Development of a Welding Condition Optimization Program for Narrow Gap SAW*

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Submerged arc welding (SAW) is widely used for butt welding of thick plates in large steel structures because of its high deposition rate and high weld quality. 1-pass per layer narrow gap welding with a narrow root width is an effective process that reduces welding time and deformation. However, compared with conventional grooves, it is at risk to occur lack of fusion due to narrow gap. And, the degradation of mechanical properties is a concern because the reheated region becomes thinner. In this study, a welding condition optimization program to control the weld shape for narrow gap SAW was developed. First, welds were conducted on plate under different welding conditions, and a weld shape model was established. Next, an optimization algorithm for deciding welding conditions that can achieve the target weld shape using the weld shape model was established. Then, welding conditions for achieving different layer thicknesses were calculated using the optimization method. The performance of the program was verified by multi-layer welding under the decided conditions.

Key Words: Submerged Arc Welding, Narrow Gap, Multiple Regression Analysis, Nelder-Mead Method

1. Introduction

Submerged arc welding (SAW) is widely used for butt welding of thick plates in large steel structures because of its high deposition rate and high weld quality. 1-pass per layer narrow gap welding with a narrow root width reduces the cross-sectional area of the groove and the number of passes. Therefore, it is more effective process that reduces welding time and deformation compared with conventional groove. Narrow gap SAW has been examined previously [1]. However, compared with conventional grooves, lack of fusion tends to occur due to narrow gap. And, the degradation of mechanical properties is a concern because the reheated region becomes thinner. Thus, SAW of a narrow gap groove requires more accurate control of the weld shape to prevent lack of fusion and to assure mechanical properties. There are few cases in which it is applied in actual production lines.

Recently, accurate control of welding conditions and high reproducibility have become possible thanks to the use of a digital power source that accurately controls the waveform [2]. Therefore, it is also expected that the weld shape can be controlled in narrow gap SAW. However, with a digital power supply, it is difficult to decide welding conditions because there are many welding parameters (EN ratio, current, phase difference, etc.). A method for deciding optimized conditions is needed, but such a method has never been established.

In this study, a welding condition optimization program to control the weld shape for 1-pass per layer narrow gap SAW was developed. First, it was conducted bead on plate welding under various welding conditions, and a weld shape model was established. Next, an optimization algorithm for deciding welding conditions that can achieve the target value using the developed weld shape model was established. Welding conditions for achieving different layer thicknesses were decided using the optimization method. The performance of the program was verified by multi-layer welding under the decided conditions.

2. Development of welding condition optimization program

2.1 Flowchart of optimization program

Fig. 1 shows the flowchart of welding condition optimization program. First, it was conducted the experiment to obtain data of welding condition (EN ratio, current, etc.) and weld shape for learning. In this study, as the simple and low cost method, bead on plate welding under some welding conditions changing welding parameter shown in next chapter were conducted. Then, weld shape model was established from experimental data. As \( \tilde{x} \) is a welding condition and \( \tilde{y} \) is a result of weld shape parameter \( \theta \) (bead width, etc.), the weld shape model was established as \( \tilde{y} \sim F(\tilde{x}) \) by multiple regression analysis. An objective function \( f \) was defined from a predicted result \( \tilde{y}^* \) and target value. And a welding condition was decided by optimization method so that \( \tilde{y}^* \) is closest to a target value.
degradation of mechanical properties is a concern because the power source that accurately controls the waveform \[2\]. Therefore, reheated region becomes thinner. Thus, SAW of a narrow gap groove requires more accurate control of the weld shape to prevent it is also expected that the weld shape can be controlled in narrow welding with a narrow root width reduces the cross-sectional area gap SAW. However, with a digital power supply, it is difficult to decide welding conditions because there are many welding parameters (EN ratio, current, phase difference, etc.). A method for deciding optimized conditions is needed, but su

