Surface Hardening of Ferritic Spheroidal Graphite Cast Iron by Friction Stir Processing

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A ferrite-based spheroidal graphite cast iron (FCD450) is difficult to harden using a conventional surface hardening method, because the carbon content in the matrix is very low. In order to solve this problem, the friction stir processing (FSP) was used in this study as a new hardening method for cast irons. The authors have clarified in a previous study that the pearlite-based cast iron, such as FC300 and FCD700, can be hardened using the friction stir processing and that there are several advantages, such as a higher hardness and no required post surface machining. In this study, it was clarified that a Vickers hardness of about 700 HV is obtained due to the formation of fine martensite even in the ferrite-based spheroidal graphite cast irons, although the optimal process range is much narrower than that of the pearlite-based cast iron due to the requirement of both the heat input for diffusion of the carbon into the matrix and the high cooling rate for the martensitic transformation.


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1. Introduction

Cast iron is used in various industrial applications, such as automobile parts, dies, and machine tool parts due to its excellent strength and fracture toughness. The surface of these parts are usually hardened by frame hardening,1) induction hardening,2) electron-beam hardening,3) laser hardening,4,5) etc. The surface hardening is indispensable in order to extend their lifetime. However, it is very difficult to use these techniques for ferrite-based cast iron which has a low carbon content in the matrix. The low carbon content leads to a deficient hardness and thickness of the hardened layer. Therefore, the microstructure of the ferrite-based cast iron is generally changed to pearlite by heat treatment before the surface hardening. On the other hand, there are some reports suggesting that an annular martensite layer around the graphite in ferrite-based cast iron can improve the wear resistance.5–7)

Friction Stir Processing (FSP) is a solid state process, which can tailor the microstructure by severe plastic deformation and frictional heat. A schematic illustration of FSP is shown in Fig. 1. The principal of FSP is the same as that of the Friction Stir Welding (FSW).8) It can modify the various properties of the material surface by the frictional heat generated by pressing the cylindrical tool against the base materials with a high rotating speed. In the processed region, the tool rotating direction and tool traveling direction are the same on the advance side (AS), while the other side is called the retreating side (RS). The frictional heat can be generated very locally, and the heat input in the surrounding area is suppressed. Accordingly, a large cooling rate can be obtained by FSP. Additionally, the deformation can be suppressed due to the low heat input compared with conventional welding methods. For aluminum alloys, FSW has been widely studied by many researchers.9–11)

The authors clarified that the pearlite-based cast iron, such as FC300 and FCD700, can be hardened due to the formation of fine martensite by the FSP.12,13) However, the main phase of these materials is pearlite. There is no report about the surface hardening of ferrite-based cast iron. In this study, the FSP conditions are optimized for the surface hardening for ferrite-based cast iron (FCD450), and the changes in the microstructure and hardness by FSP are investigated.

2. Experimental Procedure

A 5 mm thick ferrite-based spheroidal graphite cast iron (FCD450) plate was used as the work-piece. The chemical composition and the microstructure of the base material are shown in Table 1 and Fig. 2, respectively. The microstructure of the base metal is ferrite which has hardness of 180–200 HV. Mg was added in order to produce spheroidal graphite particles. The surface of the FCD450 plate was modified by FSP in order to form the hardened layer. The tool
shape for the FSP is shown in Fig. 3. The tool shape is different from the common tool that consisted of a shoulder and a probe. The tool without a probe was used so as not to change the shape of the graphite by stirring of the probe in the cast iron.\textsuperscript{12,13} The tool tilt angle of 3° was adopted. The tool rotation speed and the tool traveling speed were varied from 900–1500 rpm and 50–150 mm/min, respectively. Ar shielding gas was used during the FSP. The hardness of the matrix was measured on a cross section (0–1.5 mm depth) using a micro-Vickers hardness tester. The microstructure was observed using an optical microscope and a laser microscope.

