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Study on fabrication of butt welded joints of thick plates by laser-arc hybrid welding in horizontal position

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Abstract

Laser-arc hybrid welding (LAHW) is an advanced welding process that combines arc and laser welding as one molten pool. Compared with conventional arc welding, LAHW can be performed higher welding speeds with narrower grooves, and weld deformation can be significantly reduced. When LAHW is applied to construction of structural members, the welding is generally performed in a flat position because it is automatic welding system is applied from the viewpoint of safety in the work environment.

Flat position (PA), it is expected to be applied to many welds of large steel structures by applying LAHW to horizontal position. However, the application of LAHW in the construction of large structures is expected by expanding the applicable welding position.

In this study, butt joints with a plate thickness of 20 mm were fabricated in the horizontal position (PC) as a target of welding position in LAHW. By trial and error, referring to the welding conditions in the flat position, the welding conditions that produced a sound weld bead appearance were derived. However, molten metal was sagging at some of lower weld bead edge of the front bead. A sliding jig was designed to prevent the front bead sagging. As a result, the sagging was prevented and it was expected that the jig was effective in relaxing the shape of the weld toe for improving the fatigue strength of the joint.

In the construction stages of large structures, it is difficult to maintain a constant root gap over the entire length of the weld line, so it is desirable to extend the allowable range of the initial gap. Therefore, we attempted to process

with an initial root gap of 1.5 mm. However, we were unable to find welding conditions that would avoid undercutting and melting-in, and confirmed that the applicable limit of the initial root gap is 1.0 mm for the construction method studied in this study.

Keyword: Laser-arc hybrid welding, Horizontal Position (PC), Welding conditions, Butt welded joint

1. INTRODUCTION

For the construction of general merchant ships, thick plates with a thickness of about 20 mm or less are used, and the welding positions and processes differ at each stage of construction. For example, in Japanese shipyards, one-sided submerged arc welding is often used for butt joints of thick plates, and multi-layered welding is often used for construction of the hull blocks. Most of these welding methods require the preparation of "V" or "Y" shaped grooves, and it is preferable to control heat input by making the grooves as narrow as possible to reduce weld deformation and material degradation [1].

Laser-arc hybrid welding (LAHW) is an advanced welding method that uses the advantages of laser welding and arc welding as one molten pool. Because LAHW can significantly reduce weld deformation by localized and deep penetration welding while maintaining welding speeds equivalent to or faster than conventional arc welding methods, it is expected to be possible to weld with fewer passes with small or without grooving. However, the current LAHW process for structural members is limited to the flat position (PA) from the viewpoint of safety in the work environment. Therefore, it is expected to be applied to many welding stages for the construction of large steel structures by extending the applicable welding positions. In recent years, inexpensive and high-performance laser oscillators have been developed, and the practical application of joining technology using a laser heat source in large steel structures is increasing [2][3]. Research has already been conducted on the application of LAHW to horizontal position (PC), but the maximum applicable plate thickness is 16 mm [4]. In this study, LAHW is applied to horizontal position to fabricate butt joints with a plate thickness of 20 mm.

2. PROTOTYPE HORIZONTAL BUTT JOINT

2.1 Materials and Test procedure

Hull construction steel Grade KA36 classified by ClassNK were used as the material. J-STAR® Welding [5] using KC-550 solid wire (classified as JIS Z 3312: YGW18) which rare elements additions was applied for arc welding, while pure CO2 gas (30 L/min, 0.3 MPa) was used for shielding gas to reduce production cost.

J-STAR® Welding is capable of low low-sputter operation due to the fine and continuous spray transition of the molten droplets, and has been reported to have an affinity for LAHW [6]. Chemical compositions and mechanical properties of the material of the specimens and weld wire are listed in **Table 1**.

