Surface Hardening of Cast Irons by Friction Stir Processing*1

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A new surface hardening technology for cast irons was developed by applying the Friction Stir Processing (FSP) in which the matrix can be controlled in the solid state. Flake graphite cast iron (FC300) and spheroidal graphite cast iron (FCD700) were used to investigate the validity of this new method. As a result, it has been clarified that a Vickers hardness of about 700 HV is obtained for both the flake graphite cast iron and the spheroidal graphite cast iron, and that the hardness depends on the size and the density of the martensite phase. Moreover, the hardness can be controlled down to about 500 HV by changing the stirring degree. For previous hardening methods, post surface-processing was required because a large distortion was generated. However, with this new method, many advantages, such as a higher surface hardness and unnecessary post surface-processing, could be obtained. [doi:10.2320/matertrans.F-MRA2008835]

(Received May 12, 2008; Accepted September 4, 2008; Published November 12, 2008)

Keywords: surface modification, hardness, friction stir processing, cast iron, martensite

1. Introduction

Cast iron has excellent material characteristics, such as abrasion resistance, corrosion resistance, machinability, and vibration absorptivity, because it contains about 10 vol% graphite in its matrix. Therefore, it has been applied to various industrial fields, such as automobile parts (for example, the engine block, the brake drum, the gear boxes, and the steering wheel knuckles), industrial machine parts, and machine tool parts.

Currently, a weight saving and advanced features are being requested, and the material of choice is changing from cast irons to aluminum alloys and magnesium alloys, but in contrast to these developments, some high added values such as higher performance1–5) and thinner product 6,7) are requested for the cast iron components.

The Friction Stir Processing (FSP) performed in this study is a solid state process, which can control the microstructure using the frictional heat, and many such researches have already been intensively conducted for aluminum alloys.8–20)

For ferroalloys, on the other hand, there is no report concerning the FSP, although some research studies on the friction stir welding21–23) have begun because some issues, such as the durability of the tool, have to be solved.

In this study, the FSP is treated as one of the surface treatment methods for cast irons, and it was investigated in detail using a cylindrical tool as a new hardening method of cast irons.

The FSP uses the same principle as the friction stir welding method.24) Friction stir welding is a solid state joining method using plastic flow in which the material is not melted. It has many advantages25) that solve many problems, such as gas inclusion and grain growth in the weld of aluminum alloys. Also, neither fumes nor spatter is generated, because the material is not melted.

No practical uses are currently available though a variety of welding methods have been examined for cast iron which is well known to be a very difficult welding material.26–28)

Therefore, this new modification technique can be applied to the welding method of cast irons by making the best use of its advantages.

2. Experimental Procedure

Five-mm-thick flake graphite cast iron (FC300) and spheroidal graphite cast iron (FCD700) plates were used as the test materials. Table 1 shows their chemical compositions. As shown in Fig. 1, the matrix for both materials is perlite, and therefore, the micro Vickers hardness of the spheroidal graphite cast iron is 200–230 HV, while for the flake graphite cast iron is 170–210 HV.

The surface treatment was performed for both cast irons using the friction stir processing illustrated in Fig. 2 to harden the surface of the specimens. The conditions of the FSP are as follows:

![Fig. 1 Microstructures of base materials. (Etched by 3 mass% nitrate alcohol)](image)

(a) Spheroidal graphite cast iron, (FCD700) 200–230HV
(b) Flake graphite cast iron (FC300) 170–210HV.
Traveling speed of the tool: 50, 100 and 150 mm/min
Rotation speed of the tool: 900 rpm
Load: 1.0 × 10³ to 5.6 × 10³ kgf

A cylindrical tool with 25 mm diameter was used for the tool and the tilt angle was 3 degrees. Therefore, as shown in Fig. 2, the rear side of the tool is pushed into the cast iron in the depth direction by approximately 1.3 mm, in comparison to the front of the tool. The tool material was a tungsten carbide based alloy.

Moreover, in order to increase the thickness of the hardening layer, another tool attached with an umbo (with 4 mm diameter and 1.5 mm length) at the center of the bottom of the tool is also used for comparison.

After performing the FSP, the hardness of the matrix was measured on a cross section (0–1.5 mm depth) using a micro Vickers testing machine. In order to measure the hardness of the matrix including graphite, a Rockwell testing machine, which has a larger indenter than that of the micro Vickers testing machine, was also used. The microstructure was observed using an optical microscope.

3. Results and Discussion

3.1 Optimal condition of friction stir processing

Figure 3 shows the surface appearances of the spheroidal graphite cast iron and the flake graphite cast iron friction-stir-processed under various conditions. All experiments were performed while increasing the load during the process. The optimum conditions of the FSP were determined by regarding the groove defect formed at the center of the sample and the peeling off of the material due to the adhesion to the tool as defects.

For the FCD700 cast iron, an excellent surface without any defect was obtained at 50 mm/min using the cylindrical tool, when the load exceeded about 3.0 × 10³ kgf. On the other hand, at 100 or 150 mm/min, a load of 3.5 × 10³ kgf or more is necessary, and the required minimum load increases with the increasing tool traveling speed. Moreover, the modified region becomes narrower when comparing to the 50 mm/min case. This is because the tool is pushed upward at a higher traveling speed. It is necessary to increase the pressure to widen the hardened area.

