Friction Stir Welding (FSW) is a type of solid-state welding using a rotating tool. The rotating tool is inserted into the interface at the butt line of the metal plates and produces a highly plastically deformed zone. The metal plates are joined by the traveling of the rotating tool along the interface. Frictional heat and deformation heat are generated between the tool and the workpiece in order to soften the materials and cause material flow during the welding. Since a large strain is introduced into the stir zone during FSW, the recrystallization structure is formed, and joints with higher strength and toughness compared to conventional welding can be obtained. FSW has already been widely expanded to light metals with lower melting points such as the aluminum alloys.1–4) However, as regards metals with higher melting points or higher strength such as carbon steel, although the research has been actively conducted,5,6) it is still difficult to apply the FSW.

In order to solve these problems, it is required to develop a FSW process in which the resisting force on the tool is sufficient small during the welding and sound joints can be obtained in the FSW of high melting points or high strength materials. Several preheating methods has been adopted for the purpose of long tool life or preventing defect formation in stir zone, and it is known that reducing of resisting force on the tool and increasing of welding speed is possible by preheating with laser,8–12) high frequency induction heating,11,12) ultrasonic vibration,12,13) arc,12) heating of stage,14,15) and so on. However, it is not clarified in detail effect of the preheating on formation of stir zone, material flow behavior and resisting force on the tool. Therefore, in this study, a fiber laser was used as the preheating source during the FSW, and the effect of laser-preheating on shape of stir zone and tool rotational torque was investigated in detail by

Friction Stir Welding of Medium Carbon Steel with Laser-Preheating

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Friction Stir Welding (FSW) has expanded to many metallic materials with higher melting points or much higher strength than the aluminum alloys. If the tool travels too quickly along the welding seam during the welding process or if the melting point of the workpiece is high, the frictional heat generated between the tool and the workpiece may not be sufficient to cause material flow. Insufficient heat input results in the formation of groove or tunnel-shaped defects in the stir zone and also severe wear or breaking of the FSW tool. To solve these problems, a higher heat input is required to soften the materials. Therefore, several preheating methods have been adopted to increase the heat input. In this study, a fiber laser was used as the preheating source during the FSW. In this experiment, the effect of the laser-preheating on the defect formation and tool rotational torque during the FSW was investigated. Additionally, a difference in the material flow during the conventional FSW and laser-preheating FSW was observed by two pairs of X-ray transmission real-time imaging systems. As a result, it was found that the laser preheating reduced the defect formation and the tool rotational torque during the FSW. Furthermore, laser beam irradiation on the retreating side (RS) was the most effective in reducing the defect formation. On the other hand, the irradiation on the advancing side (AS) was the most effective in reducing the tool rotational torque.

KEY WORDS: friction stir welding; laser-preheating; material flow; tool rotational torque; carbon steel; three-dimensional visualization; X-ray radiography.

1. Introduction

Friction Stir Welding (FSW) is a type of solid-state welding using a rotating tool. The rotating tool is inserted into the interface at the butt line of the metal plates and produces a highly plastically deformed zone. The metal plates are joined by the traveling of the rotating tool along the interface. Frictional heat and deformation heat are generated between the tool and the workpiece in order to soften the materials and cause material flow during the welding. Since a large strain is introduced into the stir zone during FSW, the recrystallization structure is formed, and joints with higher strength and toughness compared to conventional welding can be obtained. FSW has already been widely expanded to light metals with lower melting points such as the aluminum alloys.1–4) However, as regards metals with higher melting points or higher strength such as carbon steel, although the research has been actively conducted,5,6) it is still difficult to apply the FSW.

In the FSW of carbon steel, it is a problem that the rotating tools face a risk of being worn or broken because a much higher resisting force is imposed on the rotating tools under high temperature during the welding.7) It is necessary to cause sufficient material flow around the tool and fill the void formed by the traveling of the tool in order to obtain the sound joints by FSW, but the material flow may not be sufficient in the workpiece with relatively high deformation resistance such as carbon steel. The insufficient material flow causes grooves or tunnel shaped defects in the stir zone. It is also a problem that the welding speed cannot increase easily due to these problems.