2.2 Weld shape model

A prediction model was established to estimate the weld shape from any welding conditions. If \( \tilde{x} = T(x_{1*}, x_m) \) is a welding condition that derived from arbitrary welding parameters, a result of any weld shape parameter \( y \) would be represented as follows [3]:

\[
f^{\text{BC}}(y) \sim C_0 + \tilde{\mathbf{C}} \cdot \tilde{x} = C_0 + \sum_{i=1}^{m} C_i x_i \tag{1}
\]

where coefficients \( C_0 \) and \( \tilde{\mathbf{C}} = T(C_{1*}, \ldots, C_m) \), \( m \) is the number of welding parameters including in the welding conditions, and \( f^{\text{BC}}(y) \) shows the Box-Cox conversion of \( y \). If the welding condition substituting the welding parameters \( \tilde{x}_j = T(x_{1,j*}, x_{m,j}) \), the unbiased variance-covariance matrix \( \mathbf{M} \) is defined as follows:

\[
\mathbf{M}_{\text{uv}} = \frac{1}{n-1} \left\{ \sum_{j=1}^{n} (x_{u,j} \cdot x_{v,j}) - n \bar{x}_u \cdot \bar{x}_v \right\} \tag{2}
\]

where \( n \) is the number of welding conditions and \( \bar{x}_u \) and \( \bar{x}_v \) are the averages of the welding parameter \( x_u \) and \( x_v \). If result \( y_j \) is obtained with \( \tilde{x}_j \), \( C_0 \) and \( \tilde{\mathbf{C}} \) are calculated by following equation:

\[
C_0 = f^{\text{BC}}(y) - \tilde{\mathbf{C}} \cdot \tilde{x} \tag{3}
\]

\[
\tilde{\mathbf{C}} = \frac{1}{n-1} \mathbf{M}^{-1} \left\{ \sum_{j=1}^{n} (x_{1,j} \cdot f^{\text{BC}}(y_j)) - n \bar{x}_1 \cdot \tilde{f}^{\text{BC}}(y) \right\} \tag{4}
\]

where \( \tilde{f}^{\text{BC}}(y) \sim C_0 + \tilde{\mathbf{C}} \cdot \tilde{x} \) is the average of \( f^{\text{BC}}(y) \). The weld shape model was established by calculating \( C_0 \) and \( \tilde{\mathbf{C}} \) with equations (3) and (4).

2.3 Optimization algorithm of welding condition

The gradient method, which is widely used for optimization purposes, needs to use derivatives. Therefore, it cannot optimize for non-differentiable or non-convex functions [4]. On the other hand, the Nelder-Mead method [5], which does not use derivatives, can optimize these functions. In this study, the optimization method followed the Nelder-Mead method. Moreover, a multi-start method [6] and genetic algorithm [7] were applied to prevent local solutions.

If \( E \) is a set of welding conditions \( \tilde{x} \) used in the weld shape model, \( X \) is the constraint condition of \( \tilde{x} \), \( Y \) is the constraint condition of result \( y \) and \( T\text{arg}_{y} \) is the target value of weld shape parameter \( \theta \), \( w_\theta \) is the weighting coefficient of each \( T\text{arg}_{y} \). \( y_\theta^* \) is the predicted result of \( \theta \), and \( \max_{\theta} \) is the maximum and \( \min_{\theta} \) is the minimum value of \( y_\theta^* \). The optimization program decides \( \tilde{x} \) to minimize the objective function \( f \) defined as follows:

\[
f = \left\{ \begin{array}{ll}
\sum_{\theta} w_\theta |y_\theta^* - T\text{arg}_{y}| & (\tilde{x} \in E, X \cap \tilde{y'} \in Y) \\
\infty & (\text{else})
\end{array} \right.
\tag{5}
\]

\rightarrow \text{min.}

3. Verification test of developed program

3.1 Experimental method

The schematic image of experimental apparatus is shown in Fig. 2. A digital power source capable of controlling waveforms was used and tandem welding was conducted. The distance between electrodes was 15 mm and CTWD (contact tip to work distance) was fixed at 30 mm. The test coupon was used of 2\(\frac{1}{2}\)/Cr-1Mo steel. The flat plate of 400 \(\times\) 70 \(\times\) 30 (L \(\times\) W \(\times\) T) and I shape groove test coupon were used. The I shape groove was formed as a 400 \(\times\) 14 \(\times\) 25 (L \(\times\) W \(\times\) T) mm insert sandwiched between two 400 \(\times\) 70 \(\times\) 30 mm plates. The groove depth was set to 20 mm. The sides of the test coupon were cooled by water-cooled copper plates to reproduce the actual cooling rate. A strong back was attached to reduce welding deformation. The preheating and interpass temperature were controlled to between 200 and 250°C.

