Heat Input Reduction in Fillet Welding Using Bypass and Root Opening

Experiments were conducted to find the optimum combination of root opening in a T-joint and travel speed using the double-electrode submerged arc process

BY Y. LU, Y. M. ZHANG, AND L. KVIDAHL

ABSTRACT

Submerged arc welding (SAW) of fillet welds is one of the major applications in the shipbuilding industry. Due to the requirement for the weld size, a sufficient amount of metal must be deposited. In a conventional SAW process, the heat input is proportional to the amount of metal melted and is thus determined by the required weld size. To meet this requirement, an excessive amount of heat is applied causing large distortions in the welded structures whose follow-up straightening is very costly. In order to reduce the needed heat input, double-electrode technology has been previously practiced creating the double-electrode SAW (DE-SAW) method for fillet welds. However, the reduction in the heat input also reduces the penetration capability. The ability to produce required weld beads is compromised. In this study, the authors propose to introduce a root opening in a T-joint between the flat and perpendicular panels forming a modified fillet weld design. Experimental results verified that the use of a root opening improves the ability of DE-SAW to produce the required weld beads at reduced heat input and penetration capability. Major parameters including the root opening, travel speed, and heat input have been selected/optimized/minimized to produce required fillet weld beads with a minimized heat input based on qualitative and quantitative analyses.

Introduction

Submerged arc welding (SAW) is a widely used process. Similar to conventional gas metal arc welding (GMAW) (Refs. 1, 2) and flux cored arc welding (FCAW) (Refs. 3, 4), it melts a continuously fed consumable solid or flux cored electrode wire (Refs. 5–7) to deposit metal into the workpiece. In the SAW process, however, the consumable wire and the arc are shielded from atmospheric contamination by being submerged under a blanket of granular, fusible flux (Ref. 8). Submerged arc welding has significant advantages (Refs. 6–9) over GMAW and FCAW including higher productivity, more stable arc, spatter-free, and harmful ultraviolet radiation-free. Moreover, the molten metal is effectively protected by a layer of flux. SAW is thus the most commonly used process for flat and horizontal welding in the shipbuilding industry, especially in joining plates for ship shells, decks, and bulkheads (Ref. 10). In a typical 150,000 DWT (deadweight tonnage) tanker, the length of a horizontal fillet weld can reach more than 70% of the whole welding length of the bottom shell block at the assembly stage (Ref. 11).

Due to the requirement of the weld size in fillet welding, a sufficient amount of metal must be melted. In conventional SAW, the heat input is proportional to the amount of metal melted and deposited in the process. As a result, a large heat input causes unwanted distortion in the welded structures whose follow-up straightening is very costly. While the cost for correction of welding-related distortion varies with ship size and structure and thus is difficult to accurately determine, it is generally considered to be higher than the cost needed to make the welds. In addition, distortion correction involves the use of flame and water, causing adverse effects on the working environment.

In order to reduce the excessive heat input in fillet welding, a double-electrode SAW (DE-SAW) process was practiced in the laboratory of Adaptive Intelligent Systems LLC (AIS) in which the total welding current is divided into the base metal current and bypass current after it melts the main wire. Since part of the current is bypassed without flowing into the workpiece, the heat input into the workpiece is reduced. When the metal from the bypass wire melted by the bypass arc is added into the workpiece, the reduced heat input is added back but the metal deposition is increased. The DE-SAW process is therefore capable of depositing the same amount of metal at reduced heat input or depositing more metal at the same heat input similarly as its original variant, i.e., double-electrode gas metal arc welding (DE-GMAW) (Refs. 12–19).

However, after having the heat input reduced greatly in the fillet welds by using the DE-SAW process, the penetration capability is also reduced due to the reduction in the base metal current. The weld beads produced become convex, causing the reentrant angle to be undesirably reduced. Decreasing the penetration capability required for producing desirable welds is thus an issue that needs to be resolved in order to effectively utilize the ability of DE-SAW in reducing the heat input to produce a desirable fillet weld bead.