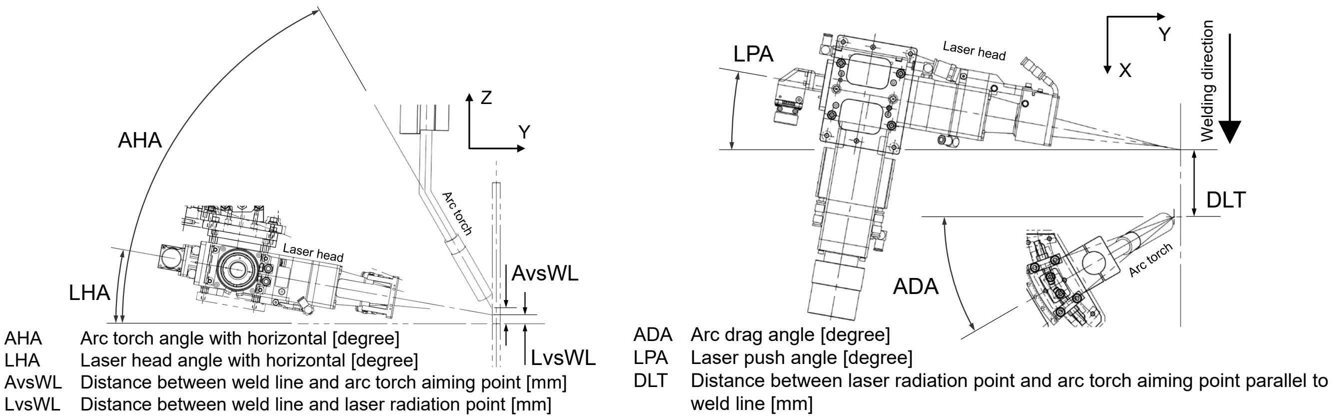
Table 1 *Chemical compositions and mechanical properties of applied steel plate and weld wire.*

Welding consumable	Chemical compositions [mass %]					Mechanical properties		
	C	Si	Mn	P	S	Yield stress [MPa]	Tensile strength [MPa]	Elongation [%]
KA36	0.157	0.442	1.067	0.013	0.002	416	542	21
KC-550	0.050	0.700	1.900	0.010	0.010	571	621	30

The dimensions of the specimens were 20 mm thick and 200 mm wide, and butt joints were fabricated using two steel plates with I-shaped groove formed by plasma cutting. Considering the possibility of directly introducing the results of this research into the hull construction stages, only oil and other contaminants were removed, leaving the rust-preventive primer near the grooves and the oxide film produced by cutting the grooves intact.

LAHW system consisting of a digital inverter-controlled automatic welding machine as an arc welding power source and a 20 kW Yb fiber laser was used. These arc and laser power sources were attached to the tip of a vertical articulated manipulator, and each welding position and laser irradiation position were taught using a programming pendant. A schematic diagram of the laser head and arc torch arrangement is shown in **Fig. 1**.

Full-line tack welding with laser welding [7] was employed for tack welding. This tack weld tends to suppress the tearing force during welding and is effective in preventing tack weld cracking and suppressing gap fluctuation during welding. Uchino et al. [8] reported that good appearance is obtained when the root gap is about 1.0 mm on the back side of the groove, so a spacer (feeler gauge, etc.) was used to set the root gap at 1.0 mm.



(A) View from the side *(B) View from the top*

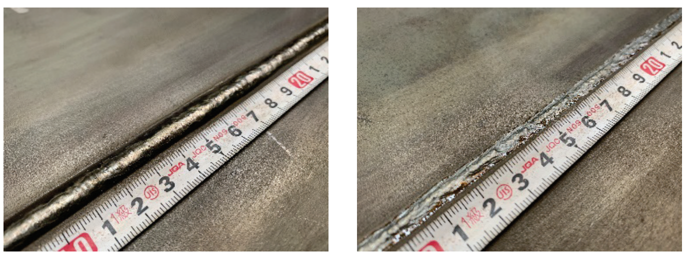
***Fig. 1** Schematic of arc torch and laser head position in LAHW-HB.*

2.2 Fabrication result

The fabrication of butt joints with a plate thickness of 20 mm was attempted by trial and error on a specimen with a weld length of 300 mm by considering the condition which a joint with a plate thickness of 14 mm [4]. As a result, it was confirmed that sound weld bead could be obtained along the entire weld line under the welding conditions shown in **Table 2**.

