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Single pass full penetration welding of high-tensile steel thick-plate using 4 kW fiber laser and MAG arc hybrid welding process*

by SHIN Minhyo** and NAKATA Kazuhiro***

Full penetration weld bead by one pass butt joint welding of 12 mm thick SM490 plate were produced using the hybrid welding system combined with 4 kW power class fiber laser and pulsed MAG arc. The fusion zone was believed to be formed by one weld pool. A sound one pass full penetration weld bead without inside defects was obtained at the groove angle of 20 degrees and the gap width of 0.7 mm. A gap width of 1.5 mm was bridged by the hybrid welding process, but underfilling occurred at the root gap width over 1.0 mm in all groove angles. In order to improve the underfilling, higher feeding rate of a filler wire was applied by increasing the arc current. However, it was not a successful method because more molten metal and higher arc pressure accelerated the melt-through on the bottom beads. According to microstructure observation and hardness profile on the cross section, there was no brittle phase caused by the laser welding.

Key Words: fiber laser, hybrid welding process, full penetration weld bead, thick plate

1. Introduction

In welding of a thick plate, the formation of a full penetration weld bead by one-pass process is great effective in a manufacturing cost point of view. A high power laser is often concerned for the deep penetration welding, however the problems such as narrow gap tolerance, porosity formation and brittle microstructure formation are pointed out as one of the obstacles for its the practical application in fields.

Among the newly-developed welding processes, the hybrid welding combining a laser and an arc is recommended as one of the promising welding processes in the high speed welding of thick-plate, because it has many advantages such as high energy efficiency, deep penetration weld bead formation, wide gap allowance, elements composition control of the fusion zone, alleviation of thermal deformation, narrow width of HAZ and heat treatment effect, etc[1－5].

As a high power CO_2 gas laser is available to use in the hybrid welding process, many results of thick-plate welding have been reported[6－8]. However, laser energy absorption by the laser induced plasma, difficulty of maintenance, large size equipment, defects formation and the complex beam delivery system with mirror reflections are reported as one of problems for practical use[9].

On the other hands, a high power fiber laser has been developed recently. It has high energy efficiency of about 25 % and is compact size attributed to a simple cooling system. Moreover, due to the laser beam wave length of 1070 nm, delivering the laser beam through a flexible optic fiber is possible and it is also feasible to adapted operate by a multi axis industry robot system[10, 11].

In addition, with reduction of the laser energy absorption by laser induced plasma, deeper weld bead formation at higher welding speed is possible comparing with other conventional types of high power laser[12, 13]. Therefore, the application of the fiber laser in the hybrid welding system has been received much attention, however there are a few reports[14].

Thus, in the present study, the characteristic of the hybrid weld bead formation of SM490 of 12 mm in thickness was investigated using 4 kW class fiber laser and pulsed MAG arc hybrid welding system for the purpose of producing one-pass full penetration weld bead. In order to define a role of the process control factors, the influence of welding parameters such as DLA, groove angles, gap width and arc current on the weld bead formation was identified as well.

2. Experimental procedures

As the hybrid weld heat sources, a 4 kW class IPG fiber laser and Daihen DC 300A pulsed MAG welder were used. Fig. 1 shows the experimental setup of hybrid welding system and specimen. The hybrid weld was performed in the combination of the laser at the leading and the arc at the trailing positions. Incident angle of the laser beam was vertical to the spacemen surface and the arc torch was tilted with 23 degrees to the laser

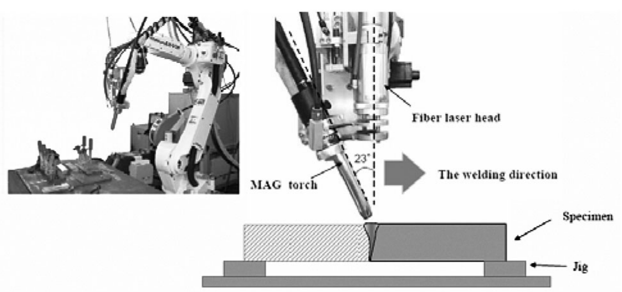

Fig. 1　Schematic experimental setup for the laser leading hybrid weld.

