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

Koichi Imagawa1,*, 1, Hidetoshi Fujii1, Yoshiaki Morisada1, Toshiyuki Hashimoto2, Yasufumi Yamaguchi3 and Shoji Kiguchi2

1Joining and Welding Research Institute, Osaka University, Ibaraki 567-0047, Japan
2School of Science and Engineering, Kinki University, Osaka 557-8502, Japan
3Komatsu, Ltd., Hirakata 573-1011, Japan

Ferritic flake graphite cast iron, which is less commonly used due to its relatively low strength, was friction stir processed (FSP) for surface hardening in this study. We clarified that a Vickers hardness of above 700 HV can be obtained even for the ferritic matrix due to the formation of the fine martensite structure which can be seen in an ordinary quenched cast iron. Additionally, the effects of the graphite shape and microstructure of the matrix on the FSP conditions were investigated.

1. Introduction

Cast iron, which is an iron alloy containing relatively larger contents of carbon and silicon, has a lower melting temperature and excellent castability when compared with steel. Its excellent castability enables the iron to be cast into complex shapes. In addition, the presence of graphite among its matrix results in many excellent characteristics in various mechanical properties such as wear resistance, corrosion resistance, machinability and vibration absorption. Therefore, it has been used in many industrial applications, such as automobile parts, industrial machine parts and machine tool parts. As described above, the microstructure of cast iron basically consists of two components (graphite and matrix), and many of its physical and mechanical properties such as tensile strength and ductility are determined mainly by the structure combination of graphite and matrix.1,2)

In this study we used a flake graphite cast iron which consists of flake-shaped graphite and fully ferritic matrix. In general, this type of ferritic flake graphite cast iron can be produced at a relatively low cost, but its mechanical properties are very poor and it is not commonly used as a useful engineering material. So, if we can improve its mechanical properties sufficiently by some means we can expect to expand its application more largely. The manufacturing method of Friction Stir Processing (FSP) is a solid-state process which can tailor the microstructures of materials with severe plastic deformation and frictional heating.3) A schematic illustration of the FSP is shown in Fig. 1. The principal of FSP is the same to that of Friction Stir Welding (FSW).4) This method can modify largely the various properties of the surface layer of a material by a large scale of plastic deformation and frictional heat generated by pressing the cylindrical tool against the base material at a high rotating speed.

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 the FSP. Additionally, the deformation can be suppressed due to the lower heat input compared with conventional welding methods. For the low-melting-point materials such as aluminum alloys and magnesium alloys, FSW has been widely studied by many researchers.5–12) Recently, even for the high-melting-point materials such as iron-based materials, it has been implemented in research studies due to the improved durability of the tools.13–17) The authors already clarified that the pearlite-based cast iron, such as FC300 and FCD700, can be hardened sufficiently due to the formation of fine martensite by means of the FSP.18,19) It was clarified that Vickers hardness of about 700 HV can be obtained due to the formation of the fine martensite even in the low hardenability ferrite-based spheroidal graphite cast iron without any pretreatment.20) In this study, the FSP conditions are optimized for the surface hardening of the ferritic flake graphite cast iron (FC100), and the changes in the microstructure and the hardness by the FSP are investigated.

2. Experimental Procedure

The work-pieces for this study were the 5 mm thick ferritic flake graphite cast iron (FC100) plates which had been produced by annealing a pearlitic flake graphite cast iron as shown in Fig. 2. The chemical composition and the micro-
structure of the base material are shown in Table 1 and Fig. 3, respectively. The microstructure of the matrix of the base metal is ferrite whose hardness is 130–180 HV. The tool shape for the FSP is shown in Fig. 4. The shape of the tool used in this study is different from that of a conventional one with a probe and a shoulder, i.e., the tool used is only a cylindrical bar (shoulder part) of 25 mm in diameter with no probe. This was done for the purpose of decreasing the amount of changing in graphite shape of the specimens. The tool tilt angle and the tool load were always kept to be 3 degree and 3000 kgf respectively, but the tool rotation speed and the tool traveling speed were varied between 900–2400 rpm and between 50–150 rpm respectively. Ar gas was used as the shielding gas during the FSP. The hardness of the matrix was measured on a cross section using a micro-Vickers hardness tester.

The microstructures were observed using an optical microscope and a laser microscope. The temperature change of a specimen during the FSP was measured at the position of 0.5 mm beneath the surface using a K type thermocouple.