In this paper, the authors first propose to intentionally introduce a root opening in a T-joint between the perpendicular and flat plates to modify the joint design as shown in Fig. 1. After the effectiveness was verified, the welding parameters were optimized so that a complete solution for DE-SAW can be provided to produce the required fillet weld at reduced heat input.

Experimental System and Conditions

Double-electrode submerged arc weld-
ing is considered a variant of DE-GMAW that was previously developed at the University of Kentucky (Ref. 12). Except for changing from gas shielding to flux shielding so as to take advantage of the desirable characteristics associated with the SAW process mentioned previously, the principle of the electrical circuit remains unchanged.

Experimental Systems

Figure 2 shows the experimental platform of the DE-SAW process. It has been established based on a conventional SAW process by adding a GMAW weld head next to the SAW head of the Lincoln LT-7 tractor (Ref. 20) to provide a second/bypass loop for the welding current. The main wire feeder is combined with the tractor, but the bypass wire needs an external wire feeder.

The relationship of the welding currents in the DE-SAW process can be explained by Fig. 3. The main loop represents the path through which the base metal current \( I_1 \) flows, and the bypass loop is the path through which the bypass current \( I_2 \) flows. The positive terminals of the two power supplies (both of them are working in constant-voltage mode (CV)) are connected together as a common positive terminal. The main SAW head is connected to the common positive terminal, and the workpiece (or base metal) is connected with the negative terminal of the main power supply. This kind of connection is based on the direct current electrode positive (DCEP) polarity mode. For most of the applications, DCEP mode is used because of its benefits to the arc stability, metal transfer, and deep penetration (Ref. 21). The bypass GMAW head is connected to the negative terminal of the bypass power supply. After the power supplies are turned on, the main arc is established between the tip of the electrode of the main welding head and the surface of the workpiece, and the bypass arc is established between the tip of the main electrode and the tip of the bypass electrode.

As shown by the arrows in Fig. 3, the base metal current \( I_1 \) flows from the main electrode to the workpiece, and the bypass current \( I_2 \) flows from the main electrode to the bypass electrode. Because both the base metal current and the bypass current flow through the main wire electrode, the current inside the electrode of the main submerged arc weld head equals the total welding current \( I \). This fundamental relationship can be expressed by Equation 1.

\[
I = I_1 + I_2
\]  

where, \( I \) is the total welding current; \( I_1 \) is the base metal current that flows through the workpiece, and \( I_2 \) is the bypass current that flows through the bypass wire.

Experimental Conditions

The experimental conditions here refer primarily to the materials of the wire electrodes, the steel plates used for the T-joint, and the model number of the flux powder. The specifications of experimental conditions are listed in Table 1. All the experiments in this paper were conducted under these conditions. C1018 cold-rolled steel was used because it is commercially available for various thicknesses and dimensions.

<table>
<thead>
<tr>
<th>Table 1 — Experimental Conditions</th>
</tr>
</thead>
<tbody>
<tr>
<td>Model Number</td>
</tr>
<tr>
<td>Perpendicular Plate C1018 Cold-Rolled Steel Plate</td>
</tr>
<tr>
<td>Flat Plate C1018 Cold-Rolled Steel Plate</td>
</tr>
<tr>
<td>Main Wire Lincoln Weld L-61</td>
</tr>
<tr>
<td>Bypass Wire Kobelco MG-51T</td>
</tr>
<tr>
<td>Flux Powder Lincoln Weld 882</td>
</tr>
</tbody>
</table>
sions and it is in the same category of DH 36 (the most widely used steel in ship structures) such that the procedures developed for C1018 can be directly used for DH 36 without requalification.

Root Opening Effect and Selection

With the purpose of illustrating the effect of the root opening, the different root sizes tested were no root opening, small root opening, and large root opening. In order to decouple from the effect of the mass, all the experiments were conducted using open-loop controls, i.e., using constant wire feed speeds without feedback control, which would adjust the wire feed speeds such that the mass would change also. Because the major concern was whether the root opening would reduce the convexity and increase the reentrant angle, analysis was first done in this section qualitatively without exact readings/measurements of the reentrant angles or leg sizes. The reentrant angle was a concern because shipyard visual acceptance criteria typically require the reentrant angle to be no less than 90 deg to reduce possible stress concentration, which would reduce the fatigue life.