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**Student Member, Graduate School of Engineering Osaka University
***Member, JWRI Osaka University

beam axis. The laser head with 240 mm of the focus length and 0.3 mm of the focus beam diameter was used. The shielding gas was supplied by the MAG torch of 16 mm in diameter and the distance to the specimen was 15 mm and it was the same as the length of the electrode extension. 600 MPa class filler wire with diameter of 1.2 mm was used for the filler wire. The filler wire feeding rates, which depend on the arc current were 2.60, 5.16, 6.60 and 8.12 m/min at 80, 160, 200 and 240 A, respectively. The specimen size is 150 mm in length, 75 mm in width and 12 mm in thickness. The groove depth was 6 mm and Y shape. The welding parameters used in the present study are shown in Table 1. The weld beads were cut by abrasive cutter and then etched by 2 % nital solutions. The evaluation of macro and micro structure of the bead was conducted using optical mirco scope. Micro hardness profile was defined using micro Vickers hardness tester with the load of 1.961 N and holding time of 5 seconds. A high speed camera used for in-situ observation of the molten metal pool during the hybrid welding. The formation of inside defects in the weld beads was assessed by x-ray radio graph inspection.

3. Results and discussion

3.1 Formation of full penetration weld bead by single pass welding

The effect of the gap groove angles on the weld bead formation was investigated and the result was summarized in Fig. 2. Partial penetration weld beads were formed at 30 and 40 degrees in the groove angles. On the other hand, in the case of the groove angle of 60 degrees, penetration depth increased and full penetration weld bead was obtained by single pass process. However, underfill was remained on the bead surface due to insufficient filler metal addition and back bead formation.

Fig. 3 shows the cross sections and the appearances of the weld beads formed by the hybrid welding when the distance of the laser to the arc (DLA) was changed in 2, 5 and 15 mm at 60 degrees in the groove angle. The laser power, welding speed and arc current were set to be 4 kW, 0.5 m/min and 80 A respectively.

Table 1 Parameters for hybrid weld

Laser	**Power**	**4 kW**
	Defocused distance	**0 mm (surface of the plate)**
MAG	**Current**	**80 ~ 240 A**
	Gas flow rate	**20% CO_2 + 80 %Ar :25 L/min**
Welding speed		**0.5 m/min**
Laser- MAG distance		**2 ~ 15 mm**
Welding direction		**Laser leading and arc trailing**

As a result, the full penetration weld bead was obtained at DLA of 2 mm. However, when the DLA was increased from 2 to 5 mm, the penetration depth slightly decreased and the back bead formation occurred discontinuously. In the case of the DLA range from 5 to 15 mm, the penetration depth was more decreased and partial penetration bead was formed and bottom bead formation not occurred. From the observation of the cross sections, it was confirmed that the laser and the arc can make one hybrid fusion zone together in DLA of 2 mm. However, the hybrid fusion zone started to be divided into each of two individual regions at DLA of 5 mm and completely separated by two fusion zones at DLA of 15 mm.

3.2 Increase of gap allowance by hybrid process

The comparison of the gap bridging ability in the case of the fiber laser welding and the hybrid welding is shown in Fig. 4. The gap bridging by the fiber laser was limited at the gap width of 0.5 mm, while the hybrid weld can increase gap bridging allowance to 1.5 mm due to the filler wire addition. However, the filler wire feeding speed of 2.6 m/min at the arc current of 80 A was not enough to make a sound reinforcement over the all gap width conditions with 60 degrees of groove angles, so we investigated the characteristics of the bead formation at higher filler wire feeding rate at the higher arc current and discussed

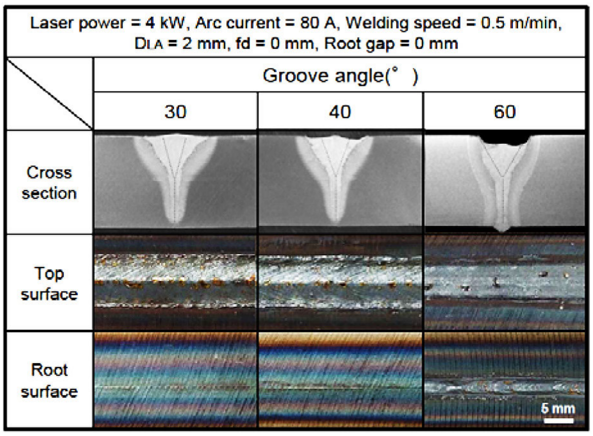

Fig. 2 The effect of groove angles for hybrid weld formation.