In order to solve these problems, it is required to develop a FSW process in which the resisting force on the tool is sufficient small during the welding and sound joints can be obtained in the FSW of high melting points or high strength materials. Several preheating methods has been adopted for the purpose of long tool life or preventing defect formation in stir zone, and it is known that reducing of resisting force on the tool and increasing of welding speed is possible by preheating with laser,8–12) high frequency induction heating,11,12) ultrasonic vibration,12,13) arc,12) heating of stage,14,15) and so on. However, it is not clarified in detail effect of the preheating on formation of stir zone, material flow behavior and resisting force on the tool. Therefore, in this study, a fiber laser was used as the preheating source during the FSW, and the effect of laser-preheating on shape of stir zone and tool rotational torque was investigated in detail by
locally changing the irradiation position of the laser in front of the tool. Additionally, the effect of the laser-preheating on the material flow during the FSW was investigated by in-situ observations using X-ray radiography.\(^{16-18}\)

2. Experimental Procedures

2.1. Laser-preheating FSW

In this experiment, a carbon steel (S55C) plate was used as the workpiece. The plates were 2 mm thick, 70 mm wide and 150 mm long. The chemical composition of the workpiece is shown in Table 1. The FSW tool, which had 15 mm shoulder diameter, 6 mm probe diameter and 1.9 mm probe length was used, and the FSW tools are made of cemented carbide or silicon nitride. The welding speed, the tool rotation speed and the tool load were kept constant at 300 mm/min, 150 rpm and 29 kN in case of the cemented carbide tool, and they were kept constant at 650 mm/min, 250 rpm and 39 kN in case of the silicon nitride tool. The tool tilt angle was kept constant at 3° and the stir-in-plate FSW was carried out. These FSW conditions were selected as conditions in which defects were formed in stir zone during FSW using each tool. A fiber laser (IPG Photonics YLS-2000-CT) was used as the preheating source during the FSW and the workpiece ahead of the tool was locally heated by the fiber laser. A schematic illustration of the laser-preheating FSW is shown in Fig. 1. The focal position of the laser is on the workpiece surface, and the spot diameter by laser irradiation is approximately 0.2 mm. The various positions of focal points of the laser beam is shown in Fig. 2. The laser beam was focused ahead of the rotating tool at the welding center, advancing side (AS) or retreating side (RS). The distance between the focal points of the laser beam and the tool was kept constant at 10 mm. The laser power of 1 000–2 000 W was used, and the irradiation angle of the laser was kept constant at 45°. The welding temperature was measured by K-type thermocouple, and the torque of servomotor rotating the tool was measured in order to evaluate the value of the tool rotational torque. The torque of servomotor was evaluated by measuring current value flowing through the motor during the FSW and calculating from the current value, and the changes in the torque of servomotor was recorded over time by using data logger. After wet polishing of the

| Material | C (wt.%) | Si (wt.%) | Mn (wt.%) | P (wt.%) | S (wt.%) |
|----------|----------|-----------|-----------|----------|---------|
| S55C     | 0.57     | 0.20      | 0.72      | 0.014    | 0.003   |

Table 1. Chemical compositions of S55C.

[Fig. 1. Schematic illustration of laser-preheating FSW.]

[Fig. 2. Schematic illustration of the various positions of focal points of the laser beam.]

[Fig. 3. Appearance of the equipment for the X-ray radiography.]

[Fig. 4. Schematic illustration of the experimental setup for the X-ray radiography during the FSW.]
cross section of the joints after FSW, buff polishing was conducted. The cross section of the joints after polishing was etched by 3% nital for about 10 seconds, and macrostructure observation was conducted by Optical Microscope (OM, Olympus BX51 M microscope).