***Table 2** Welding condition.*

Arc current [A]	400
Arc voltage [V]	36.0
Laser power [kW]	16.0
LvsWL [mm] (Ref. **Fig. 1**)	+0.5
Travel speed [cm/min.]	800



(A) Front bead *(B) Back bead*

***Fig. 2** Photograph of bead appearance of HB01.*

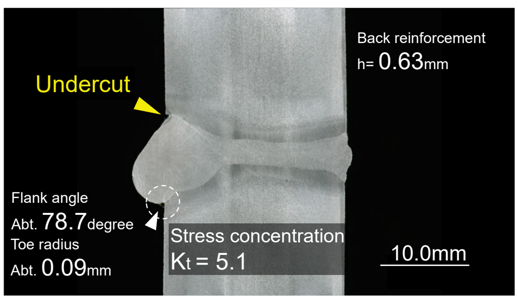


***Fig. 3** Macroscopic test of HB01.*

Figure 2 shows the bead appearance of the fabricated butt joint, and **Fig. 3** shows the macroscopic observation of test ID: HB01 at middle section of the weld length. The appearance inspection confirmed no surface defects, and a good weld bead was generally obtained along the entire weld line. However, sagging of molten metal was observed at some of lower weld bead edge of the front bead. This confirms the need for further study of the LAHW construction method for a plate thickness of 20 mm.

3. DEVELOPMENT OF FRONT BEAD SUPPORT MATERIAL

3.1 Supporting sheet

One method to improve front bead sagging is to suppress the supply of molten metal, but there is concern that the back bead will not have enough volume if the amount of molten metal supplied is reduced. Therefore, a ceramic weld bead support material, which is attached below the weld line of the material to be welded, is employed as a supporting sheet to prevent front bead sagging. Some welders use support sheet as a method of preventing the weld bead sagging in arc welding operations in the horizontal position.

Figure 4 shows a schematic diagram of the role of the support sheet in the construction. **Figure 5** shows a schematic diagram of the attached supporting sheet (FAMILIARC^{TM} FB-B3 H, Kobe Steel, Ltd.) used in this study. **Figure 6** shows the situation when the supporting sheet is installed.

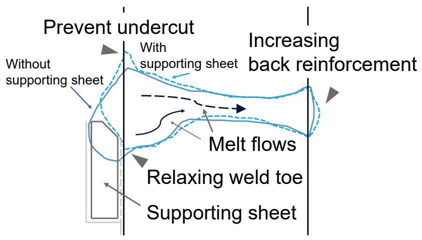


Fig. 4 Hypothesis of using supporting sheet.

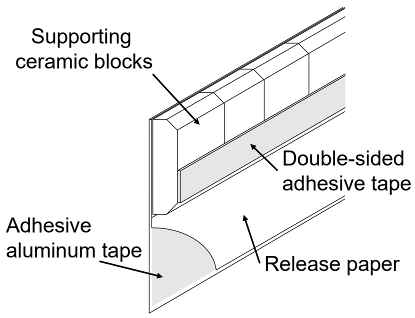


Fig. 5 Composition of supporting sheet (FB-B3 H).

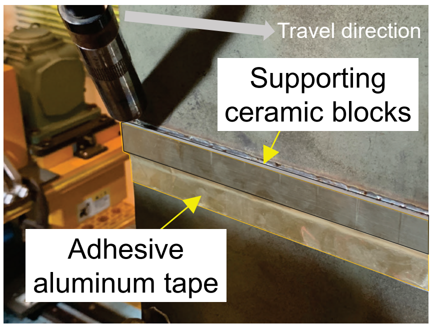
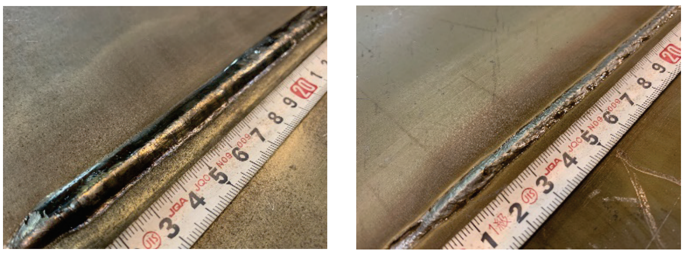


Fig. 6 Setting position view from the side.