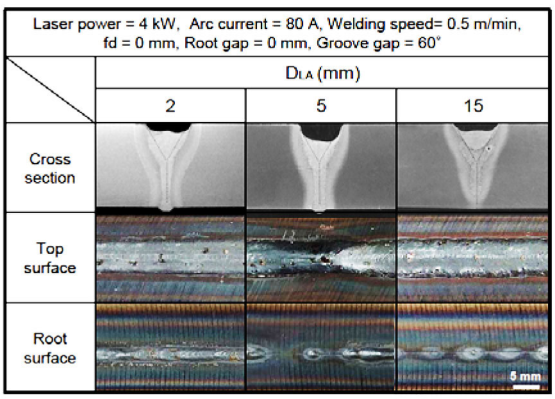

Fig. 3 The effect of DLA on the bead formation.

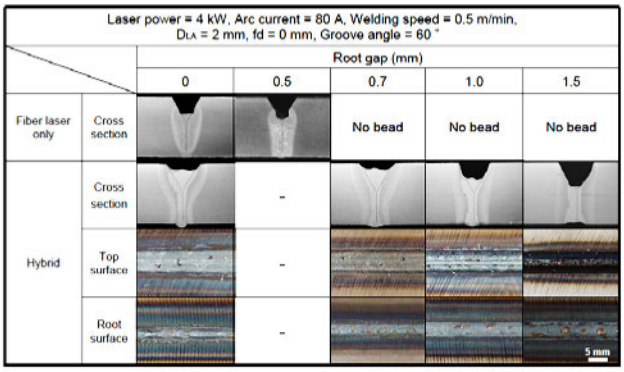

Fig. 4 Comparison of gap bridging ability between the fiber laser weld only and the hybrid weld.

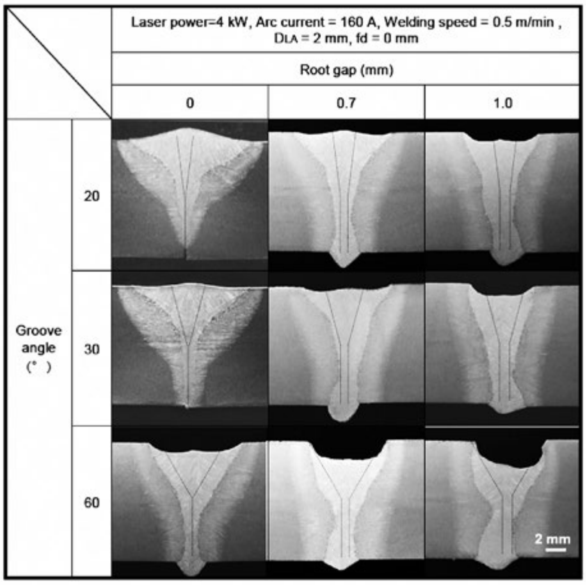

Fig. 5 Effect of groove angle and root gap on hybrid weld formation.

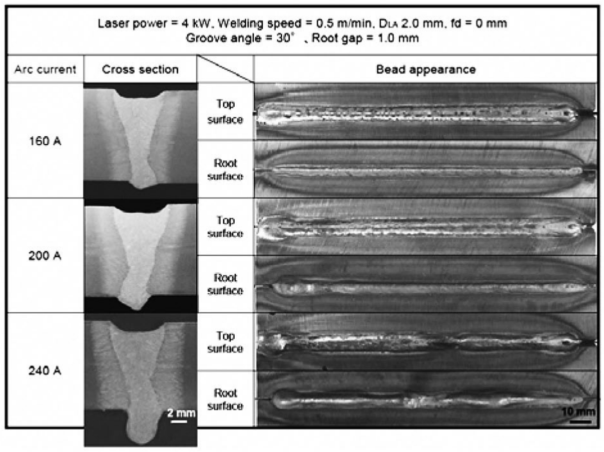

Fig. 6 Cross sections and bead appearances of hybrid welds of 160, 200 and 240 A.

about the result in the followed section.

3.3 Effect of groove angle and root gap width on the bead formation

In the case of the arc current 160 A with the wire feeding rate of 5.16 m/min, the effect of groove angle and root gap width on the weld bead formation was investigated. The result is shown in Fig. 5. Enough reinforcement was formed at the groove angle of 20 degrees and root gap of 0 mm. The height of reinforcement was decreased with increasing the groove angle and became almost flat to the base metal at the groove angle of 30 degrees. The penetrations occurred partially and full penetration beads can not be formed. In the case of the groove angle of 60 degrees with the root gap of 0 mm, full penetration weld bead, in which there was large underfill remained on the bead surface was formed. On the other hand, for the root gap width of 0.7 mm, one pass full penetration weld beads were obtained at all groove angles. In particular, at groove angles of 20 and 30 degrees, full penetration weld beads without underfill were formed. However, in the case of the root gap width of 1.0 mm, large underfill was observed in all groove angles and it was not successful to make sound weld beads with enough reinforcement.

