Evaluation of Butt Joint Produced by a Hot-Wire CO\textsubscript{2} Arc Welding Method

by Somchai WONTHAISONG**, Shinichiro SHINOHARA***, Kenji SHINOZAKI****, Rittichai PHAONIAM***** and Motomichi YAMAMOTO******

The purpose of this study was to develop a high-efficiency and low-heat-input CO\textsubscript{2} arc-welding process using hot-wire feeding. A previous paper showed that the proposed hot-wire CO\textsubscript{2} arc-welding process has the potential to simultaneously achieve both high efficiency and low heat input. This paper investigated the production of a sound joint with only two welding passes on a butt joint of 20mm-thick steel plates with no defects or unstable welding phenomena using the developed hot-wire CO\textsubscript{2} arc-welding process. Welding condition optimization was investigated using high-speed imaging and cross-sectional observations. The optimized conditions, which were the combinations of the welding current and hot-wire feeding speed as 350A and 7.5 m/min, 400A and 5 m/min, 450A and 5 m/min, 500A and 5 m/min, derived to avoid the presence of defects and molten metal precedence, which achieved sound welded joints possessing adequate properties of strength and toughness.

Key Words: hot wire, CO\textsubscript{2} arc welding, high efficiency, low heat input, joint properties

1. Introduction

Improved productivity in the welding process is urgently required, and especially in the construction of large ships whose total weld lengths can exceed several hundred kilometers\textsuperscript{1-2}. For safety, it is imperative that the welding of a butt joint of thick steel plates on large ships possesses joint properties of both strength and toughness. Although new welding processes have been developed and applied that improve efficiency in the welding stage, such as high-current CO\textsubscript{2} are welding, tandem CO\textsubscript{2} arc welding, and multi-electrode submerged arc welding (SAW), these high-efficiency welding processes generally increase the heat input\textsuperscript{3-9}. However, a considerable heat input increase results in a deterioration of the toughness and a softening of a welded joint. Therefore, a novel welding process with the potential to dramatically improve welding efficiency with minimal heat input increase to maintain joint properties is essential\textsuperscript{10-15}. The construction of large ships possesses additional requirements for the novel welding process, including low cost, large process tolerance and simple welding system\textsuperscript{16}. Although laser welding and laser-arc hybrid welding can reduce the heat input dramatically, they possess problems such as high installation cost, small gap tolerance, and added requirements for laser beam safety measures\textsuperscript{17,18}. Multi-arc processes also exhibit problems such as difficulty of welding condition optimization and small tolerances in the welding conditions on actual construction sites. With the above-mentioned background of the shipbuilding industry, the development of a novel CO\textsubscript{2} arc welding process with large flexibility that can be applied both in the current factory and the field is strongly demanded.

New welding processes combined with hot-wire feeding, such as gas tungsten arc welding (GTAW), gas metal arc welding (GMAW), SAW, and laser welding have been developed and applied to improve productivity, joint properties and process tolerances in manufacturing fields other than ship building\textsuperscript{19-27}. Optimization of hot-wire feeding conditions have been investigated in some welding processes such as GTAW, GMAW and laser welding. It has been suggested that, to achieve stable and highly efficient wire feeding, the hot-wire current must be appropriately controlled to heat the tip to its melting point independent from the heat input from the main heat source. Improvement in efficiency has been investigated for GMAW processes using CO\textsubscript{2} gas and a mixed gas (Ar+CO\textsubscript{2}). Although previous investigations suggest that combining hot-wire feeding with the welding process can potentially achieve both high efficiency and low heat input\textsuperscript{28}, the proper condition range, which achieves stable molten pool creation and stable hot-wire feeding with fully filled groove and sound joint properties, is demanded.

The purpose of this study was to obtain a sound joint using only two welding passes on a butt joint of 20mm-thick steel plates with no defects or unstable welding phenomena using the developed hot-wire CO\textsubscript{2} arc-welding process. Detailed observations using a high-speed camera was used to analyze the molten pool flow during hot-wire CO\textsubscript{2} arc-welding. Optimization of the welding conditions was investigated by varying the hot-wire feeding speed and the welding current for the second layer. Cross-sectional observations and hardness measurements were used to investigate the effect of the hot-wire addition and the combination of the welding current and hot-wire feeding speed on the joint characteristics. Charpy impact tests, tensile tests and bending tests were also performed on the welded joint produced using the optimized welding conditions.
2. Materials and experimental procedures

2.1 Materials and specimen

Table 1 provides the chemical composition and mechanical properties of the 490-MPa-Class steel plate (NK-KE36) used as the base metal. The specimen used had the dimensions of 20mm thickness, 250mm width, and 400mm length, as shown in Fig. 1. A butt joint with a V-shaped groove possessing an angle of 30° and a root gap of 4mm was employed with a 9mm-thick backing plate, as shown in Fig. 1. A 1.2mm-diameter filler wire of JIS Z3312 YGW11 was used on the first and second layers of the CO₂ arc welding; while a 1.6mm-diameter filler wire of JIS Z3312 YGW11 was used for the CO₂ arc welding and hot-wire feeding on the second layer.