![Schematic image of experimental apparatus](image-url)
3.2 Creation of experimental data for learning

The bead on plate under various welding conditions was conducted. Table 1 shows the welding experimental conditions for established model. It is selected the EN ratio (leading / trailing electrode), current (leading / trailing electrode), phase difference and welding speed as the welding parameters ($m = 6$), and their values were changed to the following 3 levels: 0.25, 0.50, 0.75 (#), 400, 600, 800 (A), 90, 135, 180 (degree), and 60, 71, 81 (cm/min).

The welding conditions were arranged so that the 6 welding parameters and 3 levels were orthogonal [3] ($n = 27$). The weld shape parameter $\theta$ was determined from the cross sectional area of deposited metal $A_R$ as an index of the deposition rate and the bead width $W_B$ as an index of the melting width in the groove. These values were the average of 3 cross-sections measured from the weld bead of test coupon. The voltage (leading / trailing electrode) was 33 / 33 (V), and the frequency was 60 (Hz).

Table 1 Welding experimental conditions for established model

| No. | Leading electrode | Trailing electrode | Phase difference (degree) | Welding speed (cm/min) |
|-----|-------------------|--------------------|---------------------------|------------------------|
| 1   | 0.25              | 400                | 0.25                      | 400                    |
| 2   | 0.25              | 400                | 0.25                      | 400                    |
| 3   | 0.25              | 400                | 0.25                      | 400                    |
| 4   | 0.25              | 400                | 0.25                      | 400                    |
| 5   | 0.25              | 400                | 0.25                      | 400                    |
| 6   | 0.25              | 400                | 0.25                      | 400                    |
| 7   | 0.25              | 400                | 0.25                      | 400                    |
| 8   | 0.25              | 400                | 0.25                      | 400                    |
| 9   | 0.25              | 400                | 0.25                      | 400                    |
| 10  | 0.25              | 400                | 0.25                      | 400                    |
| 11  | 0.25              | 400                | 0.25                      | 400                    |
| 12  | 0.25              | 400                | 0.25                      | 400                    |
| 13  | 0.25              | 400                | 0.25                      | 400                    |
| 14  | 0.25              | 400                | 0.25                      | 400                    |
| 15  | 0.25              | 400                | 0.25                      | 400                    |
| 16  | 0.25              | 400                | 0.25                      | 400                    |
| 17  | 0.25              | 400                | 0.25                      | 400                    |
| 18  | 0.25              | 400                | 0.25                      | 400                    |
| 19  | 0.25              | 400                | 0.25                      | 400                    |
| 20  | 0.25              | 400                | 0.25                      | 400                    |
| 21  | 0.25              | 400                | 0.25                      | 400                    |
| 22  | 0.25              | 400                | 0.25                      | 400                    |
| 23  | 0.25              | 400                | 0.25                      | 400                    |
| 24  | 0.25              | 400                | 0.25                      | 400                    |
| 25  | 0.25              | 400                | 0.25                      | 400                    |
| 26  | 0.25              | 400                | 0.25                      | 400                    |
| 27  | 0.25              | 400                | 0.25                      | 400                    |

3.3 Results of verification test of bead on plate welding

Different deposited metal area $A_R$ and bead width $W_B$ were formed by 3 welding conditions. Condition A was the standard condition with an EN ratio (leading / trailing electrode) of 0.50 / 0.50 (#), current of 600 / 600 (A), phase difference of 90 (degree), and welding speed of 60 cm/min. The predicted values were $A_R = 62.6$ mm$^2$ and $W_B = 24.5$ mm. If the groove width assumed with narrow gap SAW is 14 mm, the predicted layer thickness was 4.4 mm.

Conditions B and C were decided as the welding conditions with different weld shapes by the developed program. Under each condition, heat input was limited to 40 kJ/cm or less. Condition B was optimized to the high deposition rate condition with an EN ratio (leading / trailing electrode) of 0.25 / 0.75 (#), current of 650 / 800 (A), phase difference of 90 (degree), and welding speed of 72 cm/min. The welding condition was optimized so that $A_R$ was maximized. Moreover, $W_B$ was maximized to prevent lack of fusion. The predicted values were $A_R = 71.2$ mm$^2$ and $W_B = 26.2$ mm. With a groove width of 14 mm, the predicted layer thickness was 5.1 mm. Condition C was optimized to the low layer thickness condition with an EN ratio (leading / trailing electrode) of 0.25 / 0.25 (#), current of 400 / 400 (A), phase difference of 180 (degree), and welding speed of 60 cm/min. The welding conditions were optimized so that the target value of $A_R$ was 28 mm$^2$ and $W_B$ was maximized. The predicted values were $A_R = 31.9$ mm$^2$ and $W_B = 21.0$ mm. With a groove width of 14 mm, the predicted layer thickness was 2.3 mm.

