Laser-Enhanced Ar-GMA Welding*
by Terumi Nakamura**

A fiber laser was used to achieve stable consumable-electrode welding with pure Ar shielding gas (Ar-GMA). Ar-GMA welding produces a long column of liquid molten metal (CLM) at the wire tip, which causes irregular short-circuit and an unstable arc. The length of the CLM must be kept short to ensure stable welds. We have developed a method for cutting the CLM by means of a fiber laser. We investigated the cutting conditions for cold wire without an arc and the cutting conditions using a fiber laser with a pulse peak power of 6.0 kW and peak pulse time of 10 ms. Our experiments revealed that the laser irradiation position at the wire was crucial for achieving stable cutting, mainly because the recoil pressure force bends the CLM. After determining the optimum irradiation positions for cutting the CLM, laser-enhanced Ar-GMA welding was carried out. Stable welding was possible and excellent joints were obtained.

Key Words: Fiber laser, Ar shielding gas, GMA welding, Column of molten liquid metal

1. Introduction

A laser was used to stabilize the behavior of consumable-electrode welding in pure Ar shielding gas (Ar-GMA welding). Ar-GMA welding improves the characteristics of the weld metal by decreasing the amount of oxygen, which has a detrimental effect on weld metal.1) As a result, excellent joints having good toughness and ductility are obtained. However, Ar-GMA welding using a conventional commercially available solid wire is not used because of arc instability.1,2) The major cause of arc instability in Ar-GMA welding is the long column of liquid molten metal (CLM) generated at the wire tip.1,2) The irregular movement of the CLM and frequent short-circuit makes the arc unstable. As a result, the welding becomes unstable due to the large variation of the welding current and wire extension. To stabilize the Ar-GMA welding, the CLM must be kept short. We previously developed a coaxial multi-layer solid wire (CMS wire)1,2) that has a double structure consisting of a center wire (center area) and a hoop (outer area), which differ in composition. The melting temperature of the center wire is lower than that of the hoop. By using this CMS wire, large droplets and stable droplet transfer were obtained instead of generating a long CLM. As a result, we successfully shortened the length of the CLM and achieved stable Ar-GMA welding.

Thus, the most important point for stabilizing the Ar-GMA welding is to shorten the length of the CLM. If we could achieve this through other methods, we could obtain the same effect as with the CMS wire. In the present study, we investigated the possibility of shortening the CLM by using a laser, which offers high-precision cutting without contact. Basic experiments in cutting and removing the CLM in the arc were performed.

2. Materials and methods

2.1 Conditions of fiber laser

The long CLM shown in Fig. 1 was generated at the wire tip in Ar-GMA welding using conventional commercially available solid wire. The laser beam was delivered from the upper part of the GMA welding torch (nozzle) to cut this CLM. The welding torch and laser head were set as shown in Fig. 2.

We used a 10-kW fiber laser to cut and remove the CLM under the following conditions: fiber diameter of 0.2 mm and focal distance of 125 mm. A pulse laser (PW) with frequencies of 10 Hz and 20 Hz was used under the following conditions:

Fig. 1 CLM generated at the wire tip in Ar shielding gas

Fig. 2 Schematic illustration of GMA welding torch (nozzle) and laser head

---

*Received: 2014.11.28
**Member, National Institute for Materials Science
pulse peak power of 4.5 kW and 6.0 kW, laser irradiation time of 10 ms.

We selected two parameters for investigating the laser irradiation conditions. One is $H_f$, which is the distance between the focal point and the wire surface, as shown in Fig. 3(b). To change the laser irradiation area, we defocused the laser beam. The parameter $H_f$ was used to assess the laser irradiation area. To define the other parameter, we set the reference position (A). As shown in Fig. 3(a), the distance between point (A) and the contact tip is 10 mm and the focal point is the wire surface ($H_f = 0$ mm). This (A) point is shown in Fig. 1. The welding conditions for Fig. 1 are described in 2.2. To assess the effect of the irradiation position at the wire, we defined the parameter $L_s$ as the distance between point (A) and the center of the laser beam, as shown in Fig. 3(c).

![Laser beam parameters $L_s$ and $H_f$](image)

(a) $H_f = 0$ mm, $L_s = 0$ mm  (b) $H_f > 0$ mm, $L_s = 0$ mm  (c) $H_f > 0$ mm, $L_s > 0$ mm

2.2 Conditions of GMA welding

We used a commercially available welding power supply (maximum current: 500 A) and conventional commercially available solid welding wire for steel (wire diameter: 0.9 mm). The welding conditions were as follows: welding current of 250 A, welding voltage of 34 V, wire feed speed of 5 m/s and welding speed of 5 mm/s. The shielding gas was pure Ar.