No Root Opening Experiment

In the no root opening experiment, the T-joint was prepared without an intentional root opening. This experiment served as a reference to illustrate the effect of the root opening in later experiments with root openings. The welding parameters used in the no root opening as well as the experiments with root openings are listed in Table 2.

Table 2 — Welding Parameters for Root Opening Experiments

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
<th>Unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>Main Wire Speed (W1)</td>
<td>90 (288.6)</td>
<td>in./min (cm/min)</td>
</tr>
<tr>
<td>Bypass Wire Speed (W2)</td>
<td>300 (762)</td>
<td>in./min (cm/min)</td>
</tr>
<tr>
<td>Travel Speed (v)</td>
<td>50 (127)</td>
<td>in./min (cm/min)</td>
</tr>
<tr>
<td>Main Voltage (V1)</td>
<td>28</td>
<td>V</td>
</tr>
<tr>
<td>Bypass Voltage (V2)</td>
<td>28</td>
<td>V</td>
</tr>
<tr>
<td>Root Opening in T Joint</td>
<td>0, 0.06, 0.12 (0, 1.5, 3)</td>
<td>in. (mm)</td>
</tr>
</tbody>
</table>

Figure 4 shows the welding currents and wire feed speeds recorded from the data-acquisition (DAQ) system. In the legend of the plots, $I_1$ and $I_2$ represent the base metal and bypass currents and $W_1$ and $W_2$ stand for the main and bypass wire feed speeds, hereafter. As can be seen from the experimental data, after the process reaches its steady-state, the average base metal current is approximately 262 A, and the average bypass current is around 154 A. Hence, the average total welding current within the steady-state period was 416 A. Because the perpendicular and flat plates are relatively straight, the welding process was relatively stable although no feedback control was used.

Figure 5 shows the photo of the weld bead in the no root opening experiment. Figure 6 shows a typical cross section of the welded joint. It can be seen that the weld bead is convex (shown with the dashed lines in Fig. 6). Also, the reentrant angle (shown with the blue lines in Fig. 6) was close to 90 deg.

Small Root Opening Experiment

In this section, a 1.5-mm root opening was tested. Except for the root opening, all other conditions and parameters were unchanged from the no root opening experiment (shown in Table 2).

As can be seen from the recorded experimental data shown in Fig. 7, after reaching the steady-state, the average base metal current is approximately 238 A, and the bypass current is around 164 A. Hence, the total welding current in the steady-state period was 402 A. The welding process was relatively stable with only insignificant fluctuations within acceptable ranges.

Due to the root opening between the T and the panel, the relative position among the electrodes and the workpieces were different from that in the no root opening experiments. As a result, the values of welding currents in the experiment with a root opening are not exactly the same as those in the no root opening condition although the wire feed speeds and the welding voltages are exactly the same.

As can be seen from the photo of the weld bead (Fig. 8) and a typical cross section of the weld bead (Fig. 9), the convexity of the weld bead (shown with the dashed lines in Fig. 9) has been reduced by 50% approximately after the introduction of the root opening despite the reduction in the actual heat input (total current). At the same time, the reentrant angle (shown with the blue lines in Fig. 9) has also been increased accordingly. The effect of the root opening on the convexity...
and reentrant angle is clearly demonstrated.

Large Root Opening Experiment

The root opening is increased to 3 mm while other parameters and conditions are unchanged.

As can be seen from Fig. 10, after reaching the steady-state, the average base metal current is 244 A approximately, and the bypass current is around 152 A. Hence, the total welding current within the steady-state period is 396 A. The welding currents drifted more significantly than those in the no root opening and the small root opening experiments. The weld appears to be wider in the second half of the weld where the base metal current is greater — Fig. 11.