2.2 Experimental procedures

Figure 2 schematically illustrates the experimental set-up for the second pass, where the welding conditions for the first and second

| Chemical composition, mass% | Mechanical properties |
|-----------------------------|-----------------------|
| C  | Si  | Mn  | P   | S   | Y . P., N/mm² | T . S., N/mm² | El., % |
| 0.12 | 0.20 | 1.41 | 0.014 | 0.004 | 458 | 540 | 22 |

Fig. 1 Shape and size of specimen.

Fig. 2 Schematic illustration of experimental set-up.
passes are given in Table 2. The welding speed was fixed at 0.3 m/min for both the first and second passes. The first pass was welded by CO\textsubscript{2} arc welding without hot-wire feeding using a welding current of 400 A and a voltage of 41 V since the large flexibility is required and semi-automatic welding is widely used on the first pass in actual large ship construction sites. The 1.2 mm-diameter wire was used for CO\textsubscript{2} arc welding on the first pass, where the wire feeding speed was 19.9 m/min at a welding current of 400 A.

The second pass was welded by CO\textsubscript{2} arc welding with hot-wire feeding. The welding current and voltage of CO\textsubscript{2} arc welding were varied from 300–500 A and from 31–42 V, respectively. For the CO\textsubscript{2} arc welding, the 1.2 mm-diameter wire was used during lower welding current conditions up to 400 A, and the 1.6 mm-diameter wire was used during higher welding current conditions over 400 A. The feeding speeds of the 1.2 and 1.6 mm-diameter wires were respectively varied from 12.7–19.9 m/min and from 9.7–11.7 m/min. In other words, the feeding volumes for the two wire diameters were varied from 241–376 mm\(^3\)/s and from 326–393 mm\(^3\)/s, respectively. The hot wire was fed at a distance 10 mm back from the wire tip of the CO\textsubscript{2} arc welding with a feeding angle of 70°. The hot-wire feeding speed was varied from 0 to 10 m/min; in other words, the feeding volumes were varied from 0–298 mm\(^3\)/s for the 1.6 mm-diameter wire. The hot-wire current was set to sufficiently heat the filler wire tip to near its melting point. The proper hot-wire current, which was the limited current to induce fusing the filler wire tip, was calibrated by feeding the filler wire without arc welding on a bead on plate.

Figure 3 shows the calculated deposition ratio, which is the ratio of the deposited metal volume to the groove volume on the second pass (as shown in Fig. 2), for several combinations of wire feeding speeds for hot wire and CO\textsubscript{2} arc welding, as shown in Table 2. Figure 3(a) and 3(b) show the deposition ratios for welding currents of 300–400 A using the 1.2 mm-diameter filler wire and the ratios for welding currents of 450–500 A using the 1.6 mm-diameter filler wire. A deposition ratio of 1.0 indicates that the groove area was fully filled by the deposited metal during the two passes. The upper right regions in Fig.3(a)–3(b) where the

Table 2  Welding conditions.

| Pass No. | 1 | 2 |
|----------|---|---|
| Welding speed, m/min | 0.3 | 0.3 |

| CO\textsubscript{2} arc welding conditions | |
|------------------------------------------|---|
| Welding current (Setting), A | 400 | 300–400 | 450–500 |
| Arc voltage, V | 41 | 31–41 | 39–42 |
| Wire feeding speed, m/min | 19.9 | 12.7–19.9 | 9.7–11.7 |
| Wire feeding volume, mm\(^3\)/s | 376 | 241–376 | 326–393 |
| Wire diameter, mm | 1.2 | 1.2 | 1.6 |
| Shielding gas (100\% CO\textsubscript{2}), l/min | 25 | 25 | 25 |
| Extension length, mm | 22 | 23 | 25 |
| Weaving width, mm | 4 | 7 | 7 |
| Weaving frequency, Hz | 3 | 3 | 3 |

| Hot-wire conditions | |
|---------------------|---|
| Wire feeding speed, m/min | 0 | 5 | 7.5 | 10 |
| Wire feeding volume, mm\(^3\)/s | 0 | 167 | 251 | 335 |
| Wire current, A | 0 | 208 | 249 | 298 |
| Wire diameter, mm | 1.6 |
| Wire feeding angle, degree | 70 |
| Wire feeding position, mm | 10 |
| Power supplied distance, mm | 80 |
| Duty, % | 50 |

