Melting by Reflected Laser Beam during Vertical Welding via Hot-Wire Laser Welding*

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We investigated the melting of a base metal, molten pool growth, and joint creation during vertical welding via hot-wire-laser welding. Three laser-weaving conditions were investigated by changing the weaving frequency and waveform to study the effects of the irradiation duration near the groove surface. In addition, high-speed and cross-sectional imaging were performed to investigate the heating and melting processes on the groove surface during hot-wire laser welding. The irradiation duration near the groove surface had a marked effect on the melting of the groove surface. The combination of a 5 Hz laser frequency with an exponential waveform led to a longer duration near the groove surface during a cycle and realized improved fusion compared with the other combinations with a 15 Hz laser frequency and a sine waveform. The laser beam reflected from the molten pool surface was the main source of heat for melting the groove surface. Hot-wire feeding provided a continuous and efficient supply of melted material and a stable heat input on the groove surface via the reflected laser beam.

Key Words: Hot-wire, Laser welding, Diode laser, Laser-weaving condition, Reflected laser beam

1. Introduction

Different methods are used for welding long butt joints in the vertical direction; in particular, the electroslag and electrogas welding techniques are widely used for the construction of large ships, tanks, and buildings[1-4]. While both welding methods have high efficiency with a single-pass, their high heat input reduces the toughness of the welded joint and causes softening[5-13]. Therefore, there is a strong need for a new vertical welding process, which can reduce the heat input while welding the butt joint of thick steel plates with a single pass and realize joints with a high strength and toughness.

Vertical welding of thick steel plates via the hot-wire laser welding method[14-16] has been previously proposed and investigated[17-18]. For preliminary investigation of the proposed process, single-pass vertical welding of 26-mm-thick steel-plate joints was achieved using a diode laser with a long and narrow laser beam spot combined with hot-wire feeding. The effects of the laser-irradiation conditions, including the laser-irradiation angle, spot size, power density, and spot weaving on the molten pool and joint formation have previously been investigated[18-19]. The laser power density is a key parameter for obtaining a sound bead with fusion, and a critical power density that depends on the welding speed is needed to realize adequate fusion of the base metal. The weaving method with a laser beam spot of adequate width was able to form a stable molten pool and sound fusion even with a large rectangular laser spot with relatively low power density and a 10-mm groove width.

The objective of this study was to clarify the melting of the base metal (groove surface), and investigate the molten pool growth and joint creation during hot-wire-laser welding. A small dilution, low heat input, and efficient fusion of a base metal could be achieved via the weaving method with a large laser beam spot and a low energy density. Three laser-weaving conditions were investigated by changing the weaving frequency and waveform to study the effects of the irradiation duration near the groove surface on base metal melting and joint creation. In addition, high-speed and cross-sectional imaging were undertaken to investigate the heating and melting processes on the groove surface during hot-wire laser welding.

2. Experimental procedure

2.1 Materials and specimen

KE47-class steel plates and a JIS Z 3325 YGL2-6A (AP) filler wire of 1.6-mm diameter were used for all experiments. A specimen of 50 mm width, 200 mm height, and 26 mm thickness was used to investigate the effects of the laser irradiation conditions on joint creation, as shown in Fig. 1. The groove width (gap) was set to 10 mm by using a bottom spacer with a 10-mm
width, 20-mm height, and 26-mm depth. Specimens of 100-mm width, 50-mm height, and 26-mm thickness were used for observation of the groove melting, as shown in Fig. 2. A groove of 10-mm width (gap) × 30-mm depth (height) was machined to simulate the joint groove indicated in Fig. 1.

2.2 Experimental setup and welding conditions

2.2.1 Investigation of laser irradiation conditions

A schematic illustration of the apparatus and configuration for hot-wire laser welding with weaving laser irradiation is shown in Fig. 3. Table 1 gives the welding conditions used to investigate the effects of the laser irradiation conditions. A 6-kW diode laser oscillator was used as the heat source with combined focusing and homogenizing lenses providing a long, narrow rectangular shaped laser spot. The laser power density was 111 W/mm² for a laser power of 6 kW and a fixed laser spot size of 2 mm × 27 mm; the laser irradiation angle was also fixed at 0°.