As can be seen, the convexity of the weld bead (shown with the dashed lines in Fig. 12) in the large root opening experiment was greatly reduced compared to the no root opening experiment. However, the difference with that in the small root opening was not significant. The reentrant angle in the large root opening becomes greater.

Results in the three root opening experiments clearly demonstrate the effectiveness of a root opening in reducing the convexity and increasing the reentrant angle for desirable weld bead geometry. The penetration capability required to produce a desirable weld bead is thus reduced by the root opening. To determine which root opening is more appropriate (1.5 or 3.0 mm), the authors noted that the vertical leg size of the weld bead in the large root opening experiment is approximately 6 mm. However, the largest root opening allowed in production is 4.76 mm (3⁄16 in.) and for every 1.59 mm (3⁄32 in.) root opening (over ¼ in.), the weld size must be increased by ¼ in. accordingly. For example, if ¼ in. (6.35 mm) weld is needed and there is a 3.18 mm (¼-in.) (root opening between perpendicular and flat plates), then the required leg size will become 7.92 mm (¼ in.) (root opening ¼ in. less the permitted initial ¼ in., this ¼ in. is added to the ¼ in. size required, resulting in ¼ in.). As a result, the required leg size will become 6.35 mm (¼ in.) for the 4.76 mm (3⁄16-in.) workpiece thickness if a 3-mm (0.12-in.) root opening is used. Consequently, the heat input will be increased due to the increase in the required mass. On the other hand, for the 1.5-mm small root opening (0.59 in., which is smaller than the permitted ¼ in.), the leg size can still be equal to the thickness of the plate (¼ in.). Hence, the small root opening is a more appropriate root opening size.

Analysis Methods

Once the root opening was selected for the modified joint design, the travel speed was optimized, and the heat input was then minimized. Such optimization and minimization was conducted using quantitative analysis in addition to the qualitative comparison/analysis method used for the root opening study. Before the optimization and minimization were performed, the methods for quantitative analysis had to be specified first.

The leg sizes (vertical and horizontal) were measured for each of the weld beads as shown in Fig. 13. Specifically, for any

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**Table 3 — Experimental Conditions for Travel Speed Study Experiments**

<table>
<thead>
<tr>
<th>Travel Speed (in./min)</th>
<th>Incremental Main Wire Bypass Wire</th>
<th>Speed (cm/min)</th>
<th>Speed (cm/min)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Exp 5.1 30 (76.2)</td>
<td>1.0</td>
<td>60 (152.4)</td>
<td>150 (381)</td>
</tr>
<tr>
<td>Exp 5.2 35 (88.9)</td>
<td>1.17</td>
<td>70 (177.8)</td>
<td>175 (444.5)</td>
</tr>
<tr>
<td>Exp 5.3 40 (101.6)</td>
<td>1.33</td>
<td>80 (203.2)</td>
<td>200 (508)</td>
</tr>
<tr>
<td>Exp 5.4 45 (114.3)</td>
<td>1.5</td>
<td>90 (228.6)</td>
<td>225 (571.5)</td>
</tr>
<tr>
<td>Exp 5.5 50 (127)</td>
<td>1.67</td>
<td>100 (254)</td>
<td>250 (635)</td>
</tr>
<tr>
<td>Exp 5.6 55 (139.7)</td>
<td>1.83</td>
<td>110 (279.4)</td>
<td>275 (698.5)</td>
</tr>
<tr>
<td>Exp 5.7 60 (152.4)</td>
<td>2.0</td>
<td>120 (304.8)</td>
<td>300 (762)</td>
</tr>
</tbody>
</table>
weld bead, in order to ensure the accuracy of the measurement, the beginning adjustment section for the arc-establishing period (50.8 mm/2 in. long approximately) and the ending section (25.4 mm/1 in. long approximately) for turning off the contactors of the two power supplies individually were skipped from being measured. Then, along the welding direction, the full length of the rest of the weld in the steady section was divided into N short sections with a 10-mm (0.393-in.) interval except for the last section left that was not exactly 10 mm long. Within each of these short sections (section i for example), one maximum leg size (maxi) and one minimum leg size (mini) can be measured using a Vernier caliper on both the horizontal (on the panel) and the vertical (on the T) directions. In this way, a series of max-min pairs can be obtained for each weld bead.