3. Results and Discussion

3.1 Surface appearance

Figure 4 shows the surfaces of the friction stir processed FCD450 plates at the rotation speed of 900 rpm and various traveling speeds. While the FSP was carried out at a constant rotation speed and traveling speed, the applied load was increased from 2 ton (2000 kgf) to 5 ton (5000 kgf). The defect was formed during the early stage of the FSP for all samples because the lack of heat input led to cutting of the plate. Additionally, the width of the modified region was smaller than the tool diameter (about 20–23 mm) when the heat input was insufficient. The width of the modified region became narrower according to the increment of the traveling speed. It is considered that the tool was lifted during the process under the low heat input condition of the high traveling speed. Especially, groove-like defects were clearly observed in the middle part of the modified region for the sample processed at 150 mm/min and low applied loads. These results revealed that the high applied load, which provided a suitable heat input, was important for obtaining the large modified region.

Based on the results, the constant applied load of 5 ton (5000 kgf) was used for the FSP. Figure 5 shows the surface appearances of the FSPed samples. A large flash was formed on the sample processed at 1500 rpm and 50 mm/min due to the excess heat input. On the other hand, there were exfoliation and roughening on the surface for the sample processed at 1500 rpm and 150 mm/min due to the lack of heat input. Ideal modified regions could be obtained under the FSP conditions of 1200 rpm and 50 mm/min, and 1500 rpm and 100 mm/min. Based on these results, it is considered that the optimization of the FSP condition is necessary to control the heat input in order to prevent defects and increase the modified region.

3.2 Vickers hardness

Figure 6 shows the effect of the traveling and rotating speeds of the tool on the Vickers hardness of the modified region. The hardness increases to 800 HV in the large region with 12 mm width and 1.2 mm depth for the sample processed at 900 rpm and 50 mm/min. However, the depth of the hardened region with high hardness decreased due to the low heat input for the sample processed at 900 rpm and
100 mm/min. Additionally, there were some low hardness regions from the center to the RS. The hardness distribution of the sample processed at 900 rpm and 150 mm/min, the condition which provided the minimal heat input in this study, was similar to that of the sample processed at 900 rpm and 100 mm/min.

The modified region with high and uniform hardness was large for the sample processed at 900 rpm and 50 mm/min. On the other hand, the depth of the modified region increased by the increment of the rotating speed. However, there was a low hardness region near the surface for the sample processed at 1200 rpm and 50 mm/min. Although the modified region was large for the sample processed at 1500 rpm and 50 mm/min, the condition which provided the maximal heat input, the hardness increased to only 400–600 HV.

### 3.3 Microstructure

Figure 7 shows the microstructure and EDX mappings of the cross section of the sample processed at 900 rpm and 100 mm/min. The elongated particles can be identified as deformed graphite by the EDX mapping of element C. Plastic flow occurs before the base material is sufficiently softened due to the insufficient heat input, therefore a deformed graphite structure was formed.

As shown in Fig. 6, the sample processed at 900 rpm and 50 mm/min showed an obvious hardness increase. However, the sample processed at 1500 rpm and 50 mm/min showed no obvious hardness increase. Figure 8 compares the microstructure of these two samples. Figure 8(a) shows the microstructure of the samples processed at 900 rpm and 50 mm/min, which has a hardness value larger than 700 HV. Very fine martensite was formed and caused the remarkable increase in the hardness. On the other hand, in the sample processed at 1500 rpm and 50 mm/min, as shown in Fig. 8(b), the pearlite structure was formed due to the high heat input caused by the high rotation speed and low cooling rate caused by the low traveling speed. Thus, the hardness increase was not sufficient.

When the heat input is low and the temperature rise is just above the $A_1$ transformation temperature, the hardness increase in the sample is obvious. On the contrary, when
the heat input is high, the sample’s hardness is not sufficiently increased due to the insufficient cooling rate. There exists an optimal range of heat input in order to obtain a uniform hardness increase in a large hardened layer.