The measured and predicted values under each condition are shown in Table 2. The predicted value of $A_R$ was as a difference between -6.1 mm$^2$ and +0.3 mm$^2$ with respect to the measured value under each condition. With a groove width of 14 mm, the error in the layer thickness was about -0.4 mm to 0.0 mm. The predicted value of $W_B$ was as a difference between -2.1 mm and +0.8 mm. According to these results, the predicted weld shape were also almost the same as the actual one. Moreover, under Conditions B and C, the target weld shapes were obtained with the optimized welding conditions.

Table 2 Measurement result of weld shape with bead on plate

| Condition | $A_R$ (mm$^2$) | $W_B$ (mm) |
|-----------|---------------|------------|
| Measured  | Predicted     | Difference |
| A         | 62.3          | 62.6       | +0.3        |
| B         | 72.6          | 71.2       | -1.4        |
| C         | 38.0          | 31.9       | -6.1        |

3.4 Result of verification test of narrow gap welding

1-pass per layer narrow gap SAW was conducted under Conditions B and C. The bead appearance and the macroscopic test result of section are shown in Fig. 3.

Fig. 3 Bead appearance and cross-section under each welding condition

Under Condition B with the high deposition rate, build-up was completed in 4 passes for a groove depth of 20 mm. And, under Condition C with the low layer thickness, build-up was completed
in 8 passes. Under Condition B, the bead width \( W_B \) of the final layer was 28.2 mm, slightly wider than the bead on plate welding. Under Condition C, \( W_B \) was 20.7 mm, almost the same as the bead on plate. Measurement results of the deposited metal area \( A_R \) and melting width in the groove \( W_G \) in each pass are shown in Table 3. The \( A_R \) was almost constant from 69.2 mm\(^2\) to 70.1 mm\(^2\) under Condition B and from 33.4 mm\(^2\) to 34.5 mm\(^2\) under Condition C in each layer. And, these values were almost the same as the predicted values of 71.2 mm\(^2\) and 31.9 mm\(^2\). The \( W_G \) was constant from 18.6 mm to 19.2 mm under Condition B and from 15.4 mm to 16.4 mm under Condition C.

### Table 3 Measurement result of weld shape in narrow gap

| Pass | Condition B | Condition C |
|------|-------------|-------------|
|      | \( A_R \) (mm\(^2\)) | \( W_G \) (mm) | \( A_R \) (mm\(^2\)) | \( W_G \) (mm) |
| 1    | 69.4        | 19.2        | 33.7        | 15.4        |
| 2    | 70.1        | 18.6        | 33.9        | 16.0        |
| 3    | 69.2        | 19.1        | 33.4        | 15.7        |
| 4    | 69.2        | 18.8        | 34.1        | 15.9        |
| 5    |              | 34.5        | 15.9        |
| 6    |              | 34.3        | 15.6        |
| 7    |              | 34.0        | 16.4        |
| 8    |              | 33.8        | 15.8        |

### 4. Discussion

#### 4.1 Accuracy of developed program

If \( \hat{y}_{b,j} \) is the predicted result for arbitrary welding conditions \( \bar{x} \) and \( \tilde{y}_{b,j} \) is the result obtained by actual welding, so the prediction interval of \( \hat{y}_{b,j} \) is defined as follows [4]:

\[
\hat{f}^{bc}(\hat{y}_{b,j}) - t(\frac{\alpha}{\sqrt{n}}, D_e) \sqrt{V_e \left( 1 + \frac{1}{n} + \frac{D_{sq}}{n - 1} \right)} \\
\leq \hat{f}^{bc}(\tilde{y}_{b,j}) \\
\leq \hat{f}^{bc}(\hat{y}_{b,j}) + t(\frac{\alpha}{\sqrt{n}}, D_e) \sqrt{V_e \left( 1 + \frac{1}{n} + \frac{D_{sq}}{n - 1} \right)}
\]