For practical applications, sound weld beads with enough reinforcement at the gap width of 1.0 mm is needed. Thus, the cross sections of the weld beads were investigated with increasing the MAG arc current in the gap width of 1.0 mm. The maximum welding speed for full-filling the space of groove and root gap in given welding parameters can be assumed. From the calculated result, it can be assumed that when the welding speed is set at 0.5 m/min, the wire feeding rate needed for full filling the 30 degrees of groove and 1 mm of root gap is about 10.5 m/min and the arc current is 300 A. However, as shown in Fig. 6, large melt-through and underfill occurred and bead formation became to be unstable even at the arc current of 240 A. Those results are contrary to the expectation of improving the underfill and the melt-through on the back bead was increased with increasing the arc current. In MIG and MAG arc weldings, it is well known that high arc current induces the strong arc pressure, which increases in proportion to the square of arc current[15)], and pushes the molten surface downward. Thus, the melt-through increased in spite of the increase of filler wire feed rate.

3.4 Effect of DLA on root bead formation

In order to investigate a role of laser in hybrid welding, the in-situ observation of the weld pool was conducted using a high speed camera during welding. The high speed images and cross sections of the hybrid welding with different DLA and MAG arc welding are compared and the results are summarized in Fig. 7.

The small bright spot located on the front of the arc pool in welding direction is assumed as the fiber laser keyhole. The keyhole retained even in the strong fluctuation of the molten metal caused by pulsed arc during the welding and the process was performed in a stable state. The distance of the keyhole to the MAG arc was depended on DLA. The keyhole was observed

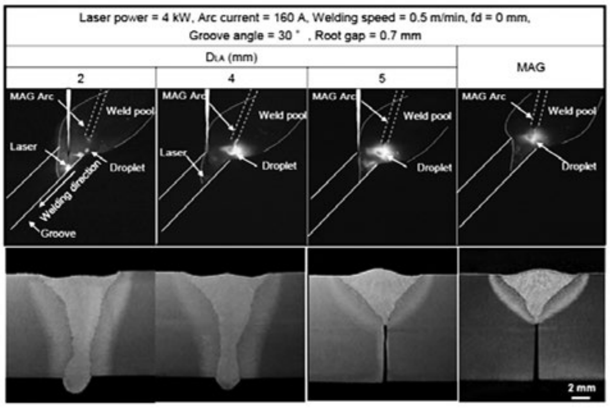

Fig. 7 High speed camera images and cross sections of weld beads with varied DLA.

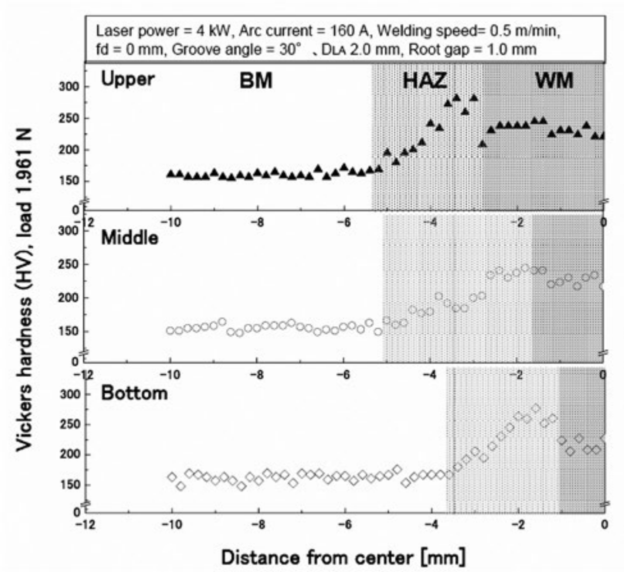

Fig. 8 Hardness profiles of the cross sections of the 1 pass full penetration hybrid weld bead.

within DLA from 2 to 4 mm, however, disappeared at the DLA of 5 mm. According to the cross sections of the weld beads, it was also known that full penetration was achieved within 4 mm in DLA, while partial penetration occurred at the DLA of 5 mm. Moreover, the cross section shape of the hybrid weld bead at 5 mm in the DLA was almost the same as that of the single MAG arc weld.

