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Development of a high-efficiency / high-quality hot-wire laser fillet welding process†

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KEY WORDS: (Hot wire) (Fillet welding) (Laser welding) (High efficiency)

1. Introduction

The GMA welding process has been widely used for fillet welding because of its convenient and economical efficient advantages compared with other welding processes. However, the process conditions for high speed and high deposition rate often leads to defects like undercut etc. and increase the deformation amount due to excessive heat input. Laser and laser-arc hybrid welding are the promising processes to achieve the high welding speed and the low deformation. However, to apply laser welding process to fillet welding requires a high power source for full penetration welds. In addition, it is also necessary to have high positional accuracy and the addition of filler metals for stable bead formation. It is hard to control the melting phenomenon of the filler stably since both the filler and the base material are heated by the laser. On the other hand, in the case of laser-arc hybrid welding, it is difficult to prevent forming defects caused by arc phenomenon.

The aim of this work is to develop the hot-wire laser welding process which has both advantages of high efficiency (high deposition rate, high speed etc.) and high quality (low heat input and deformation). This process combines a laser and hot-wire system in which the filler wire is melted by current heating. Thus, each melting of filler wire and the base material can be controlled independently. In this study, influence of welding conditions on melting phenomena was investigated using an in-situ monitoring system using a high speed camera. Cross sections and mechanical properties were evaluated as the characterization of the welded joint.

2. Experimental procedure

Mild steel plate (SS400, thickness: 9 mm) and filler wire (JIA Z3321 YGW, ϕ 1.4 mm) were used. **Table 1** shows the chemical compositions of used materials.

Table 2 indicates the welding conditions. The conditions relating with laser and filler wire were changed as experimental parameters. A fiber laser was used as a heat source. The laser power and the welding speed were fixed. Spot diameters of laser were controlled by the distance from the focal length of a laser head. A laser head and a wire torch were leaned 45° to the vertical direction of the traveling one. In addition, the laser head was also leaned 5° to the traveling direction. Filler wire was fed into the backward part of the laser irradiated area toward the welding direction.

In-situ observation was carried out using a high speed camera to investigate the melting phenomena of the base material and the wire during welding. As quantitative evaluation, throat thickness and leg length were measured from the cross section of each obtained sample. In order to characterize the property of the welded joint, microstructural analysis and mechanical tests were carried out.

3. Result and discussion

Firstly, we focused on the clarification of the influencing factors on the melting phenomenon of filler wire. Wire current, wire feeding position (distance from laser center) and wire feeding angle were applied as the experimental factors. **Figure 1** shows the images taken by a high speed camera on each wire current. 110 A of wire current indicates the stable melting of filler wire. In the case of the lower current, the wire can reach the molten pool bottom because of the heating insufficiency. On the other hand, the higher current induces the meltdown of the wire due to the excessive heat input. Thus, the adequate wire current value is required for the stable melting.

Table 1 Chemical compositions of used materials.

	C	Si	Mn	P	S	Cu	Al	Ti+Zr
SS400	<0.16	<0.17	<0.73	<0.016	<0.006	-	-	-
YGW11	0.04	0.68	1.55	0.014	0.013	0.03	<0.01	0.23

Table 2 Welding conditions.

Welding speed, m/min	0.3
Laser power, kW	3.0
Laser irradiation angle, deg	45
Spot diameter, mm	3.0 – 7.5
Wire feeding position, mm	0 – 3.0
Wire current, A	70 – 149
Wire feeding speed, m/min	0.8 – 3.6
Wire feeding angle, deg	55 - 75

The high speed camera images for each of the wire feeding distances forming the laser spot are indicated in **Fig. 2**. The stable melting can be confirmed if the fire is fed into 2 mm of the position from the spot center. However, the filler wire is melted before touching the base material due

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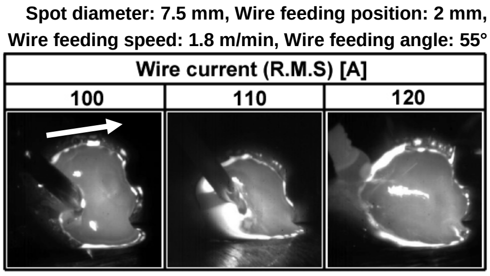
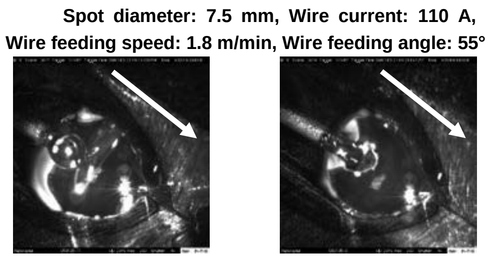


Fig. 1 High speed images on each wire current.

to the direct irradiation of laser, when the wire is introduced at the center of the laser spot. On the other hand, the wire is not able to be inserted into the molten pool for more than 3 mm of wire feeding position. These result means that the filler wire should be introduced into the molten pool backward without the laser irradiation

In addition, we also investigated the wire melting phenomena as the function of the wire feeding angle. In the case of 55 and 75˚ of the feeding angle, the continuous feeding and the stable melting of filler wire were obtained. However, 35˚ of the feeding angle led to form the poor geometry of the bead since the wire tends to touch the solid part at the backward part of the molten pool due to the wire softening by heating.