The weaving system could sweep the large rectangular laser spot parallel to the gap width, the weaving amplitude could be adjusted for a variable gap, and the weaving frequency and waveform could also be changed. Figure 4 shows the three types of weaving waveforms over 1 second used in this investigation. For the weaving parameters, the weaving amplitude was set to fit the 10-mm gap, the weaving waveform was set as a sine or exponential waveform, and the weaving frequency was set at either 5 or 15 Hz. As a result, while the duration of the laser spot near a groove surface varied between 11.5, 34, and 72.5 ms, the total average duration near the groove surface over 1 second varied between 172.5, 170, and 362.5 ms, as shown in Table 1.

Double hot-wire feeding was used during this study. The welding speed and the wire feeding speed were fixed at 1.7 cm/min and 1.24 m/min, respectively, for each wire. The hot-wire feeding speed was adjusted to fill the groove, and the wire current was set to heat the filler wire tip to near its melting point. Argon gas was used for shielding.

![Fig. 3 Schematic of the experimental setup for hot-wire laser welding with weaving laser irradiation.](image)

![Fig. 2 Specimen dimensions for observation of melting.](image)

![Fig. 4 Weaving waveforms over 1 second.](image)

<table>
<thead>
<tr>
<th>Table 1 Welding conditions for investigation of the effect of laser irradiation conditions.</th>
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<tr>
<td>Laser power, kW</td>
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<td>Spot size (Defocus), mm</td>
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<td>Defocus amount, mm</td>
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<td>Laser power density, W/mm²</td>
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<td>Laser irradiating angle, deg.</td>
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<td>Weaving form</td>
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<td>Weaving frequency, Hz</td>
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<td>Duration time near groove surface, ms</td>
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<td>Total duration time near groove surface for 1 second, ms</td>
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<td>Welding speed, cm/min</td>
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<td>Wire feeding speed for one wire, m/min</td>
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<td>Wire current for one wire, A</td>
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<tr>
<td>Wire feeding angle, deg.</td>
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<td>Shielding gas (Ar), l/min</td>
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2.2.2 Observation of melting on the groove surface

Table 2 gives the welding conditions used to observe melting of the groove surface and molten pool creation during hot-wire laser welding. A laser power of 6 kW, laser spot size of 2 mm × 27 mm, laser irradiating angle of 15°, and a welding speed of 3.3 cm/min were used. For the single hot-wire feeding, a wire feeding speed of 5.31 m/min and a welding speed of 3.3 cm/min were used. An exponential waveform and a 5-Hz weaving frequency were applied for this investigation. Two conditions were investigated: the first was using only laser beam irradiation without hot-wire feeding (pre-irradiation period); and during the second, laser beam irradiation was accompanied by hot-wire feeding.

Figure 5 shows a schematic of the high-speed imaging setup for observation of the melting phenomena on the groove surface and molten pool formation. A high-speed camera with an 810-nm band-pass filter was used for this observation. For image acquisition, a frame rate of 50 fps and a shutter speed of 1/20000 s were used. After high-speed imaging during laser irradiation with and without hot-wire feeding, images of the cross-section were obtained for both specimens.

3. Results and discussion

3.1 Effect of laser irradiation conditions on joint creation

Figure 6 shows the sample cross-sections in the horizontal direction (transverse to the welding direction) and the vertical direction (parallel to the welding direction). The magnified images near the fusion boundary on the vertical cross-sections, indicated by the red rectangular regions on the vertical cross-sections, are also shown in Fig. 6. These cross-sections were obtained at the middle of the welded joint in the welding direction as a section in the quasi-steady state. The vertical cross-section was cut at the middle of the joint thickness. It can be observed that the weaving laser irradiation method with a long, narrow rectangular laser spot allowed for stable joint creation for a relatively large gap of 10 mm.

Unfilled regions and lack of fusion can be clearly observed at both edges of the horizontal cross-section under all conditions. All the vertical cross-sections show perfect joints for the macro-scale cross-sectional images; however, the magnified images show a lack of fusion for welding at 15-Hz and 5-Hz weaving frequencies with a sine waveform. The combination of a 5-Hz weaving frequency and an exponential waveform resulted in complete fusion for the vertical cross-section cut at the middle of the thickness. The durations of 11.5 and 34 ms with a 15-Hz and 5-Hz weaving frequency and a sine waveform, respectively, are smaller...
than the duration of 72.5 ms obtained for a weaving frequency 5-Hz with an exponential waveform.