2.2. In Situ Observation of Material Flow Behavior
In this study, the material flow during the conventional FSW and laser-preheating FSW was observed by two pairs of high brightness X-ray inspection apparatuses consisting of X-ray generators and high responsive image intensifiers.\textsuperscript{16–18} The perspective images observed from two different direction were recorded by high speed cameras. The appearance and schematic illustration of high brightness X-ray inspection apparatuses were shown in Figs. 3 and 4. The perspective point of imaging system was located in the stir zone, and a cemented carbide ball with a diameter of 500\,µm was used as a tracer. Actual orbit of tracer during FSW was calculated by using the tracer movement observed from two directions and three dimensionally displayed in order to visualize the material flow. As shown in Fig. 4, the tracer was located at the welding center or on the retreating side ahead of the probe. The depth from the workpiece surface is 0.5 mm. In the FSW when observing in situ material flow behavior by using high brightness X-ray inspection apparatuses, the welding speed and the tool rotation speed were kept constant at 100 mm/min and 300 rpm. The silicon nitride tools consisting of light elements with sufficient X-ray permeability were adopted. The spot diameter by laser irradiation is approximately 1.5 mm and the laser power is 700 W. Other conditions were same as section 2.1. In the photographing by high brightness X-ray inspection apparatuses, tube voltage and tube current of micro-focus X-ray generator were kept constant at 230 kV and 950 μA, and tube voltage and tube current of mini-focus X-ray generator were kept constant at 225 kV and 7.5 mA. X-ray perspective images were recorded at frame rate of 250 fps.

3. Results and Discussion

3.1. Effect of Laser-preheating for Preventing Defect Formation
A cross sectional image of stir zone formed by conventional FSW using the cemented carbide tool is shown in Fig. 5. Cross sectional images of stir zone formed by laser-preheating FSW under said conditions are also shown in Fig. 6. As shown in Fig. 7, the laser irradiation was conducted at three types of laser power with depth of fusion. The results indicate that the higher laser power leads to a significant effect on the restriction of the defect formation in spite of the laser irradiation positions. Especially, it is clarified that the laser preheating on the retreating side is the most effective for preventing defect formation. Sound stir zone with defect free is formed when the laser power is more than 1 500 W. As a result of the temperature measurement during the FSW by setting the K-type thermocouples on the back surface of the workpiece to be located at the welding center, the maximum temperature at the time of the tool passing was 520°C when the laser preheating was not conducted, 646°C when the preheating occurred on the advancing side, 602°C when the preheating occurred at the welding center and 688°C when the preheating occurred on the retreating side. These results show that the heat input during the FSW is the highest when the preheating occurred on the retreating side. Therefore, it is considered that the material flow around the rotating tool is significantly promoted and the defect formation is the most effectively restrained. The reason that the material flow is the most effectively promoted when the preheating occurred on the retreating side is discussed later in section 3.4.

3.2. Effect of Laser-preheating on Tool Rotational Torque
The change in the tool rotational torque over time during the conventional FSW and the laser-preheating FSW using the cemented carbide tool is shown in Fig. 8. The tool rotational torque during the conventional FSW increased over...
time. It seems that the heat input generated when the rotating tool was inserted into the workpiece could be maintained as soon as the tool moved, but the heat input decreased over time because the traveling speed of the tool was too fast for the heat generation under the FSW conditions. On the other hand, the increase of the tool rotational torque during the laser-preheating FSW was not observed. It seems that the increase of the torque was able to be prevented since the sufficient heat input during the FSW was maintained by laser preheating, and this suggests that the laser is effective for increasing the welding speed. When comparing the tool rotational torque during the FSW with laser preheating at each irradiation position, it is the lowest when preheating occurs on the advancing side. As a result, it is revealed that the preheating on the advancing side is the most effective for decreasing the tool rotational torque. In general, it has

Fig. 8. Effect of preheating position on the tool rotational torque in case of the cemented carbide tool.

Fig. 9. Effect of preheating position on the tool rotational torque in case of the silicon nitride tool.

Fig. 10. Changes in the tool rotational torque during the FSW without laser-preheating using each tool.
been reported that the strain and strain rate of the workpiece during the FSW of carbon steel is higher on the advancing side, and the resisting force is the highest on the advancing side. Therefore, in the case of preheating on the advancing side, the workpiece on the advancing side is softened, so that the resisting force imposed on the rotating tool during the welding is the most effectively decreased. On the other hand, in the case of preheating on the retreating side, the reduction of the resisting force on the advancing side is negligible. Thus, it seems that preheating on the retreating side is not very effective for decreasing the tool rotational torque.