After obtaining the raw data pairs as specified above, analyses for travel speed optimization and heat input minimization can be conducted quantitatively. To this end, four major performance indices can be calculated as shown in Fig. 13. The specific calculations are as follows using one weld bead as example:

First, after comparing the max-min pairs, two extreme values — the absolute maximum and minimum leg sizes — can be found for both horizontal and vertical directions, respectively. Then, the difference between these two extreme values gives the extreme difference of the leg size. Third, within the steady section, the average leg sizes can be calculated by Equation 2.

\[
\bar{x} = \frac{1}{N} \sum_{i=1}^{N} \left( \frac{\text{max}_i + \text{min}_i}{2} \right) 
\]

Here, \( \bar{x} \) represents either the horizontal or the vertical average leg size. The horizontal and vertical average leg sizes can give the average leg size by averaging the leg sizes in two directions together. At last, the standard deviation of the leg sizes can be calculated by Equation 3.
Experimental Results and Analysis

Seven experiments, under the same basic conditions (Table 1) as designed and unchanged linear deposition speed, have been conducted following the sequence listed in Table 3. Figure 14 shows the plots of the welding currents and wire feed speeds recorded from the data-acquisition system. As shown in Fig. 14, the welding currents are relatively stable after the establishment of the bypass arcs. Careful observation of Fig. 14 shows that the fluctuation on the base metal currents is relatively strong when the travel speed equals 30, 35, and 40 in./min (the first three plots in Fig. 14); when the travel speed, however, is equal to and greater than 45 in./min, then the base metal current becomes much smoother. Figures 15 and 16 give the weld beads and typical cross sections in the travel speed study experiments, respectively. From these photos, it can be seen that when the travel speed is equal to and lower than 45 in./min, there is no obvious difference with the convexity of the weld beads. All of them are fairly flat. However, when the travel speed is equal to or greater than 50 in./min, convexity begins to appear, and with the increase in the travel speed, the convexity of the weld beads gets noticeably greater and greater. In particular, the convexity of the weld beads is approximately proportional to the travel speed.

Standard Deviation and Extreme Difference Analysis

Standard deviation and extreme difference are two important performance indices in statistics that are used to describe the spread of the distribution of a group of experimental data (Refs. 22–24). Using the statistical data of the seven experiments with different travel speeds, Fig. 17 shows the changing tendency of the standard deviation and extreme difference of the leg sizes.

It is not difficult to see that when the travel speed is at 30 in./min (lowest travel speed), the standard deviation and the extreme difference in the leg sizes are both at their largest. The high standard deviation and extreme difference are actually coherent to the fluctuating base metal current (see the first plot in Fig. 14) and the rough surface and uneven edges of the weld bead with 30 in./min travel speed (see the first photo in Fig. 15) because fluctuations in base metal current increase the fluctuations in the penetration capability, and thus evenness of the welds produced. Then, as the travel speed increases (from 35 to 45 in./min), the standard deviation

- Standard Deviation and Extreme Difference Analysis
- Traveling Speed Optimization
- Experiment Design and Study Approaches

Experiment Design and Study Approaches

In this section, a series of experiments was conducted using different travel speeds. In particular, the travel speed was increased progressively at 5 in./min increments within the attainable range from 30 to 60 in./min. The wire feed speeds (main wire and bypass wire) were adjusted proportionally with the travel speed, as shown in Table 3, to maintain the linear deposition speed (mass deposition) unchanged. The “Incremental Ratio” in Table 3 represents the ratio of the travel speed relative to the lowest travel speed in the series of experiments, and certainly also the ratio of the wire feed speed to the lowest wire feed speed.