Fig. 3  Deposition ratio for various combinations of wire feeding speeds during hot-wire feeding and CO\textsubscript{2} arc welding. (a) Welding current from 300 to 400 A, (b) Welding current from 450 to 500 A.
deposition ratio exceeded 1.0 signifies that the groove volume was adequately filled by the deposited metal with two passes. Thus, hot-wire feeding clearly has the capability of efficiently improving the deposition ratio and resulting in filled regions with deposition ratios over 1.0.

High-speed imaging was used to observe the stabilities of the molten pool and the hot-wire feeding during welding. The high-speed imaging conditions as a frame rate of 500 fps and shutter speed of 1/1000 s were applied with the external laser lighting and 980 nm band-pass filter. In particular, excessive molten metal flow to the front of the molten pool was observed during welding on the second pass with hot-wire feeding because the excessive molten metal flow created incomplete fusion on the boundary of two passes. The weld beads were evaluated via cross-sectional observations and the deposition ratio, where the weld metal hardness was measured along a line 3 mm from the plate surface on the cross-section. The weld joint properties were evaluated via a tensile test, a bending test and the Charpy impact test, according to the Class-NK rule.

3. Results and discussion

3.1 Capability of bead formation on hot-wire CO₂ arc welding

A flow of molten metal preceding the molten pool (called molten metal precedence) was observed in high-speed observations during hot-wire CO₂ arc welding for several combinations of wire feeding speeds during hot-wire feeding and CO₂ arc welding. Figure 4 shows examples of high-speed images during hot-wire CO₂ arc welding showing sound molten pool creation without molten metal precedence (Fig. 4(a)) and molten metal precedence from the front and bottom of the molten pool (Fig. 4(b)). It can be clearly seen in Fig. 4(a) that the CO₂ arc creates an arc force just under the tip of the CO₂ arc welding wire that pushes down the molten pool surface. The hot-wire feeding is also clearly observed behind the CO₂ arc wire, where a 7.5 m/min feeding speed provides an adequate volume of additional material into the molten pool while the arc force of the 350 A welding current maintains a stable molten pool front with no molten metal precedence. However, excessive additional material volume with 10 m/min hot-wire feeding increases the molten pool height. This is especially the case at the front of the molten pool, whereupon the arc force of the 350 A welding current cannot maintain stability of the molten pool front and induces molten metal precedence, as shown in Fig. 4(b). In addition, the molten metal precedence causes incomplete fusion at the bottom of the molten pool of the second pass.

Figure 5 shows the results of the evaluations of the deposition ratio and molten metal precedence on combinations of hot-wire feeding and CO₂ arc welding volumes. The bottom-left green region in Fig. 5 shows the conditions necessary for low metal...
deposition volumes under a low welding current and low hot-wire feeding speed. In this region where the deposition ratio is under 1.0, the groove volume was not adequately filled by the deposited metal in two passes, though a molten metal precedence was not observed and a stable molten pool front was maintained. The upper-right yellow region in Fig. 5 shows the conditions necessary for high metal deposition volumes under a high welding current and high hot-wire feeding speed. In this region where the deposition ratio exceeds 1.0, a molten metal precedence occurred and the stable molten pool front was not maintained, though the groove volume was adequately filled by deposited metal in two passes. The four conditions indicated by the blue symbols in Fig. 5 achieved a sufficient filling of the groove volume by two passes without molten metal precedence. These conditions provided an adequate volume of additional material via hot-wire feeding and could sufficiently fill the groove volume and avoid molten metal precedence at the corresponding welding current.

Figure 6 shows the cross-sections of the weld beads obtained using the four suitable conditions exhibiting a deposition ratio greater than 1.0 with no molten metal precedence during welding (blue symbols in Fig. 5). Sound beads with no defects and only a small volume of excess weld metal was observed in all cross-sections. This was expected owing to the fact that the deposition ratios on the actual cross-sections were just over 1.0 (Fig. 3).