### 3.3. Effect of Tool Material on Laser-preheating Effect

The change in the tool rotational torque over time during the conventional FSW and the laser-preheating FSW using the silicon nitride tool is shown in Fig. 9. These results are different from those in case of the cemented carbide tool. When using the silicon nitride tool, the reduction in the tool rotational torque is not clearly observed regardless of the preheating positions. This is due to the difference in affinity between the workpiece and the surface of each tool consisting of cemented carbide and silicon nitride. The affinity between the workpiece and the tool has been investigated from the term of wettability of the workpiece on the tool surface. It was reported that the workpiece easily sticks to the tool surface when the contact angle is small and wettability is good, so that the tool rotational torque over during the FSW increases. The changes in the tool rotational torque during the conventional FSW using each tool are shown in Fig. 10. They were measured under the same welding conditions for both tools. As you can see, a higher tool rotational torque is measured when using the cemented carbide tool compared to the silicon nitride tool. When comparing each tool material, the contact angle $\theta$ of molten Fe to WC and Si3N4 is $0^\circ$ and $90^\circ$ respectively, the wettability of the workpiece (S55C) to the cemented carbide tool mainly consisting of WC is better than that to the silicon nitride tool. This is consistent with previous studies that when comparing the relationship between the contact angle and the cutting frictional force of free-cutting steel on cemented carbide tools and Si3N4 ceramic tools, the contact angle is smaller and the cutting frictional force is greater in case of cemented carbide tools. Therefore, when using the silicon nitride tool whose rotational torque during the conventional FSW is small because of low affinity with the workpiece, the laser preheating was not effective, compared with the case of the cemented carbide tool.

Cross sectional images of stir zone formed by the conventional FSW and the laser-preheating FSW using silicon nitride tools is shown in Figs. 11 and 12. The higher laser power leads to a significant effect on the restriction of the defect formation. Especially, the laser preheating on the retreating side is the most effective for preventing defect formation. The results show the same tendency about the effect of laser preheating for restraining the defect formation in stir zone when using cemented carbide tools. However, when comparing the effect of laser preheating for preventing the defect formation when using each tool, it seems that the laser preheating is more effective in case of the silicon nitride tool because a coarser groove is restrained by the preheating in that case. When using either tool, the total heat input increases and the material flow is promoted, but the tool rotational torque is reduced by laser preheating in case of the cemented carbide tool. These results show that the frictional force between the tool and the workpiece decreases, so that the material flow generated by the frictional heat and the frictional force is prevented. On the other hand, in case of the silicon nitride tool, the frictional heat and the material flow is sufficiently maintained since the tool rotational torque is not decreased by the laser preheating. Therefore, the material flow generated by the frictional heat and the frictional force is not easily reduced during the laser-preheating FSW when using the silicon nitride tool, and the increase in the total heat input and the promotion of material flow is effectively occurred by laser preheating. As a result, the defect formation was more clearly restrained.

### 3.4. In Situ Observation of Material Flow Behavior

In this study, in situ observation and three-dimensional visualization of material flow by high brightness X-ray inspection apparatuses in order to investigate the relationship between the shape of stir zone and the material flow during the laser-preheating FSW. Cross-sectional images of the stir zone and two-dimensional graphs of the tracer coordinates on TD-WD plane during the FSW with or without...
laser-preheating are shown in Figs. 13 and 14. The stir zone was significantly enlarged by laser preheating. Especially, the largest stir zone was formed by the FSW with laser preheating on the retreating side. These results show the same tendency as the section 3.2 that the heat input during the FSW with laser preheating on the retreating side is the highest. As for the flow of the tracer, the tracer did not orbit around the probe during the conventional FSW, but the tracer orbited by the laser preheating. Especially, the flow region of the tracer is the largest when preheating occurs on the retreating side, so that the stir zone is considered to be the largest. On the other hand, when preheating occurs on the advancing side, the plot interval of the tracer position of each frame was narrowed in the region in which the tracer flew from the tool front to the retreating side. These results indicate the stagnation of material flow was noticeable. It was also confirmed that the material flow region on both the advancing side and the retreating side when preheating occurred on the retreating side, while the material flow region on the advancing side was only enlarged when preheating occurred on the advancing side. Therefore, It seems that it is possible to produce sufficient material flow around the rotating tool by preheating on the retreating side.