As the second step, the phenomenon of bead formation was evaluated. **Figure 3** shows the change of average leg length with spot diameter of laser. Average leg length was obtained from both the lengths of vertical (L_1) and horizontal (L_2). The broken line indicates the laser irradiated length calculated from the spot diameter.



a) 0 mm b) 2 mm

Fig. 2 High speed images on each wire feeding position.

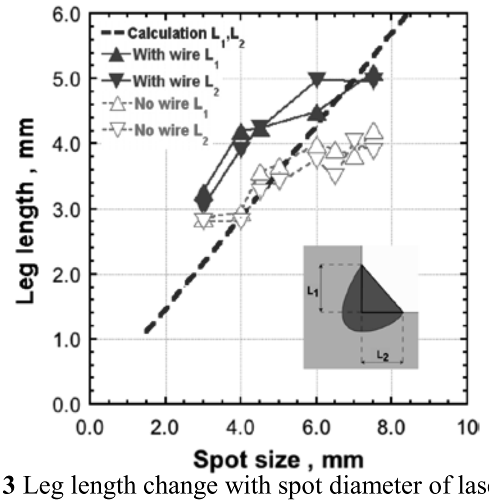


Fig. 3 Leg length change with spot diameter of laser.

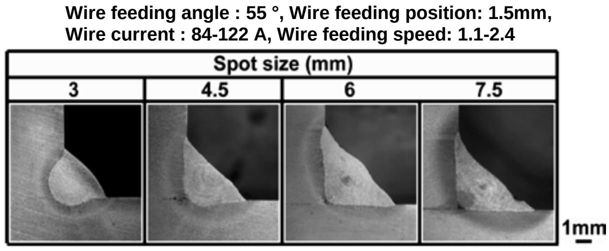


Fig. 4 Cross sections of weld bead on each spot diameter.

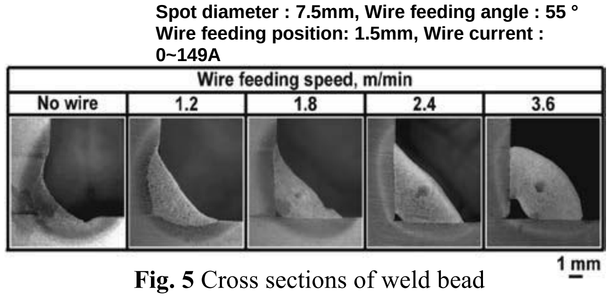


Fig. 5 Cross sections of weld bead on various wire feeding speeds.

Regardless of the filler wire addition, the length increases with increasing spot diameter. Besides, those values of no wire samples are smaller than those of the wire added ones. It can be assumed that this is caused by the reflection of the laser beam. The laser beam has a great tendency to reflect on the molten pool surface due to high optical reflectivity of liquid metal. Thus, the reflected beam contributes to melting of the base material since the beam irradiates the surroundings of the distended geometry of the molten pool.

Figure 4 indicates cross sections of the beads welded under identical condition shown in Fig. 3. In the case of 3 mm of the spot diameter, the penetration is deeper compared with another samples because of the high energy density. If we apply the laser spot diameter which is more than 4.5 mm, the dilutions of the base materials are quite low. In addition, defects like overlaps and undercut at the welding toe never form in any spot diameters. However, lack of fusion at the root observed in the samples fabricated under 6.0 and 7.5 mm diameter of the laser spot due to the low heat input corresponding to large spot diameter.

Figure 5 also shows cross sections as the function of wire feeding speed. There is not much difference between the leg lengths of the weld bead. However, the cross section geometry transits from triangle to sector. Furthermore, increasing the wire feeding speed induces to the formation of larger lack of fusion at the root. Thus, there is a limit to improving the leg length by the laser beam reflection changing with only the wire feeding speed. We should consider the factor interaction between laser energy density, wire feeding speed and welding speed.

The welded joint fabricated under the optimized conditions has following properties; average grain size in the coarse grain zone: 60 μm, dilution ratio: a few percent, thickness of heat affected zone: 1 mm.

These results reveal that this process includes various factors influencing on the welding phenomenon. However, the parameter optimization contributes to the stable melting of base materials and the filler wire and the obtained welds indicate attractive properties, namely low heat input and low dilution.

4. Conclusions

In order to develop the high efficiency / high quality fillet welding technique, the welding phenomena on the hot-wire laser fillet welding were investigated. Obtained conclusions are as follows.

(1) The melting of filler wire depends on wire current and there is an optimum vale of the current at each wire feeding speed.

(2) The filler wire should be fed into the molten pool backward without the laser irradiation.

(3) The leg length increases by the addition of filler wire compared with the non filler welding due to the laser beam reflection at the molten pool surface.

(4) The formation of lack of fusion at the root must be caused by the excessive wire feeding and the insufficiency of the heat input by laser.

(5) The parameter optimization leads to the stationary welding phenomenon. In addition, the obtained weld has attractive properties, namely low heat input and low dilution.