High-Efficiency and Low-Heat-Input \( \text{CO}_2 \) Arc-Welding Technology for Butt Joint of Thick Steel Plate Using Hot Wire

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The purpose of this study was to develop a high-efficiency and low-heat-input \( \text{CO}_2 \) arc-welding process using hot-wire feeding. The optimization of welding conditions using only two welding passes on the butt joint of 20-mm thickness steel plates was investigated using several combinations of hot-wire feeding speed and welding current. Stable welding phenomena, such as molten pool formation and hot-wire feeding during welding, were observed for all tested conditions. A sound joint without any defects could be obtained in only two welding passes using the optimized conditions. The proposed hot-wire \( \text{CO}_2 \) arc-welding process has potential to simultaneously achieve both high efficiency and low heat input. Use of a higher hot-wire feeding speed with a lower welding current enabled a lower dilution ratio, narrower width of the heat-affected zone, and higher weld metal hardness owing to the resultant lower molten pool temperature and higher cooling speed. The proposed hot-wire \( \text{CO}_2 \) arc-welding process also achieved about 50% reductions in the power consumption and arc time compared with those of the conventional \( \text{CO}_2 \) arc-welding process on the butt joint of 20-mm thickness steel plates.

Key Words: hot wire, \( \text{CO}_2 \) arc welding, thick steel plate, high efficiency, low heat input

1. Introduction

In large-scale ship construction, there is strong demand for improvements in productivity and quality, especially in the welding process used for thick steel plates [1-7]. New processes have been developed and conditions optimized to improve welding efficiency without the need for a large increase in heat input to maintain joint quality and properties. In addition, new steel plates and filler wires have been developed and applied to maintain or improve joint properties, even with an increase in heat input, to obtain higher welding efficiency [8-17].

For the welding of a butt joint of thick steel plates, \( \text{CO}_2 \) arc welding and submerged-arc welding (SAW) are conventionally used [9]. High-efficiency welding processes, such as high-current \( \text{CO}_2 \) arc welding, tandem \( \text{CO}_2 \) arc welding, and multi-electrode SAW are generally used for ship construction [9-16]. Although these processes can obtain higher efficiency, i.e., a larger deposited metal volume, than conventional welding, the heat input increases considerably and joint properties deteriorate, especially with respect to toughness. Multi-arc processes also have problems, such as difficulty in optimization of welding conditions and small tolerances in welding conditions on an actual construction site.

New welding processes, such as gas–tungsten arc welding (GTAW), gas–metal arc welding (GMAW), SAW, and laser welding, in combination with hot-wire feeding have been developed and applied to improve productivity in manufacturing fields other than ship building [17-25]. Welding phenomena and optimization of hot-wire feeding conditions have been investigated for the GTAW process. It has been suggested that the hot-wire current must be appropriately controlled to heat the tip to its melting point to achieve stable welding phenomena and higher efficiency. It has also been clarified that the deposited volume, i.e., hot-wire feeding speed, can be controlled independently of the arc current as the main heat source. Improvement in efficiency has been investigated for GMAW processes using \( \text{CO}_2 \) gas and a mixed gas (Ar + \( \text{CO}_2 \)). From previous investigations, it was expected that combining hot-wire feeding with the welding process has potential to achieve both high efficiency and low heat input.

The purpose of this study was to develop a high-efficiency and low-heat-input \( \text{CO}_2 \) arc-welding process using hot-wire feeding. Optimization of welding conditions using only two welding passes on the butt joint of 20-mm thickness steel plates was investigated using several combinations of hot-wire feeding speed and welding current. High-speed imaging was performed to observe welding phenomena, stabilities of molten pool formation, and hot-wire feeding during welding. Cross-sectional observation and hardness measurement were also performed to investigate the effect of hot-wire addition and the combination of the welding current and hot-wire feeding speed on the joint characteristics. The power consumption and arc time of the proposed hot-wire \( \text{CO}_2 \) arc-welding process were evaluated and compared with those of conventional \( \text{CO}_2 \) arc welding.
2. Materials and experimental procedures

2.1 Materials and specimen

Steel plates of 490 MPa class (NK-KE36) with dimensions of 20-mm thickness, 50-mm width, and 200-mm length were used as the base metal. A butt joint with a V-shaped groove with an angle of $30^\circ$ and a root gap of 4 mm was employed, as shown in Fig. 1. A filler wire of JIS Z3312 YGW11 with 1.2 mm diameter was used on the first and second passes of CO$_2$ arc welding; a filler wire of JIS Z3312 YGW11 with 1.6 mm diameter was used for hot-wire feeding on the second pass.

2.2 Experimental procedures

A schematic illustration of the experimental set-up and the welding conditions are shown in Fig. 2 and Table 1, respectively.

![Fig. 1](image1.png)  
**Fig. 1** Shape and size of specimen.