From this result, it is concluded that the fiber laser irradiation played an important role for making the gap bridging in the hybrid welding of the butt joint with the opened gaps and the effective process range of the DLA was within 4 mm in the case of laser beam leading and MAG arc trailing for the joint with 0.7 mm gap.

3.5 Hardness distribution and micro structure

Fig. 8 shows the hardness profiles on the cross section of the hybrid weld. The groove angle was 30 degree and the width of the root gap was 1.0 mm. Three upper, middle and bottom parts were scanned for hardness profile, namely 3 mm below the top surface, center and 3 mm above from the bottom surface of the bead were evaluated for the hardness profiles. The HAZ hardness increased up to 300 HV and also the fusion zone hardness increased to about 240 HV in comparison with the hardness of the base metal, about 150 HV. There was no significant difference in the hardness distributions among the three parts.

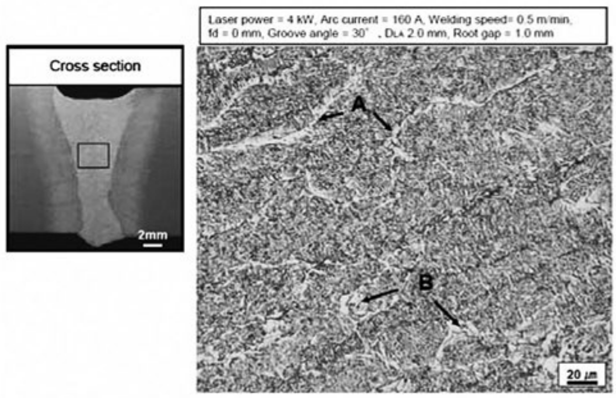

Fig. 9 Microstructure of the hybrid weld.

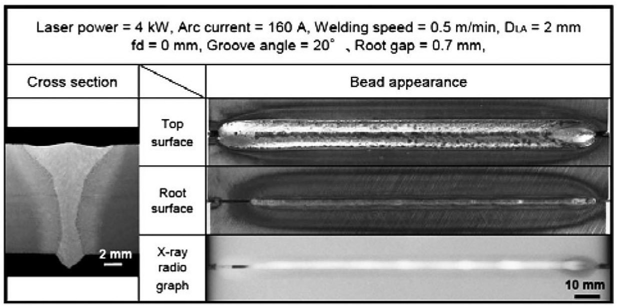

Fig. 10 X-ray radiograph inspection result.

The typical microstructure of the hybrid weld bead is shown in Fig. 9. It is defined that A and B are grain boundary ferrite and polygonal ferrite respectively. Considering that it is generally known that the most of the laser fusion zone is consisted of a brittle high cooling phase, such as martensite and bainite[5] and there is a small amount of ferrite phase due to its high cooling rate of the fusion zone, as shown in Fig. 9, the amount of ferrite in the hybrid weld is significant. Thus, it is expected that the mechanical properties of the one-pass full penetration hybrid weld is improved compared with that of the laser weld only.

3.6 Defects in the weld

X-ray radiograph inspection was carried out to evaluate the defect formation in the hybrid weld. The welding parameters were the arc current of 160 A, groove angle of 20 degree and root gap widths of 0.7 mm. It is confirmed that there is no defect formation in the weld as shown in Fig. 10. For the typical laser welding only, it is generally known that the formation of the defects such as porosity is caused by trapping of a floating bubble in the molten metal[16]. Moreover, according to the composition analysis of the inside gas of the porosity, it is also confirmed that the most of the vapor came from the shielding gas or the metal vapor formed by an intensive vaporization in the bottom of the keyhole[17].

In the present study, because the root is opened, it is believed that the shielding gas or metal vapor can escape through the open root.

4. Summary

The hybrid process combined with 4 kW class fiber laser and MAG arc make a sound one pass full penetration weld bead in the root gap width of 0.7 mm and 20 degrees of the groove angle at 0.5 m/min of welding speed. However, in the case of the root gap of 1.0 mm, underfilling occurred in all groove angles and increasing of the filler wire addition by increasing the arc current was not successful method because the melt-through on the bottom beads was accelerated by more molten metal and stronger arc pressure. Based on microstructure observation and hardness profile results of the cross section of the bead, it was confirmed that there was no brittle phase caused by the laser welding only as well.

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