Figure 7 shows the bead appearance of the butt joint of a specimen with a weld length of 300 mm (Test ID: HB02) to which the supporting sheet was applied. **Figure 8** shows the macroscopic observation of HB02 at middle section of the weld length. The same welding conditions shown in **Table 2** were applied. It can be seen that the use of the supporting sheet prevents the front bead sagging.



(B) Front bead *(B) Back bead*

Fig. 7 Photograph of bead appearance of HB02.

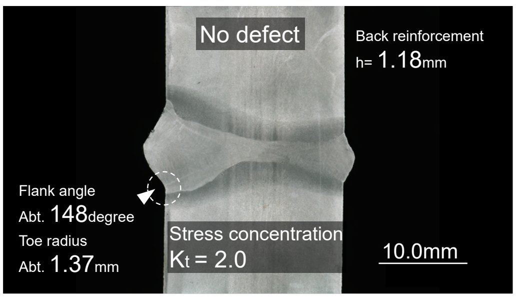


Fig. 8 Macroscopic test of HB02.

It was also confirmed that the height of the back bead increases with the use of the supporting sheet. Furthermore, using the approximate Eq. **(1)** for the stress concentration factor at the weld toe below the surface [9], $K_t = 5.1$ for Test ID: HB01 and $K_t = 2.0$ for Test ID: HB02. These results suggest that the method using the supporting sheet is effective in improving the fatigue strength of the joint.

$$\boldsymbol{K_t = 1 + C \cdot F(h/t) \cdot F(w/t) \cdot F(\theta) \cdot (t/\rho)^{0.5}} \tag{1}$$

$$F(h/t) = 1.0 - \exp(-10.4 \cdot (h/t)^{0.70})$$

$$F(w/t) = 1.0 - \exp(-4.92 \cdot (w/t)^{1.13})$$

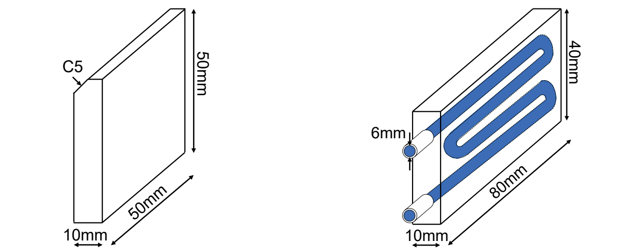
$$F(\theta) = \{1.0 - \exp(-4.10 \cdot (\rho/t)^{0.10} \cdot (\pi\ /\ 180) \cdot \theta)\} / \{1.0 - \exp(-4.10 \cdot (\rho/t)^{0.10} \cdot (\pi/2))\}$$

$$C = 0.322$$

h: Reinforcement height [mm], t: Thickness [mm], w: Bead width [mm], θ: Flank angle [degree], ρ: Toe radius [mm]

3.2 Proposal for sliding jigs

The installation method using the supporting sheet is effective in improving the fatigue strength of the joint. However, the installation work of the supporting sheet in the actual process may cause a decrease in production efficiency. Therefore, we designed an installation method using sliding jigs that slide along with the movement of the laser head. The sliding jigs are composed of a copper block cooled by water and a chamfered copper plate that supports the molten metal as shown in **Fig. 9**. Water-cooling copper plate was used because the melting point of copper is lower than that of steel and there is a risk of copper plates melting due to heat accumulation during welding. **Figure 10** shows the appearance of the arrangement.