![Fig. 2](image2.png)  
**Fig. 2** Schematic illustration of experimental set-up.

| Table 1 | Welding conditions. |
|---------|---------------------|
| Pass No. | 1 | 2 |
| Welding speed, m/min | 0.3 | 0.3 |
| Welding current (Setting), A | 300 | 300 | 350 | 400 |
| Welding voltage, V | 31 | 31 | 38 | 41 |
| Wire feeding speed, m/min | 12.7 | 12.7 | 15.7 | 19.9 |
| Wire diameter, mm | 1.2 | 1.2 |
| Extension length, mm | 22 | 22 |
| Weaving width, mm | 4.5 | 7 |
| Wire feeding speed, m/min | 0 | 5 | 10 | 15 |
| Wire current, A | 0 | 208 | 298 | 384 |
| Wire diameter, mm | 1.6 |
| Wire feeding angle, degree | 70 |
| Wire feeding position, mm | 5 |
| Power supplied distance, mm | 90 |
| Duty, % | 50 |
the arc, molten pool, and hot-wire feeding during welding. Weld beads were evaluated by cross-sectional observation, deposit ratio (deposited metal volume/groove volume), and dilution ratio, as shown in Figs. 3(a) and (b). A deposit ratio of 1.0 means that the groove area was fully filled by deposited metal in the two passes. The heat-affected zone (HAZ) width and hardness distribution were also measured along the line under 3 mm from the plate surface on the cross-section, as shown in Fig. 3(c). The power consumption and arc time of the proposed hot-wire CO$_2$ arc welding process were compared with those of conventional CO$_2$ arc welding. The power consumption was calculated as the sum of the power consumptions for CO$_2$ arc welding and hot wire heating.

3. Results and discussions

3.1 Capability of bead formation on hot-wire CO$_2$ arc welding

The measured welding current and wire feeding speed of the CO$_2$ arc welding are used in the following figures. Figure 4 shows the deposition capability for each combination of welding current and hot-wire feeding speed. Only welding current condition of 350 A was applied for the hot-wire feeding speed of 15 m/min since unstable molten pool formation on the welding current of 300 A and excess volume of weld metal on the welding current of 400 A were observed under the hot-wire feeding speed of 15 m/min. The increase in volume caused by an increase of 100 A in welding current was about 27 mm$^2$, as shown in Fig. 4. Although the deposited volume increased on increasing the welding current, the heat input and arc pressure also increased and spattering became worse. In contrast, the volume increases for hot-wire feeding at 5 – 15 m/min were about 33 – 100 mm$^2$, as shown in Fig. 4. It became clear that hot-wire feeding could increase the deposited volume more efficiently without an increase of arc pressure and spatters, while minimizing the increase in heat input, compared with the effect of increasing the welding current.

Figure 5 shows the calculated deposit ratio for several combinations of welding current and wire feeding speeds for CO$_2$ arc welding with hot-wire feeding, as shown in Table 1. The upper right region, where the deposit ratio exceeded 1.0, indicated that the groove volume was properly filled by deposited metal in two passes. It is clear that hot-wire feeding can efficiently improve the
deposit ratio and spread the filled region with the deposit ratio over 1.0. For the experimental conditions shown in Table 1, two conditions achieved a deposit ratio above 1.0: the combinations of welding current and hot-wire feeding speed of 350 A and 15 m/min and 400 A and 10 m/min. Sound filled joints were expected to be obtained using these two combinations.

Stable molten pool, weld bead formations and stable hot-wire feeding without spattering were observed for all conditions shown in Fig. 5 on the high-speed videos. Figure 6 shows an image from a high-speed video captured during actual welding with hot-wire feeding using these two conditions that gave a calculated deposit ratio above 1.0. It can be clearly seen from Fig. 6 that the hot-wire tip maintained a set distance from the arc, indicating that the hot wire was properly heated up to just below its melting point; extra heat input from the arc was not needed for hot-wire melting.

Figure 7 shows the cross-sections obtained for the above two conditions with a deposit ratio above 1.0. Sound beads without any defects were obtained. A small volume of excess weld metal is also seen on both cross-sections, indicating that the deposit ratios on the actual cross-sections were just over 1.0.

### 3.2 Weld bead properties

Figure 8 shows the relationship between the dilution ratio and total wire feeding speed, which is a summation of the wire feeding speeds for CO₂ arc welding and hot-wire feeding. The summation of the wire feeding speeds is used as a parameter on the following figures to clearly show the effects of hot-wire feeding on the weld bead properties and its capability on the welding conditions. The dilution ratio without hot-wire feeding was very high, exceeding 50 % even when a welding current of 300 A was used. The dilution ratio decreased almost linearly with the increase of hot-wire feeding speed under all welding current conditions. The effect of hot-wire feeding on the dilution ratio became larger as the welding current became smaller: for example, dilution ratios for welding currents of 300, 350, and 400 A were 36 %, 46 %, and 51 %, respectively, when the hot-wire feeding speed was fixed at 5 m/min, and 34 %, 38 %, and 44 %, respectively, when the hot-wire feeding speed was fixed at 10 m/min. It is assumed that the ratio of deposited metal volume from hot-wire feeding to the volume from CO₂ arc welding...
mainly affected on the dilution ratio since the welding current affected largely on the melting volume of the base metal and the temperature of the deposited metal from hot-wire feeding was just under its melting point. For the two conditions shown in Figs. 6 and 7, the dilution ratios were 29% and 43%. It became clear that hot-wire feeding could achieve a lower dilution ratio with a significant increase in deposited metal volume without an increase of welding current; in other words, the combination of hot-wire feeding and lower welding current lowered the dilution ratio by maintaining the same deposited metal volume as would be obtained under the higher welding current condition.