On the other hand, a sufficient surface was also obtained at the travel speeds of 50 and 100 mm/min, even when a tool with an umbo (probe) was used in order to increase the thickness of the hardened layer. However, an excellent surface could not be obtained at 150 mm/min even when the load was increased to 4.2 × 10³ kgf. A higher minimum load is necessary for a tool with the umbo, when compared to that without the umbo.

In addition, for a different kind of cast iron, FC300, a sufficient surface without any defect was also obtained at the traveling speed of 100 mm/min as well as 50 mm/min when the load exceeded 3.0 × 10³ kgf. The hardened area becomes narrower with the increased traveling speed. At 150 mm/min, the defects could not be removed even when a 5.6 × 10³ kgf load was applied, which is also similar to that of the FCD700.

The formation of the defects is significantly related to the heat input, as stated above. When the heat input is insufficient, for example, under the conditions of 900 rpm and 2 × 10³ kgf, the defect is formed during the early stage by scooping out the material, as shown in Fig. 3. This is because the cast iron does not soften due to the insufficient heat input, and then a flash is formed by a cutting-like phenomenon. When the heat input is excessive, the surface material is peeled off as if the material is melted because it softens too much. A microstructure formed by the plastic flows without the surface being peeled off can be obtained by controlling the heat input properly. Therefore, it is necessary to adjust the process conditions, such as the rotation speed and the traveling speed, in order to optimize the heat input. In this case, there was neither warp nor a change in the dimensions of the material, which is completely different from that obtained by other surface hardening methods.

3.2 Hardness and microstructure

Figure 4 shows the macrostructure of a cross section the sample friction stir processed under the following conditions; a traveling speed of 50 mm/min, a rotational speed of 900 rpm, a load of 3.2 × 10³ kgf and a 0 mm umbo length.

At the center, the spheroidal graphite is crushed and striated, then becomes surrounded by a lamellar perlite and martensite structure. Since the tool is inclined by three
degrees, the rear side of the tool is pushed into the material by approximately 1.3 mm compared to the forward side, and accordingly, it is natural that the plastic flow region is observed in the center part of the cross section. Furthermore, both in the advancing side (the direction of the tool rotation is the same as the direction of the tool movement) and in the retreating side (the direction of the tool rotation is opposite to the tool movement), the region where the spheroidal graphite is crushed and striated is observed up to about 0.1 mm in depth.

Figures 5 and 6 as well as Table 2 show the change in the hardness of the spheroidal graphite cast iron due to the FSP. Figures 5 and 6 show the micro Vickers hardness distribution on a cross section vertical to the welding direction. Table 2 shows the Rockwell hardness distribution on the surface. At this time, the Rockwell hardness was measured at four points at 3 and 6 mm from the center on the advancing and the retreating sides and at the center to confirm the distribution of the hardness values.

Figure 5 shows the Vickers hardness distribution in the depth direction at the central part and at 6 mm from the center on the advancing and the retreating side. It is found that a high and comparatively steady hardness is obtained in the area from 0.2 to 1.0 mm in depth while a low value was observed at 0.1 mm from the surface. The hardness between 0.2 to 1.0 mm exceeds 700 HV.

Figure 6 shows the hardness distribution at 2 mm intervals within the range of 10 mm on the advancing side to 10 mm on the retreating side. An average value exceeding 700 HV is obtained from 6 mm on the advancing side to
8 mm on the retrating side at a depth of 0.5 mm, and from 2 mm on the advancing side to 4 mm on the retrating side even at a depth of 1.4 mm. However, in the neighborhood of the surface, a low value of about 200 to 500 HV is obtained, because the graphite is uniformly distributed, as shown in Figure 4, and perlite occupies the most of the base microstructure.

Unlike the micro Vickers examination, the Rockwell examination measures a wider range hardness of the base microstructure which includes the graphite, however, a 50 or higher HRC was obtained except for in the central part. For the central part, the hardness was about 30 HRC. Figure 7 shows the microstructure at a high magnification. A very fine needlelike martensite structure is observed. It is considered that this structure generated because the material was locally heated and rapidly cooled during the FSP. On the other hand, the size and density of the martensite are changed even in the same martensite structure. The martensite structure is fine, and its density is high in a very hard microstructure which exceeds 700 HV. When the martensite is larger and its density is lower, the hardness also decreases. The homogeneity of the martensite should be regarded important when this method is used in actual applications. It is considered that the homogeneity of the carbon is lower in this method because the heating and the cooling periods are shorter than that of the other methods. As a result, the size of the martensite may not be uniform.

Therefore, it is recommended that the perlite microstructure of the base material be homogenized and the density of the carbon of the mother material be constant as much as possible in order to make the size of the martensite uniform.

A mixture of perlite and martensite microstructures is formed in the low hardness area of 200 to 500 HV, as shown in Fig. 8. It is thought that the decrease in cooling rate and the increase in amount of perlite in this region is attributable to the higher heat input.