(A) Supporting plate *(B) Water-cooling plate*

***Fig. 9** Dimension of sliding jigs.*

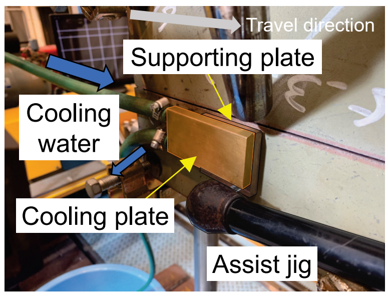
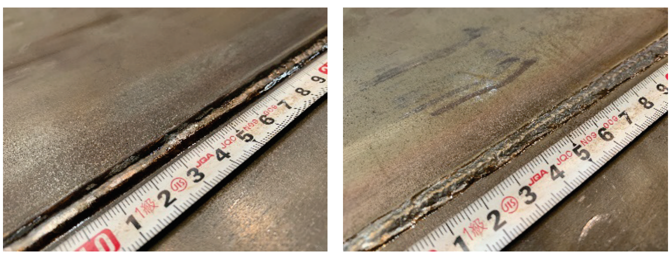


***Fig. 10** Setting position view of sliding jigs.*

Figure 11 shows the bead appearance of the butt joint of a specimen with a weld length of 300 mm (Test ID: HB03) to which sliding jigs were applied. **Figure 12** shows the macroscopic test ID: HB03 at middle section of the weld length. As with the supporting sheet, front bead sagging was eliminated, and no clearly harmful undercuts or internal defects were observed.



(A) Front bead *(B) Back bead*

***Fig. 11** Photograph of bead appearance of HB03.*

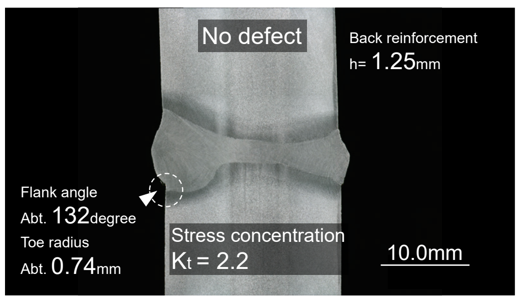


***Fig. 12** Macroscopic test of HB03.*

4. WELDING PROCEDURE QUALIFICATION TESTS

To confirm the quality of the welding procedure and to guarantee the mechanical properties of the welded joint, welding procedure qualification tests in accordance with the Guidelines [10] of Laser-Arc Hybrid Welding published by Nippon Kaiji Kyokai (ClassNK) should be carried out before introducing the supporting sheet and sliding jigs into the construction of actual ships. The minimum weld length for butt joints in welding procedure qualification tests is 1,000 mm. Therefore, butt joints with a weld length of 1,000 mm were fabricated using supporting sheets and sliding jigs (test IDs were set to HB02-L and HB03-L). The same welding conditions shown in **Table 2** were applied. The bead appearance of the fabricated joints is shown in **Fig. 13**. It was confirmed that the bead height and bead width were almost constant along the entire weld line in both specimens. The fabricated joints were inspected and tested according to the guidelines and the results are shown in **Table 3**. The results of non-destructive tests (NDT) and mechanical tests did not detect any defects that exceeded the criteria for both specimens.

(A) Front bead *(B) Back bead*
Test ID HB02-L (Supporting sheet), At 750 mm point.

(A) Front bead *(B) Back bead*
Test ID HB03-L (Sliding jigs), At 750 mm point.