### 3.2 Weldment properties

Figure 7 shows the relationship between the Vickers hardness of the weld metal on the second pass and the heat input using the four suitable conditions shown in Fig. 6. It was found that the conditions of a lower welding current and higher hot-wire feeding speed correspond with a higher hardness, while the conditions of a higher welding current and lower hot-wire feeding speed correspond with a lower hardness. An adequate weld metal hardness compared with the base material value of 190 HV were obtained with all four conditions even when a higher welding current of 500 A was applied. We note that the application of hot-wire feeding allows the use of lower welding currents while maintaining an adequate amount of deposited metal. In other words, the application of hot-wire feeding can achieve a lower heat input and avoid deterioration of weld metal hardness while maintaining process efficiency.

![Fig. 6 Cross-sections of optimized conditions with welding current and hot-wire feeding speed, (a) 350 A and 7.5 m/min, (b) 400 A and 5 m/min, (c) 450 A and 5 m/min, (d) 500 A and 5 m/min.](image)

![Fig. 7 Vickers hardness of weld metal on second pass.](image)
Figure 8 shows the absorbed energy obtained from the Charpy impact test at 0°C using two kinds of specimens: one with its notch position at the weld metal and the other at the fusion line, according to the Class-NK rule. It is clearly seen in Fig. 8 that the absorbed energy both at the weld metal and the fusion line exhibit adequate values over 47 J at 0°C.

### 3.3 Welded joint evaluations

Tensile tests were carried out according to the Class-NK rule to evaluate the joint properties of the specimens welded by the four suitable conditions described in Figs. 5 and 6. Testing was performed on two specimens cut from a single butt joint sample welded using one of the four conditions, where all four samples were tested. Figure 9 shows the tensile test specimens after breaking, and Table 3 shows the tensile test results of the tensile strength and breaking position. It is clear from Fig. 9 that the breaking positions of seven of the specimens were located in the base metal region and one specimen broke at the edge of the weld metal. It can be also seen that all joints welded using the four suitable conditions achieved adequate tensile strength equivalent

| Conditions       | Tested position | Tensile strength [N/mm²] | Breaking position |
|------------------|-----------------|--------------------------|-------------------|
| (a) 350A-7.5m/min| Welding Start   | 536                      | Base metal        |
|                  | Welding End     | 536                      | Base metal        |
| (b) 400A-5m/min  | Welding Start   | 539                      | Base metal        |
|                  | Welding End     | 536                      | Base metal        |
| (c) 450A-5m/min  | Welding Start   | 536                      | Base metal        |
|                  | Welding End     | 545                      | Weld metal        |
| (d) 500A-5m/min  | Welding Start   | 538                      | Base metal        |
|                  | Welding End     | 540                      | Base metal        |

*Tensile strength of base metal : 540 N/mm²*
to that of the base material of 540 N/mm². The specimen that broke in the weld metal also exhibited an adequate tensile strength of 545 N/mm² compared with the value of the base material. It is assumed that an adequate tensile strength and fracture in the base metal can be obtained with appropriate weld metal hardness (Fig. 7) and a low heat input of the hot-wire CO₂ arc welding.

Figure 10 shows the specimens welded by the four suitable conditions after performing transverse side bending tests[^29]. All specimens exhibited sound results with no defects and with breaking both on the weld metal region and the fusion line.

The above test results indicate that hot-wire CO₂ arc welding has great potential for achieving both extremely high efficiency, owing to requiring only two passes for a butt joint of 20 mm-thick plates, and adequate mechanical joint properties of tensile strength and toughness, owing to a lower heat input compared with conventional welding processes with the same efficiency.

4. Conclusions

Optimization of welding conditions using only two welding passes on a butt joint of 20 mm-thick steel plates was investigated based on high-speed imaging for several combinations of welding current and hot-wire feeding speed. Cross-sectional observation and mechanical tests were performed to evaluate the joint properties.

The conclusions are as follows:

1. Efficient hot-wire addition on the second pass was sufficient to fill the groove area with only two passes for each welding current, though molten metal precedence was observed via high-speed imaging for conditions with relatively high wire feeding speeds.

2. Optimized combinations of the welding current from 350–500 A and hot-wire feeding speed for a butt joint of 20 mm-thick plates at a welding speed of 0.3 m/min could be obtained after only two welding passes with no defects or molten metal precedence during welding.

3. The combination of lower welding current and higher hot-wire feeding speed achieved higher weld metal hardness since the combination employs the lower heat input compared with the combination of higher welding current and lower hot-wire feeding speed.

4. Sound properties as revealed by the Charpy impact test, tensile test, and transverse side bending test were obtained on welded joints created with the optimized combinations of welding current and hot-wire feeding speed.
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