3. Results and Discussion

3.1 Surface appearance

Figure 5 shows the surface appearance of the specimens which were FSPed in various conditions. In many cases of the other kinds of materials the FSP method is recognized to produce relatively smooth surfaces on the specimens. However, in the case of this material of ferritic flake graphite cast iron the relatively rough surfaces were obtained by the FSP in all the conditions between 900–2400 rpm in rotation speed. This phenomenon is quite different from that of spheroidal graphite cast iron. In the case of spheroidal graphite cast iron all of the graphite nodules are located independently among the matrix, and the matrix is observed to keep a very good continuity condition. However, in a case of a flake graphite cast iron many long and thin graphite flakes are observed to divide the matrix into many small and fine units of matrix. This fine and less continuous condition of the matrix of a flake graphite cast iron is considered to result in the surface which are much rougher than that of

<table>
<thead>
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<th>Rotation speed</th>
<th>50 mm/min</th>
<th>100 mm/min</th>
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<td>2100 rpm</td>
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<td>2400 rpm</td>
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<td>2700 rpm</td>
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<td>3300 rpm</td>
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Fig. 5 Surface appearances of each FSPed ferritic flake graphite cast iron.
spheroidal graphite cast iron. This is considered to be resulted from the sufficient softening effect of the specimen caused by the sufficient amount of heat input due to the higher rotation speed and the lower travelling speed.

3.2 Vickers hardness

The optimal surface hardening of the ferrite-based cast iron requires both a sufficient heat input for diffusion of the carbon into the matrix and a high cooling rate for the martensitic transformation.20) The surface hardening of the ferritic flake graphite cast iron also required the diffusion of the carbon into the matrix and the high cooling rate, as shown in Fig. 6. Figure 7 shows the effect of the traveling and rotating speeds of the tool on the Vickers hardness distribution in the modified region on the cross section of the samples. In the lower heat input conditions up to 1200 rpm some local portions were measured to be some 700 HV but the overall hardness was measured to be some 600 HV. This is considered to be resulted from the lack of diffusion of carbon into the ferritic matrix due to the dearth of heat input even though the specimen temperature had reached up to the $A_C$ transformation point during the FSP. The hardened layer with a hardness of above 700 HV was obtained near the surface at a rotation speed that ranged from 1500 to 2400 rpm. However, the hardened layer was nonuniformly distributed at the area beneath the surface due to the insufficient and non-uniform diffusion of the carbon under these processing conditions. In the condition of 2700 rpm in rotation speed, the hardened layer was widely and homogeneously distributed when the traveling speed was 100 mm/min. On the other hand, a sufficient hardness could not be obtained near the surface when the travelling speed was 50 mm/min. In this case, although the carbon diffusion was sufficient, the cooling rate was too low to harden the surface sufficiently.

3.3 Microstructural characterization

The sample processed at 1500 rpm and 50 mm/min showed a monogenesis hardness increase over a wide area near the surface. In addition, the sample processed at 3000 rpm and 100 mm/min showed a hardness increase up to 700 HV. However, the sample processed at 3000 rpm and 50 mm/min showed no obvious hardness increase near the surface. Figure 8 shows the comparison of the microstructures of these samples. The microstructures of Figs. 8(a)–8(f) were observed in the middle of the stir zone, and the microstructure of Fig. 8(g) was observed near the surface of the sample. Figure 8(a) indicates that the volume fraction of the untransformed ferrite structure was quite high when the sample was processed at 1500 rpm and 100 mm/min. On the other hand, as shown in Fig. 8(d), the fine martensitic structure was formed in the region near the graphite, and a hardness of 700 HV or more was obtained. Secondly, the martensitic structure was widely formed near the surface, and the volume fraction of the untransformed ferrite structure was relatively lower when the sample was processed at 3000 rpm and 50 mm/min. In this case, although the carbon diffusion was sufficient, the cooling rate was too low to harden the surface sufficiently.
\[ D = 2.3 \times 10^{-5} \text{ m}^2/\text{s} \exp\left(-\frac{148 \text{kJ}}{RT}\right) \] (1)

\( R \): gas constant (JK\(^{-1}\)mol\(^{-1}\)), \( T \): absolute temperature (K).

Figure 9 shows the calculated temperature history and the carbon diffusion distance when the sample was processed at 3000 rpm and 100 mm/min. Under this FSP condition a widely hardened layer was obtained as previously discussed. The graphite distance in the cast iron used in this study was about 50–100 µm. The carbon diffusion distance is 111 µm as shown in Fig. 9. Therefore, the carbon can diffuse into the base matrix sufficiently under this condition. Therefore, it is possible to obtain a widely hardened layer when the temperature was sufficient for the diffusion of the carbon element. Finally, a mixed microstructure consisting of martensite and pearlite was obtained, as shown Figs. 8(c) and 8(g). Under this condition, a sufficient cooling rate could not be obtained due to the excess heat input, because the travelling speed was too slow for such a high rotating speed as 3000 rpm. Thus, the hardness was not sufficient near the surface.

On the other hand, the fine martensite formed at a sufficient cooling rate was obtained as shown in Fig. 8(f). In this case, there might be a good hardness distribution for industrial applications, because the soft surface area can be removed by post-processing. As described above, the results of the microstructure observations show a good agreement with the hardness distribution.