Fig. 13 *Photographs of bead appearance.*

Table 3 *Approval test type, requirements, and results.*

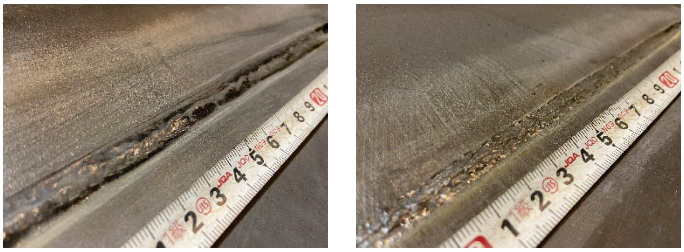
Test type	Requirements	Results	
		Test ID HB02-L (Sheet)	**Test ID HB03-L (Sliding plate)**
Radiographic testing	Reference: ISO 5817 Level B	No defect	No defect
Tensile test	Tensile strength ≥ 490 MPa	542 MPa, 544 MPa	543 MPa, 545 MPa
Side bending test	Clack length < 3 mm	No defect	No defect
Charpy impact test	At DEPO: ≥ 34 J At fusion line (F.L.): ≥ 27 J At HAZ, 2 mm from F.L.: ≥ 27 J	At DEPO: 179 J At fusion line: 162 J At HAZ: 104 J	At DEPO: 185 J At fusion line: 149 J At HAZ: 89 J
Macroscopic test	Nothing obvious defects	No defect	No defect
Vickers hardness test	Maximum hardness ≤ 380 HV	240 HV	247 HV

5. ALLOWABLE INITIAL GROOVE GAP

It is difficult to maintain a constant root gap in the actual process. Therefore, we attempted to fabricate butt joints by extending the initial root gap from 1.0 mm to 1.5 mm. The test specimens and welding wires were those described in Section **2.1**, and welding was performed under the construction conditions shown in **Table 4** by changing the arc current, arc voltage, laser power and welding speed. The bead appearance of HB1-A3, which obtained the best bead appearance, is shown in **Fig. 14**, and the macroscopic test of HB1-A3 at middle section of the weld length are shown in **Fig. 15**. The study did not find welding conditions that avoided undercut and root concavity at an initial root gap of 1.5 mm. As a result, it was confirmed that it is difficult to construct LAHW in horizontal position with an initial root gap of 1.5 mm, and that the applicable limit of the initial root gap is 1.0 mm.

Table 4 Weldability test conditions in horizontal position.

<table>
<tr><th>Condition parameter</th><th>Arc current
[A]</th><th>Arc voltage
[V]</th><th>Laser power
[kW]</th><th>Travel speed
[cm/min.]</th></tr>
<tr><td>Test ID. HB1-A1</td><td>430</td><td rowspan="3">37.5</td><td rowspan="4">16.0</td><td rowspan="5">800</td></tr>
<tr><td>Test ID. HB1-A2</td><td>450</td></tr>
<tr><td>Test ID. HB1-A3</td><td rowspan="4">475</td></tr>
<tr><td>Test ID. HB1-B1</td><td>36.0</td></tr>
<tr><td>Test ID. HB1-C1</td><td rowspan="2">37.5</td><td>18.0</td></tr>
<tr><td>Test ID. HB1-D1</td><td>16.0</td><td>650</td></tr>
</table>



(A) Front bead *(B) Back bead*

***Fig. 14** Photograph of bead appearance of HB1-A3.*

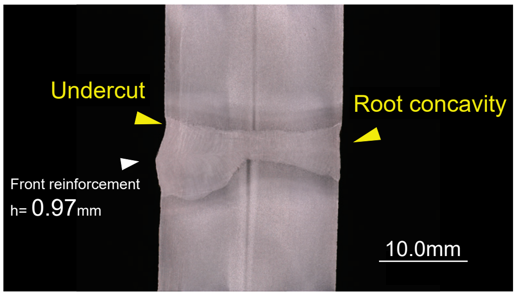


***Fig. 15** Macroscopic test of HB1-A3.*

6. CONCLUSION

In this study, LAHW was applied to the horizontal position to investigate the construction conditions for the sound butt joints with a plate thickness of 20 mm. The results showed that sound joints can be fabricated by using supports to prevent sagging of the weld metal that occurs over the front bead surface. Furthermore, a joint with a weld length of 1,000 mm was fabricated for confirming the welding procedure specification to be introduced into the hull fabrication process, and a series of joint strength tests required for the WPS were conducted. As a result, the upper limit of allowable groove gap was confirmed to be 1.0 mm for the construction of a horizontal butt joint with a plate thickness of 20 mm.

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