Table 5 — Heat Input Comparison

<table>
<thead>
<tr>
<th></th>
<th>Main Wire Speed (in./min)</th>
<th>Total Current (A)</th>
<th>Travel speed (in./min)</th>
<th>Heat Input (J/in.)</th>
<th>Heat Input Ratio</th>
</tr>
</thead>
<tbody>
<tr>
<td>Single Wire</td>
<td>75</td>
<td>400</td>
<td>30</td>
<td>22300</td>
<td>100%</td>
</tr>
<tr>
<td>Exp 5.1</td>
<td>70</td>
<td>320</td>
<td>45</td>
<td>11947</td>
<td>53%</td>
</tr>
<tr>
<td>Exp 5.2</td>
<td>80</td>
<td>380</td>
<td>45</td>
<td>14187</td>
<td>63%</td>
</tr>
<tr>
<td>Exp 5.3</td>
<td>90</td>
<td>420</td>
<td>45</td>
<td>15680</td>
<td>70%</td>
</tr>
<tr>
<td>Exp 5.4</td>
<td>100</td>
<td>465</td>
<td>45</td>
<td>17360</td>
<td>78%</td>
</tr>
<tr>
<td>Exp 5.5</td>
<td>110</td>
<td>510</td>
<td>45</td>
<td>19040</td>
<td>85%</td>
</tr>
</tbody>
</table>
and extreme difference both become smaller, reaching their lowest points at 45 in./min, and then rise a little bit as the travel speed continues to increase (from 45 to 60 in./min).

From 35 to 60 in./min, however, the deviations and the extreme differences are all relatively small. Hence, 35 to 60 in./min can be considered as an acceptable range for the travel speed. Although in the vertical direction the deviation and extreme difference are very low at 35 in./min, the speed of 45 in./min is still a better choice because both directions should be equally important.

Average and Minimum Leg Size Analysis

In addition to the standard deviation and extreme difference, the average leg sizes and minimum leg sizes are two other important indices that can be used to evaluate the welding performance for fillet joints. In practice, the average and minimum leg sizes of the weld beads are more of a concern.

Figure 18 shows the changing tendency of the average and minimum leg sizes. It can be seen that, with the increase in the travel speed, the average and minimum leg sizes increase gradually at the beginning, reach their largest sizes between 35 and 45 in./min, and then decrease gradually. Because making weld beads absolutely symmetrical on both the vertical and horizontal directions is relatively difficult in laboratory but it may not be in shipyards, the average leg size, i.e., the average between the weld sizes in the two directions as given by the black line in Fig. 18, may be a better measurement for the weld size. Considering the average leg sizes together with the vertical and horizontal minimum sizes, 45 in./min is optimal.

Remarks on Travel Speed Optimization

From the changing tendencies of all the four important performance indices, it is apparent that both the leg sizes and their distributions are undesirable if the travel speed is too slow or too fast. The travel speed from 35 to 50 in./min is considered most appropriate to produce welds meeting size and smoothness requirements.

Specifically, the changing tendencies of the quantitative indices are coherent to the changes on the convexity and shapes of the weld beads, and can be explained through the physical process. When the travel speed is relatively slow, the wire feed speeds (main and bypass wire) have to be reduced accordingly due to the limit on the constant linear deposition speed (mass deposition). Naturally, the welding currents will be relatively low because of the reduced wire feed speeds. Unfortunately, the welding currents fluctuate more in their low ranges — Fig. 14. As a result, the fluctuating welding currents lead to the relatively large standard deviation and extreme difference. On the contrary, if the travel speed is too fast, the formation of even welds at high speed becomes an issue resulting in large standard deviations and extreme differences in the leg sizes as well as uneven narrow and convex weld beads. Therefore, the quantitative statistical results and the qualitative analysis on the convexity of the welds both suggest the moderate 45 in./min is the optimal travel speed for the DE-SAW process for fillet joints.