3. Results and discussion

3.1 Cutting behavior of cold wire

First, we investigated the cutting conditions of the wire without an arc. Table 1 shows the results of wire cutting, and Fig. 4 shows the cutting behavior. When the focal point was located at the wire surface ($H_f = 0$ mm) and a pulse peak power of 4.5 kW was used, the laser beam could not cut the wire. It was able to melt the wire surface locally and the molten area was blown off by the recoil pressure force of the laser. However, it was unable to cut the entire surface of the wire (Fig. 4 A-(c)). Next, we used a high-power laser with a pulse peak of 6.0 kW to increase the melting area. We could cut the wire, but the laser beam could not cut the entire surface of the wire. After laser irradiation, the wire broke under its own weight. So, as shown in Fig. 4 B-(b), the wire was barely cut under these conditions.

To widen the laser-irradiated area, the laser beam was defocused. The distance between the focal point and the surface ($H_f$) was increased from 2.0 mm to 4.0 mm. The laser-irradiated area were 0.0008 mm² and 0.0032 mm², respectively. When $H_f$ of 2.0 mm was used, it was possible to cut the wire with the laser at a peak power of 6.0 kW, but not with the laser at a peak power of 4.5 kW. When $H_f$ of 4.0 mm was used, it was possible to cut the wire with the laser at a peak power of 4.5 kW and 6.0 kW. Figure 5 shows the cutting behavior. The cutting time with the laser at a peak power of 6.0 kW was 6.6 ms. In contrast, the cutting time with the laser at a peak power of 4.5 kW was 30.5 ms; the wire was cut by breaking under its own weight and sometimes even this failed to occur. We obtained stable cutting conditions for the wire without an arc.

![Table 1 Wire cutting conditions without arc](image)

<table>
<thead>
<tr>
<th>Mark</th>
<th>Pulse peak power (kW)</th>
<th>Average power (kW)</th>
<th>Position of focal point $H_f$ (mm)</th>
<th>Cutting wire</th>
<th>Cutting time $t_c$ (s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>4.5</td>
<td>0.45</td>
<td>0.0</td>
<td>X</td>
<td>-</td>
</tr>
<tr>
<td>B</td>
<td>6.0</td>
<td>0.60</td>
<td></td>
<td>Δ</td>
<td>0.0117</td>
</tr>
<tr>
<td>C</td>
<td>4.5</td>
<td>0.45</td>
<td>2.0</td>
<td>X</td>
<td>-</td>
</tr>
<tr>
<td>D</td>
<td>6.0</td>
<td>0.60</td>
<td>4.0</td>
<td></td>
<td>0.0087</td>
</tr>
<tr>
<td>E</td>
<td>4.5</td>
<td>0.45</td>
<td></td>
<td>Δ</td>
<td>0.0305</td>
</tr>
<tr>
<td>F</td>
<td>6.0</td>
<td>0.60</td>
<td></td>
<td></td>
<td>0.0066</td>
</tr>
</tbody>
</table>

○: Possible, △: Failure sometimes, ×: Impossible

![Fig. 4 Wire cutting behavior without arc.](image)

(A) Early stage of laser irradiation  Laser irradiation  After the end of laser irradiation

(B) Early stage of laser irradiation  Laser irradiation  After the end of laser irradiation

$H_f = 0.0$ mm
3.2 Cutting behavior of CLM

Next, we investigated the cutting behavior of the wire in an Ar arc using the same cutting conditions as for the wire without an arc. The distance between the focal point and surface \( H_f \) was 2.0 mm. The position of the laser \( (L_s) \) was 0.0 mm. The welding conditions were as follows: welding current of 250 A, welding voltage of 34 V and welding speed of 5.0 mm/s. Results are shown in Table 2 and images of the wire cutting behavior are shown in Figs. 6 and 7.

The CLM was generated at the wire tip before laser radiation (Fig. 6(a)). When the laser is applied to the wire, the CLM is cut and then breaks (Fig. 6(b)). The CLM gradually grows longer after the cutting, and then bends as shown in Fig. 6(c). This state continues until the end of laser irradiation and then immediately returns to the state before laser irradiation, as shown in Fig. 6(d).