In this study, the difference of material flow behavior in case of each preheating position was compared from material flow velocity during the FSW evaluated by calculating the moving velocity of the tracer. Average velocity of material flow during FSW with or without laser preheating is shown in Fig. 15(a). The material flow velocity during the FSW with laser preheating at the welding center and on the retreating side is more than twice as high as that without laser preheating and with laser preheating on the advancing side. It is clear that sufficient material flow is obtained by laser preheating at the welding center and on the retreating side. Average angular velocity of material flow calculated by using radius of material flow region is shown in Fig. 15(b). The same tendency was recognized on the angular velocity. The angular velocity rate of the material flow to the tool rotation speed of 300 rpm has increased to approximately 30% when preheating occurs at the welding center and on the retreating side, while the angular velocity rate is approximately 10% when preheating is not conducted and occurs on the advancing side. It is reported that the angular velocity rate of the material flow during the conventional FSW of aluminum alloy and low carbon steel is about 70%, whereas the angular velocity rate dur-
Fig. 16. Schematic illustration of temperature distribution around the rotating tool with (a) insufficient or (b) sufficient heat input.

ing the conventional FSW of medium carbon steel is about 10%. These results indicate that laser preheating at the welding center and on the retreating side is more effective to obtain sufficient material flow. Regarding this material flow behavior during the conventional FSW, sufficient material flow region is formed on both the advancing side and the retreating side during the FSW of aluminum alloy whose heat conductivity is higher than that of carbon steel. This is because the frictional heat and the deformation heat generated on the advancing side is sufficiently transported to the retreating side by the material flow during the FSW of aluminum alloy. On the other hand, the heat generated on the advancing side is insufficiently transported during the FSW of carbon steel whose heat conductivity is lower, so that the material flow region on the retreating side is smaller than that on the advancing side as shown in Fig. 16(a). Therefore, it is expected that the problems such as the defect formation become more serious in the FSW of carbon steel because of insufficient material flow. Thus, it is considered that sufficient material flow around the rotating tool can be formed and the defect formation can be restrained by effectively expanding the material flow region on the retreating side by laser preheating on the retreating side as shown in Fig. 16(b).

4. Conclusion

In this study, cross sectional observation of stir zone, measurement of the tool rotational torque and the three-dimensional visualization of the material flow was conducted in order to clarify the effect of laser preheating on the defect formation and the tool rotational torque during the FSW of carbon steel. As a result, the following knowledge was obtained.

(1) The defect formation can be prevented by laser preheating even in the welding conditions in which the defect is formed during the conventional FSW. Especially, preheating on the retreating side is the most effective for restraining the defect formation.

(2) When using the cemented carbide tool, the tool rotational torque during the FSW can be reduced by laser preheating. Especially, preheating on the advancing side is the most effective for reducing the tool rotational torque. On the other hand, when using the silicon nitride tool, the tool rotational torque is not reduced by laser preheating. The reason is that the softening of the workpiece by preheating cannot effectively reduce frictional resistance between the workpiece and the tool in case of the silicon nitride tool with low affinity to the workpiece, while the frictional resistance can be effectively reduced by laser preheating in case of the cemented carbide tool with high affinity to the workpiece.

(3) When preheating occurs on the retreating side, the material flow region during the FSW is largest, so that sufficient material flow is formed around the rotating tool, compared with the case of non-preheating. The average velocity of material flow when preheating occurs at the welding center and on the retreating side is higher than that when preheating is not conducted and occurs on the advancing side. In the FSW of carbon steel, the total heat input can increase and sufficient material flow can be obtained by preheating not on the advancing side where the frictional heat and deformation heat is mainly generated during the FSW but on the retreating side.

As stated above, it was clarified that the resisting force on the tool can be effectively reduced and sound stir zone can be formed by laser preheating. It was also clarified that the effect of preheating obviously varies by preheating position.

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