The ratio of the filling and fusion to the total groove length were measured on the horizontal cross-sections. The filling ratio was obtained as the value of the weld metal filling length divided by the sum of the groove lengths on both sides. The fusion ratio was obtained by dividing the melting and joining length between the weld metal and groove surface with the filling length. Figure 7 shows the relationship between the duration and the filling ratio or fusion ratio. An almost constant filling ratio of \( \approx 82\% - 84\% \) can be seen even when the irradiation duration varied from 11.5 to 72.5 ms. The fusion ratio increased from 50 to 83\% with increasing duration time from 1.5 to 72.5 ms. The combination of a 5-Hz weaving frequency and an exponential waveform resulted in the longest irradiation duration of 72.5 ms and achieved perfect fusion between the filled weld metal and the groove surface with a fusion ratio of 83\%. In addition, while the 15-Hz and 5-Hz weaving frequency with sine waveforms have almost the same total duration over 1 second of \( \approx 170\) ms, the fusion ratio with a weaving frequency of 5-Hz was larger than for 15-Hz.

From the above results, it can be determined that the irradiation duration near the groove surface has a large effect on the melting of the groove surface. In other words, a longer irradiation duration can increase fusion under the condition of a stable molten pool formation.

### 3.2 Investigation of the groove surface melting by reflected laser beam

3.2.1 High-speed imaging of the groove surface melting

Figure 8 (a) and (b) show high-speed images and schematic illustrations of the groove surface melting during the pre-irradiation period without hot-wire feeding and during the period with continuous hot-wire feeding with the specimen moving vertically. The high-speed camera was set to observe the groove surface melting just above the original side corner on the groove bottom during pre-irradiation and just above the side edge of the molten pool during wire feeding under oblique laser irradiation conditions. The high-speed image shows clear detection of the groove corner and the molten pool edge. Both Fig.8(a) and (b) show three major steps in one cycle: weaving as the laser spot moves to the groove surface; the laser spot being held near the groove corner or molten pool edge for a duration of 72.5 ms; and the laser spot moving out from the groove surface.

The laser beam did not directly irradiate the groove surface because the irradiation angle of \( \approx 1^\circ \) to the groove wall was very small and the weaving width was set as 9.5 mm, which was slightly narrower than the groove width of 10 mm. Therefore, the heat input on the groove wall during the pre-irradiation period was only

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**Fig. 7** Effect of weaving duration on filling ratio and fusion ratio.

**Fig. 8** High-speed images and schematic illustration of the groove surface melting.

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from reflection of the laser beam from the molten metal surface at the bottom of the groove; heat conduction from the small molten pool was minimal.

High-speed images for a 1 s pre-irradiation period are shown in Fig. 8(a). It can be seen that the high-temperature bright region moves to the groove bottom with laser spot weaving; a slightly brighter heating zone is created just above the original groove corner, which is indicated as a white dashed line while the laser beam is maintained stationary near the groove surface. The high-speed images for a longer irradiation time of 5 s shows a larger molten pool fully covering on the bottom of the groove, and a large brighter area can be seen just above the original groove corner. It can be expected that this brighter region just above the groove corner melted separately from the molten pool, and the larger region on the groove surface heated up to near its melting point. As the laser beam spot moved out from the groove surface, the molten pool edge connected with the newly created region just above the original groove corner; then, the new molten pool corner was created, as indicated by a white line in Fig. 8(a). The residual heating zone just above the new molten pool corner can be observed even as the laser beam spot moved away from the groove surface.

Figure 8(b) shows melting on the groove surface with hot-wire feeding as the specimen moves downwards. The larger amount of molten metal and laser beam sweeping on the molten pool surface can be observed clearly. On the high-speed image for the 5 s period, a larger melted region compared with the pre-irradiation period can be seen, as indicated by the white dash line while the laser spot is held steady near the groove surface. Then, the molten metal generated by hot-wire feeding covers this region and the molten pool edge spreads upward while the laser beam spot is held steady and while it is moved out from the groove surface. A larger residual heating zone just above the new molten pool corner can be also observed. This is because the larger volume of molten metal derived from hot-wire feeding allows for a large amount of heat conduction around the molten pool. For high-speed images of the 10 s period, the melted region by the reflected laser beam can also be clearly seen just above the molten pool edge. In addition, the residual heating zone is observed continuously while the laser spot is both moving toward and moving away from the groove surface with continuous laser irradiation and hot-wire feeding.