Heat Input Minimization

With the root opening and travel speed selected/optimized, the heat input for fillet welds using the DE-SAW process can be minimized.
Experiment Design

Different from the constant ratio used in the travel speed optimization, if the ratio between the main and bypass wire feed speeds can be adjusted, then the same linear deposition rate can be achieved at reduced/increased main wire feed speed (thus the total current that determines the heat input), but higher/lower bypass wire feed speed does not affect the heat input directly, so the heat input can be adjusted accordingly to maintain the linear deposition rate unchanged. When viewing Table 4, one should note that the diameter of the main wire and that of the bypass wire are different (2:1 approximately, see Table 1). The adjustment on the bypass wire speed is exactly calculated based on this diameter ratio.

After conducting these five experiments, the leg sizes (vertical and horizontal) were measured for each of the five weld beads with the same method shown in Fig. 13. Similarly, the analysis as to the welding performances was qualitative and quantitative. In addition, the heat input was now added as another measurement. If the weld sizes are all acceptable within a certain range of the linear deposition, then the lower heat input resulted from the lower main wire feed speed should be selected to minimize the heat input to the maximum.

Experimental Results and Analysis

Under the same basic conditions (Table 1) and unchanged linear deposition speed as designed, five experiments were conducted following the sequence listed in Table 4. Figure 19 shows the plots of the experimental data recorded from the data-acquisition system.

As shown in Fig. 19, with the increase of the main wire speed (from 70 to 110 in./min) and the decrease of the bypass wire (from 382 to 206 in./min), the heat input consequently increased, and the average steady-state base metal current (red lines in Fig. 19) increased accordingly. Careful observation on Fig. 19 also shows that the fluctuation on the base metal current is relatively strong and obvious when the wire feed speed is set at 70 in./min. Apart from this, the welding processes in the four experiments are quite stable.

Figures 20 and 21 give the weld beads and typical cross sections in the heat input optimization study respectively. From these photos, it can be seen that when the main wire feed speeds equal 70 and 110 in./min (two extreme settings in this series), the weld beads appear to be convex. Additionally, at 70 in./min, the edges of the weld bead are quite rough and uneven. However, when the main wire speed is between 80 and 100 in./min, the quality of the weld beads is quite satisfactory. Especially, when viewing the typical cross sections, the surface and reentrant angle of the weld beads within this range are all fairly acceptable.

Standard Deviation and Extreme Difference Analysis

Similar to the quantitative analysis used in the travel speed optimization, four
performance indices were calculated. According to the statistical data from the five experiments with different heat inputs, Fig. 22 shows the changing tendency of the standard deviation and extreme difference on the leg sizes.

After taking the data on both horizontal and vertical directions into consideration, it can be seen that when the main wire feed speed was at 70 in./min (lowest heat input in the series of experiments), the standard deviation and extreme difference of the leg sizes were both at their largest. Then, from 80 to 100 in./min, the standard deviation and extreme difference of the leg sizes are both on a declining trend. Actually, the deviation and the extreme difference are all relatively small within this range. Hence, 80 to 100 in./min can be considered as an acceptable range for the heat input. Comparatively, the heat input when $W_1 = 100$ in./min gave the best performance. At last, when the main wire feed is close to 110 in./min (the highest wire feed speed in the series of experiments), both the standard deviation and extreme difference rise up rapidly.

The changing tendencies on deviation and extreme difference are coherent to the welds shown in Figs. 20 and 21. From $W_1 = 80$ in./min to $W_1 = 100$ in./min, the surfaces of the weld beads are relatively smooth, and the edges of the welds are quite uniform. However, when the heat input is either too high or too low, the surfaces of the welds appear to be convex and the edges of the welds are relatively rough and uneven. Hence, simply from the standard deviation and extreme difference of the leg sizes, the appropriate range of the main wire feed speed (represents the range of heat input) should be between 80 and 100 in./min.

