td>
<td>—</td>
<td>—</td>
<td>—</td>
<td>—</td>
</tr>
</tbody>
</table>

Fig. 8 Shape and size in millimeters of fatigue test piece.

Fig. 9 S-N curves obtained from the fatigue tests of the FCD specimens made by the RPFM, Green sand mold, and CO\(_2\) process mold.
strength. On the other hand, some dendrite structures were observed in the microstructure of the FCD specimen made by the CO\textsubscript{2} process mold. This was caused by the fact that carbon was crystallized to form cementite rather than graphite because of the rapid cooling rate during the solidification. Therefore, the FCD made by the CO\textsubscript{2} process mold showed a lower fatigue strength value than that made by the others. That is to say, the fatigue strength value significantly depends on the base matrix of the materials. Although there may be a concern about the possibility of forming the unexpected chilled structure caused by the rapid solidification by the frozen mold used in the RPFM casting process, no such structure was observed in this study.

The fractured faces of the FCD specimens made by the RPFM, Green sand mold, and CO\textsubscript{2} process mold after the highest-cycle fatigue tests were observed using a scanning electron microscope (SEM). Figure 11 shows the results of the SEM observations. In these figures, similar structures were observed; the black-colored graphite nodules were surrounded by a pearlite base matrix. In addition, the beach marks, which were characteristic of a fatigue structure, were observed in the base matrix. As a consequence, it can be considered that the FCD made by the RPFM casting process is similar to those made by castings using the Green sand mold and CO\textsubscript{2} process mold based on the fatigue fractural characteristics.

From the results mentioned above, the FCD specimens made by the RPFM casting process have no problems from the view point of its mechanical properties including the tensile strength, hardness, Charpy impact value, and fatigue strength when compared to conventional casting methods. The RPFM casting process is expected to be an alternative casting method.

5. Conclusions

In the present investigation, the FCD specimen was made by the RPFM casting process, and its mechanical properties including the fatigue strength, which is indispensable for materials, were evaluated. The conclusions are listed below:

The FCD made by the RPFM casting process has almost the same mechanical properties as the FCD made by the conventional method. For the FCD made by the RPFM casting process, there was no unexpected chilled structure. Considering its good working condition and excellent sand recyclability, the RPFM casting process is expected to be a promising molding method in the future.
Acknowledgements

Finally, thanks for MYCOM to variety of cooperation in the process of the research.

REFERENCES