3.2.2 Cross-sectional observation of the groove surface melting

Figure 9 shows the macro cross-section at one side of the groove surface for specimens obtained after 5 s of pre-irradiation without hot-wire feeding and for 20 s laser irradiation with hot-wire feeding. Figure 10 shows the magnified cross-sections and images of the top of the melted region and molten pool.

![Fig. 9](image)

Macro cross-sections at one side of the groove surface.

![Fig. 10](image)

Micro cross-sections with magnified images on the top of the melted region and the molten pool edge at one side of groove surface.
On the macro cross-section for samples with 5 s of pre-irradiation without hot-wire feeding in Fig. 9, the melted region is formed on the groove bottom and its edge separate from the groove surface. Direct laser beam irradiation and heating of the groove surface did not occur because the irradiation angle with the groove wall was very small and the weaving width was slightly narrower than the groove width. A heat affected zone (HAZ) also formed around the melted region as indicated by the white dashed line. For the micro cross-sectional image at the top of the melted region and HAZ, the transformed region separated from the melted region and the HAZ can be observed just above, as shown by a yellow dashed line in Fig. 10(a). The magnified images of area-A and area-B indicated in Fig. 10(a) clearly shows that the partially-transformed region obviously separated from the HAZ, and the peak temperature of this region was elevated in Ac1–Ac3 of the base metal.

The heating process on the groove surface during the pre-irradiation period can be described as follows. First, the groove bottom partially melts at the start of the pre-irradiation period; then, the reflected laser beam on the bottom of the melted starts to heat the groove surface just above the groove corner. This step was observed by the high-speed images taken for the specimens with 1 s pre-irradiation in Fig. 8(a). Second, the whole groove bottom area melts and a stable large molten pool formed; then, the reflected laser beam irradiates the groove surface continuously during weaving of the laser beam spot. The heat input from the reflected laser beam creates small melted region just above the molten pool and the molten pool edge connects to the melted area on the groove surface. This step can be observed from the high-speed images for the specimen subject to 5 s pre-irradiation in Fig. 8(a). However, the molten pool surface does not move upward and the heated region is created separately from the molten pool. This is because additional molten material is not added during the pre-irradiation period without hot-wire feeding.

On the macro cross-sectional image of the 20 s laser irradiation specimen with hot-wire feeding in Fig. 9, a large fusion zone formed and its edge moved upward and connected to the groove surface. On the micro cross-sectional image at the top of the fusion zone, a continuous upward growth of the molten pool edge on the groove surface can be observed. The magnified images of area-A in Fig. 10(b) clearly shows a new melted region just above the molten pool edge on the groove surface, and the molten pool edge connects to this new melted region. This process of groove surface melting and molten pool growth can be observed in the high-speed images shown in Fig. 8(b).

From the above observations, it can be concluded that groove surface melting is mainly due to the laser beam reflected from the molten pool surface during beam weaving. Hot-wire feeding can provide a continuous and efficient supply of melted material and stable heat input to the groove surface just above the molten pool edge by the reflected laser beam. As a result, a stable and continuous molten pool growth can be efficiently achieved with minimal penetration of the laser beam. It can be also noticed that the reflected laser beam around the groove surface during the holding period markedly affects melting of the groove surface; therefore, to obtain adequate fusion of the groove surface, the laser irradiation duration in a cycle during beam weaving is the key parameter.

4. Conclusions

The effect of the laser-weaving parameters, including the weaving frequency and waveform on base metal melting and weld-bead creation were investigated via hot-wire laser welding. High-speed and cross-sectional imaging were performed to investigate the heating and melting processes on the groove surface during the welding process. The conclusions are as follows:

1. A 5-Hz weaving frequency and an exponential waveform achieved a more efficient fusion of the groove surface compared with a higher frequency of 15 Hz and a sine waveform. The combination of a 5-Hz weaving frequency and an exponential waveform provided the longest laser irradiation duration near the groove surface in a cycle compared with the other investigated parameter combinations.

2. The irradiation duration near the groove surface in a cycle markedly affected the melting of the groove surface. A longer duration in a cycle resulted in a higher fusion ratio.

3. The laser beam reflected from the molten pool surface was the main heat source for melting the groove surface in the hot-wire laser welding method. Hot-wire feeding allowed for the continuous and efficient supply of melted material and a stable heat input on the groove surface by the reflected laser beam.

Acknowledgments

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