**Average and Minimum Leg Sizes Analysis**

In addition to the deviation and the extreme difference, Fig. 23 shows the changing tendencies of average and minimum leg sizes. By referring to the statistical data on both horizontal and vertical directions, it can be seen that the average and minimum leg sizes are all on the rising trend at the beginning. After reaching their largest sizes when the main wire speed equals 90 in./min, the leg sizes become shorter instead of increasing with the continuing rising of the heat input. This decreasing phenomenon was different from our previous expectation. The excessive penetration that appeared following the high heat input should be the major reason for the narrow and uneven welds.

In typical applications, the vertical and horizontal leg sizes must be greater than the thickness of the workpieces (4.7 mm approximately). From this point of view, only the leg sizes that resulted from the heat inputs $W_1 = 90$ in./min and $W_1 = 100$ in./min are fully qualified. At 80 and 110 in./min, although the average leg sizes are acceptable, the minimum leg sizes are excessively undersized. And after observing
the weld beads at 80 and 110 in./min, more than one spot appeared along the welds where the leg size was less than 4.7 mm. Hence, considering the average leg sizes together with the vertical and horizontal minimum sizes, only the heat inputs when the main wire feed speed equals 90 and 100 in./min can be accepted.

**Heat Input Comparison**

Heat input reduction is the primary purpose to use the DE-SAW process. Table 5 shows the heat input comparison among the five heat input optimization experiments and shipyard single-wire SAW benchmark. The “Heat Input Ratio” in Table 5 represents the heat input in relation to that of the benchmark.

Table 5 clearly shows that the DE-SAW process with 1.5-mm root opening lowers the heat input. Meanwhile, as analyzed in the quantitative comparison, the welding sizes at \( W_1 = 90 \) in./min and \( W_1 = 100 \) in./min are all satisfactory.

**Remarks on Heat Input Optimization**

From the changing tendencies of all the four important performance indices and the convexity of the welds, it is apparent that both the leg sizes and their distributions are undesirable if the heat input is too low or too high. Meanwhile, on the premise of minimizing the heat input, it is reasonable to say that the heat input when the main wire feed speed equals 90 in./min with a bypass wire feed speed of 294 in./min is optimal with a 30% reduction on the heat input relative to the conventional SAW process for fillet joints. As further demonstrated in Fig. 24, the resultant welds appear to be visually acceptable.

**Conclusions and Future Work**

The use of a root opening in a T-joint between the perpendicular and flat plates provides an effective way to reduce the penetration required to produce desirable weld beads. The heat input reduction capability of the DS-SAW process can thus be effectively utilized to produce desirable fillet welds with minimized heat input. A 1.5-mm root opening is recommended for fillet welding on \( \frac{3}{16} \)-in.-thick plates.

Quantitative and qualitative analysis methods were used to optimize the welding parameters for minimized heat input. The resultant optimized practice for DE-SAW of \( \frac{3}{16} \)-in. fillet welds is to use a 1.5-mm root opening, 45 in./min travel speed,
90 in./min feed speed for ¾-in. (2.4-mm) diameter main wire and 294-in./min feed speed for 0.045-in.- (1.2-mm-) diameter bypass wire.

The optimized practice results in 30% reduction in heat input from the shipyard single-wire benchmark.

The use of a root opening introduces an additional procedure in production. Quick and economic methods need to be developed to set the root opening conveniently with the needed accuracy. Weakly magnetized steel spacers of the workpiece material appear to serve this purpose well although the effectiveness needs to be verified.

In general, the distortion increases with he heat input, and the cost and time needed for distortion correction increase with the degree of the distortion. Studies are needed to quantify the cost and time reductions due to the heat input reduction provided by the proposed method before it may be considered for possible use in production.

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References


Fig. 24 — Cross sections and metallic phases when W1 = 90 in./min.

AWS Expands International Services

With international membership on the rise, the American Welding Society (AWS) launched a series of country-specific websites known as microsites for members to access information in their native languages.

Multilingual microsites are now live for Mexico at www.aws.org/mexico, China at www.aws.org/china, and Canada (English/French) at www.aws.org/canada. They feature information on services offered by AWS in each country, membership benefits, exposition information, online education, and access to AWS publications and technical standards. Other countries will be added later.