3.4 Revolution pitch

As discussed in 3.1–3.3, the optimal range of the heat input was important for the FSP in order to harden the FCD450 plate. The “revolution pitch”, which was defined by the following equation, was used in order to clarify the optimal range of the heat input.

\[
\text{Revolution pitch} = \frac{V}{N}
\]

where \(V\) and \(N\) are the traveling speed and rotating speed, respectively. The revolution pitch is the traveling distance per one rotation of the tool. The high revolution pitch value means a low heat input during the process. Table 2 shows the relationship between the revolution pitch and optimal process range. The optimal process range was defined as the process condition which led to the hardened layer with more than 1 mm of depth. The optimal condition for the FCD450 was 0.042–0.067 mm/r. On the other hand, it was 0.056–0.300 mm/r for the pearlite-based cast iron. The optimal process range of ferrite-based cast iron was narrower compared with that of the pearlite-based cast iron. Although 0.042 mm/r was out of the optimal process range of the pearlite-based cast iron due to excess heat input, it was adequate for the ferrite-based cast iron. As shown in Fig. 9, the narrow optimal process range of the ferrite-based cast iron, which has a low carbon content in matrix, is reasonable for the following reasons. (a) Maximal solubility limit of the matrix for carbon should be increased by austenitizing using the FSP, (b) nodular graphite is the carbon source for the

<table>
<thead>
<tr>
<th>Rotation speed [rpm]</th>
<th>Traveling speed [mm/min]</th>
<th>Revolution pitch [mm/r]</th>
<th>Heat input for hardness</th>
</tr>
</thead>
<tbody>
<tr>
<td>1500</td>
<td>50</td>
<td>0.033</td>
<td>Excess heat input</td>
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<tr>
<td>1200</td>
<td>50</td>
<td>0.042</td>
<td></td>
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<tr>
<td>900</td>
<td>50</td>
<td>0.056</td>
<td>Optimal heat input</td>
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<tr>
<td>1500</td>
<td>100</td>
<td>0.067</td>
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</tr>
<tr>
<td>1200</td>
<td>100</td>
<td>0.083</td>
<td>Insufficient heat input</td>
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<tr>
<td>1500</td>
<td>150</td>
<td>0.100</td>
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<tr>
<td>900</td>
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<tr>
<td>900</td>
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Fig. 8 Microstructures of FSPed FCD450. (a) Rotation speed: 900 rpm, Traveling speed: 50 mm/min (b) Rotation speed: 1500 rpm, Traveling speed: 50 mm/min.

Fig. 9 Processes required for hardening of Ferrite-based cast irons in FSP.
matrix, (c) a high cooling rate is needed for the martensitic transformation, and (d) both a sufficient heat input for diffusion of the carbon into the matrix and high cooling rate for the martensitic transformation were required to harden the ferrite-based cast iron. Therefore, the optimal process range of the ferrite-based cast iron was narrower than that for the pearlite-based cast iron.

The FSP is very useful for the surface hardening of the ferrite-based cast iron because the high cooling rate can be obtained by the local heating. Ferrite-based cast iron can be hardened by the FSP at the revolution pitch of 0.042 mm/r which leads to the excess heat input for the pearlite-based cast iron because the thermal conductivity of ferrite (71–80 W/mK) is higher than that of perlite (50 W/mK).

4. Conclusions

The Friction Stir Processing was used in this study as a new method of surface hardening for cast irons. The following conclusions can be drawn:

(1) The Friction Stir Process is very useful for the surface hardening of ferrite-based cast iron because the rapid heating and the following rapid cooling can be obtained by this method. Therefore, after FSP, it is possible to form a hardened layer on the ferrite-based cast iron.

(2) By performing FSP with the optimal heat input, Vickers hardness of about 700 HV is obtained even for the ferrite-based cast irons due to fine martensite formation.

(3) The optimal process range of ferrite-based cast iron is much smaller than that of the pearlite-based cast iron due to the requirement of both the sufficient heat input for diffusion of the carbon into the matrix and the high cooling rate for the martensitic transformation.

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REFERENCES