The recoil pressure force of the laser bends the CLM, preventing stable cutting. When a pulse frequency of 20 Hz was used, the wire cutting behavior was almost the same as that for 10 Hz. The effect of the pulse frequency is not large.

To prevent CLM bending, we applied the laser beam to a solid area having higher stiffness than that of the CLM area. The stiffness area exists near the contact tip, because the temperature rapidly decreases with increasing distance from the tip.\(^3\)

<table>
<thead>
<tr>
<th>Mark</th>
<th>Frequency (Hz)</th>
<th>Position of focal point ( H_f ) (mm)</th>
<th>Position of laser ( L_s ) (mm)</th>
<th>Current (A)</th>
<th>Voltage (V)</th>
<th>Cutting wire</th>
</tr>
</thead>
<tbody>
<tr>
<td>G</td>
<td>10</td>
<td>+2.0</td>
<td>0.0</td>
<td>250</td>
<td>34</td>
<td>( \bullet )</td>
</tr>
<tr>
<td>H</td>
<td>20</td>
<td>+2.0</td>
<td>0.0</td>
<td>240</td>
<td>34</td>
<td>( \Delta )</td>
</tr>
<tr>
<td>I</td>
<td>10</td>
<td>+2.0</td>
<td>+2.0</td>
<td>245</td>
<td>34</td>
<td>( \Delta )</td>
</tr>
<tr>
<td>J</td>
<td>10</td>
<td>+2.0</td>
<td>+4.0</td>
<td>255</td>
<td>34</td>
<td>( \circ )</td>
</tr>
</tbody>
</table>

\( \bullet \): Possible, \( \Delta \): CLM bending \( \times \): Impossible

Table 2  Wire cutting conditions in Ar arc

![Fig. 5](image)

Wire cutting behavior without arc.

\( H_f = 4.0 \) mm

![Fig. 6](image)

Wire tip behavior in arc

Laser conditions: Peak power 6.0 kW, 10 Hz
Welding conditions: \( I = 250 \) A, \( V = 34.0 \) V, \( L_s = 0.0 \) mm

![Fig. 7](image)

Wire tip behavior in arc

Laser conditions: Peak power 6.0 kW, 10 Hz
Welding conditions: \( I = 255 \) A, \( V = 33.5 \) V, \( L_s = 4.0 \) mm
The cutting behavior at $L_s$ of 2.0 mm was almost the same as that for $L_s$ of 0.0 mm. Next, we investigated the cutting behavior at $L_s$ of 4.0 mm. Figure 7 shows the results. The broken lines (A) and (B) indicate the position of the laser beam at $L_s$ of 0.0 mm and 4.0 mm, respectively (Fig. 7(a)). As soon as the laser irradiates the wire, the CLM is cut and broken, as shown in Fig. 7(b). This state continues until the end of laser irradiation (Fig. 7(c), (d), (e)) and then immediately returns to the state before laser irradiation (Fig. 7(f)). Broken CLM became droplets with a diameter of less than the wire diameter. And these droplets fell down to the molten pool. Those were not scattered on a wide area like spatters in conventional welding. We were able to cut the CLM using this method. Selecting the appropriate irradiation position of the laser beam is crucial. Figure 8 shows the excellent bead shape obtained under the laser irradiation conditions.

![Image](image_url)

**Fig. 8** Bead shape of laser-enhanced Ar-GMA welding

Laser conditions: Peak power 6.0 kW, 10 Hz
Welding conditions: $I = 255$ A, $V = 33.5$ V, $L_s = 4.0$ mm

In this way, we were able to achieve stable Ar-GMA welding by using the fiber laser. Hung\(^4\) attempted to control the droplet detachment at low welding current conditions in CO\(_2\)-rich shielding gas or mixed gas of Ar and oxygen by using a laser. The laser beam was applied to the droplet so that the recoil force would detach the droplet. In the present study, we attempted to shorten the CLM by using laser irradiation under large welding current conditions in pure Ar shielding gas. As a result, we were able to obtain the laser irradiation conditions for stable cutting of the CLM.

4. Conclusions

We developed a stable Ar-GMA welding process using conventional commercially available solid wire instead of CMS wire. A fiber laser was used to cut the CLM generated at the wire tip in pure Ar shielding gas. In this process, the laser irradiation position at the wire was a crucial factor. When the laser beam was applied to the CLM, the recoil pressure force bent the CLM and stable cutting was impossible. To prevent the bending of the CLM, the laser beam was applied to a rigid area of the wire. As a result, stable cutting of the CLM was possible and an excellent bead shape was obtained.

References