Figure 9 shows the relationship between HAZ width and total wire-feeding speed. The HAZ width widened with an increase of welding current when hot-wire feeding was not applied because the heat input from the arc and the deposited metal volume increased. In contrast, although the deposited metal volume significantly increased with increase of the hot-wire feeding speed, the HAZ width became linearly narrower. It is assumed that the molten pool temperature was lowered with the increase in ratio of the hot-wire feeding speed to the wire speed of CO$_2$ arc welding because the temperature of the deposited metal from hot-wire feeding was lower than that from CO$_2$ arc welding. The HAZ widths of the two conditions shown in Figs. 6 and 7 were 1.7 and 1.9 mm. Figure 9 shows that these two conditions achieved a narrow HAZ width, almost the same as that achieved by 300 A welding current without hot-wire feeding, with a doubling of the deposited metal volume. Hot-wire feeding was able to decrease the HAZ width with a significant increase in deposited metal volume, even if a relatively high welding current was employed.

Figure 10 shows the Vickers hardness of the weld metals used several combinations of welding current and wire feeding speeds for CO$_2$ arc welding with hot-wire feeding. A higher welding current gave a higher wire feeding speed for CO$_2$ arc welding, i.e., a larger metal volume was deposited, but the weld metal hardness was lowered. In contrast, although an increase of hot-wire feeding speed gave a larger volume of deposited metal, the weld metal hardness increased for each welding current condition. It is assumed that the higher hot-wire feeding speed created a lower molten pool temperature and higher cooling speed, thereby giving rise to higher hardness of the welded metal. It is suggested that a combination of higher hot-wire feeding speed and lower welding current should be selected to maintain weld metal hardness when high-efficiency welding is required.

### 3.3 Reduction of power consumption and arc time

Figure 11 compares the power consumption and arc time of hot-wire CO$_2$ arc welding and conventional CO$_2$ arc welding using a test sample having 400-mm length and the same thickness of 20 mm and groove shape as shown in Fig. 1. Hot-wire CO$_2$ arc welding was performed in two passes using the optimized conditions: 300 A welding current on the first pass; 400 A welding current and 10 m/min hot-wire feeding speed on the second pass, as shown in Figs. 6(b) and 7(b), respectively. Conventional CO$_2$ arc welding was performed in four passes using conditions employed in actual shipbuilding: 160–460 A welding current and 0.2–0.33 m/min welding speed.

Figure 11(a) shows that the power consumption of 2267 kJ achieved during hot-wire CO$_2$ arc welding was much lower than that of 4221 kJ during conventional CO$_2$ arc welding. In this comparison, the application of hot-wire CO$_2$ arc welding improved the power consumption by 46% reduction compared with that of conventional CO$_2$ arc welding. Figure 11(b) shows that the arc time of 160 s during hot-wire CO$_2$ arc welding was much shorter than that of 375 s during conventional CO$_2$ arc welding, representing an
Hot-wire CO$_2$ arc welding can significantly increase the deposition volume without the need to increase welding current and heat input. This advantage makes it possible to reduce the number of welding passes, i.e., from four to two in this research. A reduction in number of passes can be expected to significantly improve welding time by reducing not only the arc time, but also the setup time on an actual construction site.

4. Conclusions

Optimization of welding conditions using only two welding passes on the butt joint of 20-mm thickness steel plates was investigated using several combinations of hot-wire feeding speed and welding current. Cross-sectional observation was performed to investigate the effect of hot-wire addition and the combination of welding current and hot-wire feeding speed on the joint characteristics. The conclusions are as follows.

(1) Efficient hot-wire addition at up to 15 m/min using a filler wire of 1.6 mm diameter could be achieved, using an appropriate current to heat the hot-wire tip up to its melting point, for several combinations of welding currents, giving stable welding phenomena.

(2) A sound joint without any defects could be obtained in only two welding passes using the optimized welding conditions at a welding speed of 0.3 m/min.

(3) Hot-wire addition can achieve a lower dilution ratio, narrower HAZ width, and higher weld metal hardness with a significant increase in deposited metal volume without an increase of welding current; in other words, the combination of higher hot-wire feeding speed and lower welding current resulted in much lower heat input while maintaining the same deposited metal volume as achieved using a higher welding current.

(4) The proposed hot-wire CO$_2$ arc-welding process reduced power consumption by 46% and arc time by 57% compared with those of the conventional CO$_2$ arc-welding process on a butt joint of 20-mm thickness steel plates.

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