3.3 Effect of probe

As mentioned in the previous section, a hardening layer of about 1 mm can be obtained from the surface by performing the FSP using a flat tool without an umbo (probe). It seems that the 1 mm hardened layer is thick enough for normal use. However, for the case when a thicker hardening layer is necessary, the FSP is similarly performed using a tool with an umbo in order to increase the thickness of the hardening layer. The spheroidal graphite cast iron was friction stir processed under the conditions of the traveling speed of 50 mm/min, the rotation speed of 900 rpm, and the load of $3.2 \times 10^3$ kgf. The macrostructure of a cross section is shown in Fig. 9.
It can be seen that the graphite is crushed, striated, and then stirred up to about 1.0 mm depth from the surface at the central part. This stirred zone is significantly expanded comparing to the case using a flat tool and reaches about 0.7 mm on the advancing side to about 0.4 mm on the retreating side. Figures 10 and 11 show the hardness distributions of a cross section measured by the micro Vickers hardness equipment in order to compare the difference in the hardness with the flat tool without the umbo. A constant hardness value of 200 HV, which does not change from that before the FSP, is obtained on the surface of the central part, and the hardness of about 400 to 500 HV is obtained even at 0.1 mm or deeper. On the other hand, both on the advancing side and the retreating side, the hardness exceeding 800 HV is obtained at a depth of 0.1 mm. Especially, an average hardness of 800 HV is obtained up to about 0.9 mm on the advancing side. However, the hardness does not show a high value in regions deeper than 1.0 mm, similar to when using a flat tool.

Although the values exceeding 800 HV are measured at a depth of 0.5 mm from the sample surface, as shown in Fig. 11, the hardness in the central part has clearly decreased to less than 500 HV. In addition, the area is expanded to 2 mm on the advancing side and 2 mm on the retreating side compared to when using the flat tool. This range is clearly related to the umbo diameter because it is 4 mm. Thus, when the portion of the striated graphite accompanied by the perlite microstructure is increased, the hardness significantly decreases.

Therefore, a tool with an umbo is used, and the thickness of the stirred zone can be increased, however, the hardness itself is significantly decreased. For the FSP aiming to harden about a 1 mm region from the surface, a flat tool without the umbo is much in suit. On the other hand, it is also possible to
increase the stirring power in this way so as to maintain a hardness of 400 to 500 HV for the component whose hardness of 700 to 900 HV is too high to machine after the FSP.

3.4 Effect of graphite shape

Figures 12 and 13 show the Vickers hardness distribution of the flake graphite cast iron friction stir processed in a way similar to the spheroidal graphite cast iron. Table 3 shows the Rockwell hardness distribution. A sufficient appearance is obtained, as shown in Fig. 3.

Figure 12 shows that an average value higher than 700 HV is obtained to about 1 mm depth, and values higher than 800 HV were also measured at many points. From Fig. 13, a very high hardness of 700 to 900 HV was also measured at 4 to 8 mm from the center on the advancing side and at 2 to 6 mm on the retreating side to a depth between 0.3 and 0.6 mm from the surface. Figure 14 shows an example of the microstructure. A martensitic structure is formed throughout the region, however, neither the size nor density of the martensite is uniform.

It can be seen in Fig. 12 and Fig. 13 that the hardness of the central part decreases. Since the hardness of the mother material is lower, the bottom of the tool enters more deeply compared to the FCD 700. Accordingly, the domain is expanded where the same phenomenon happened as shown in Section 3.3. In the central part, the spheroidal graphite was crushed and striated by plastic flow.

According to the Rockwell test results shown in Table 3, the area whose hardness exceeds 50 HRC is very limited. The hardness itself is lower than that of the FCD700.

This difference should be attributable to the shape of the graphite between the flake graphite and the spheroidal graphite. It is considered that the ratio of graphite in the pressed area by the Rockwell indenter is higher in the case of the flake graphite cast iron.

4. Conclusions

A new technique for hardening surface has been established by pushing the surface of cast iron with a rotating φ25 mm cylindrical tool at the speed of 900 rpm (friction stir processing), and the following points have been clarified:

(1) The average hardness of about 700 HV for the matrix is obtained for both the flake graphite cast iron and the spheroidal graphite cast iron. This is because an extremely fine martensite is formed by this process.

(2) It is considered that a very fine martensite structure is formed because the FSP generates the heat very locally, and a very high cooling is constantly obtained.

(3) The hardness changes depending on the size of the martensite, which can be controlled by the process conditions, such as the tool traveling speed and the load.

(4) When a tool without an umbo (probe) is used, the domain in which graphite is crushed and striated is decreased. This leads to a much harder sample obtainment.
Based on these results, it was clarified that the FSP has many advantages on cast irons, such as higher hardness and lower distortion. As a result, no post surface heat treatment and no post machining are required to obtain the required hardness, while these processes are generally required in the traditional methods.

Acknowledgement

The authors wish to acknowledge the financial support of the Grobal COE, the Cooperative Research Project of Nationwide Joint-Use Research Institute, the Toray Science Foundation, the ISIJ Research Promotion Grant, the Iketa Foundation, the Japan Society for Promotion of Science and Japan Foundry Engineering Society.

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