### 3.4 Optimal process range of FSP

From the hardness distribution described in section 3.2, the optimal process condition is defined as the condition to obtain a hardness of above 700 HV in the area at 1 mm deep from the surface. Generically, in order to estimate the heat input during FSP or FSW the Frigaard equation and revolution pitch are used. Equations (2) and (3) show the Frigaard equation and revolution pitch, respectively.

\[ Q = 4/3\pi \mu \frac{P}{R^3}N = 16/3\pi \mu LNR \] (2)

\( Q \): heat input (W), \( \mu \): friction coefficient, \( P \): pressure (N/m\(^2\)), \( L \): load (N), \( N \): rotation speed (rad/s), \( R \): shoulder diameter (m).

\[ \text{Revolution pitch} = \frac{V}{N} \] (3)

\( V \): travelling speed, \( N \): rotation speed.

In this study, the heat input (\( q \)) is defined based on these equations using the rotation speed (\( N \)), travelling speed (\( V \)) and load (\( L \)).

\[ q = LN/V \] (4)

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Fig. 8 Microstructure of FSPed ferritic flake graphite cast iron.

Fig. 9 Temperature history and diffusion distance during FSP; (a) Temperature history, (b) Diffusion distance during FSP.
The frictional heat is based on the value that is obtained by multiplying the rotation speed of the tool and the applied load and dividing by the travelling speed. And the amount of heat input per unit length becomes larger if this value becomes larger. We tried to calculate this optimal value range of frictional heat during FSP for ferritic graphite cast iron and found that it is between $90 \times 10^3$–$198 \times 10^3$ rev·kgf/mm. The optimal ranges for ferritic spheroidal graphite cast iron and pearlitic flake graphite cast iron, which were obtained in our previous studies, are $75 \times 10^3$–$120 \times 10^3$ rev·kgf/mm and $9 \times 10^3$–$72 \times 10^3$ rev·kgf/mm, respectively.\textsuperscript{19–21} Figure 10 is the summarization of the optimal ranges of these cast irons. This figure indicates that the two cast irons with ferritic matrix require larger optimal heat input than the cast iron with pearlitic matrix. When compared in detail, the ferritic flake graphite cast iron required more heat input than the ferritic spheroidal graphite cast iron. In comparison of ferritic flake graphite cast iron and ferritic spheroidal graphite cast iron, the former requires a larger heat input than the latter and also the former has a wider optimal range than the latter. These differences are considered to be resulted from the difference in graphite shapes. As shown in Table 2 the thermal conductivity of the former is much larger than that of the latter.\textsuperscript{25,26} Therefore, the ferritic flake graphite cast iron can obtain a sufficient cooling rate for the hardening with a high heat input, because its thermal conductivity is higher than that of the pearlitic flake graphite cast iron.

### 4. Conclusion

The FSP conditions were optimized for the surface hardening of the ferrite flake graphite cast iron, and the changes in the microstructure and the hardness by the FSP were investigated. The following conclusions were obtained.

1. Vickers hardness of about 700 HV can be obtained due to the fine martensite formation by the FSP with the optimal heat input.
2. A smooth surface can be obtained when the heat input is large enough to soften the material sufficiently. However, the crack propagation easily occurs during the FSP of the ferritic flake graphite cast iron due to its graphite shape.
3. The optimal conditions in FSP of cast iron depend on the base matrix and the graphite shape largely. The ferritic flake graphite cast iron requires a comparably larger heat input for carbon diffusion, because the flake graphite has a comparably stronger tendency of heat release. Even though a larger heat input is applied to a flake graphite cast iron, this stronger tendency of heat release helps the transformation of its matrix into martensite. In the case of pearlitic flake graphite cast iron, the martensite transformation can be obtained without much diffusion of the carbon from the graphite to the matrix for the pearlitic flake graphite cast iron and the surface hardened layer was obtained because of the sufficient carbon content in the pearlite matrix. On the other hand, its excess heat input value is much lower than that of the ferritic flake graphite cast iron. It is because the thermal conductivity of the ferritic matrix is much larger than that of the pearlitic matrix as shown in Table 3.\textsuperscript{25,26}

### Acknowledgments

This research was supported by the Japan Science and Technology Agency (JST) under Collaborative Research Based on Industrial Demand “Heterogeneous Structure Control: Towards Innovative Development of Metallic Structural Materials”, by the Global COE, by the Japan Society for the Promotion of Science, by the ISIJ Research Promotion Grant, and by the Japan Foundry Engineering Society.

![Fig. 10 Optimal process range of various cast irons.](image)

#### Table 2 Effect of graphite shape on thermal conductivity.

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<th>Material</th>
<th>Thermal conductivity (W/m·K)</th>
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<td>Flake graphite cast iron</td>
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<td>Spherical graphite cast iron</td>
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#### Table 3 Thermal conductivity of base structure.

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<td>Pearlite</td>
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