Where, the significance level \( \alpha = 0.05 \), \( D_e \) is the degree of freedom of error, \( t(\alpha/2, D_e) \) is the \( t \) value of the rejection region in two-sided tests with \( \alpha \) and \( D_e \), and \( V_e \) is the square mean of error and \( D_{sq} \) is the square of Mahalanobis distance calculated by the following equation:

\[
V_e = \frac{SS_{e}}{D_e}
\]

\[
D_{sq} = \sum_{i=1}^{m} \sum_{j=1}^{n} \left( \vec{x}_i - \bar{x}_j \right) \left( \vec{x}_i - \bar{x}_j \right)^T (M^{-1})_{ii}
\]

The prediction interval of the deposited metal area \( A_R \) and bead width \( W_B \) calculated under Conditions A, B and C from Equation (6) are shown in Table 4. The measurement value of 3 cross-sections are also shown. Under each condition, the measurement results were in each prediction interval. The prediction interval were approx. \( \pm 10 \) mm\(^2\) for \( A_R \) and approx. \( \pm 2.5 \) mm for \( W_B \). The measured value of \( A_R \) under each condition was smaller than prediction interval. However, under Condition B, the difference of measured values were -5.8 mm\(^2\) to +3.9 mm\(^2\). It is thought to be due to accidental error during welding. It indicates the possibility occurring the same difference as in the prediction interval depending on the conditions during actual welding. And, with a groove width of 14 mm, the range of predicted layer thickness is \( \pm 0.7 \) mm. If the difference is within \( \pm 1.0 \) mm, there will be no significant effect on actual use. Therefore, the prediction accuracy of \( A_R \) by the developed program is sufficient for practical use.

#### 4.2 Effect of narrow gap on weld shape

As shown in Tables 2 and 3, the deposited metal area \( A_R \) was almost same for bead on plate and 1-pass per layer on narrow gap weld, and could be predicted by the developed program. In addition, almost constant \( A_R \) was obtained in each pass. Fig. 4 shows the measurement results of the average wire feeding rate during welding. The average wire feeding rate with narrow gap welding was from 3.9 to 4.0 m/min in each pass under Condition B and from 1.6 to 1.7 m/min under Condition C. These were almost constant. Average wire feeding rate with bead on plate was 3.9 m/min and 1.6 m/min under Conditions B and C, almost same value for narrow gap welding. Halmoy showed that the wire feeding rate, that is, wire melting rate \( \nu_m \) was calculated by
following equation [8]:

\[ \nu_m = \frac{\Phi_{ew} + K_1 L_E}{(H_0 - K_2)} \]  

(10)

Where, \( \Phi_{ew} \) is the equivalent voltage of melting due to arc heating [V], \( j \) is the current density [A/m²], \( L_E \) is the wire extension [m], \( H_0 \) is the heat content of the molten droplet when detaching from wire end [J/m³], and \( K_1 \) and \( K_2 \) are constant values. Equation (10) shows that \( \nu_m \) depends on the current density and wire extension significantly. Thus, it is considered that, if the welding conditions including current and CTWD are the same, the wire feeding rate was unaffected by the shape of groove.

![Fig. 4 Wire feeding rate under Condition B and C](image)

The bead width \( W_b \) of the final layer was within the prediction interval estimated in Table 4. However, the average melting width in the groove \( W_g \) was, respectively, 18.9 mm and 15.8 mm under Conditions B and C, which was smaller than \( W_b \) for bead on plate. With narrow gap welding, it is considered that the flow of the weld pool was different from that with bead on plate, so the thermal diffusion region [9] expanded to the both sides groove walls. With bead on plate, \( W_b \) under Condition B was about 5 mm wider than under Condition C, and the wider range melted in the direction perpendicular to weld line. It is thought that the amount of melting of both groove walls was large with narrow gap welding. The qualitative tendency that \( W_g \) is larger under welding conditions with larger \( \nu_m \) was agreement.

According to these results, the developed welding condition optimization program using the experimental results of bead on plate can sufficiently control \( \nu_m \) in narrow gap SAW. And, although the value does not match \( W_g \), qualitative control, such as to widen \( W_g \) is possible by maximizing \( W_b \). It can control \( W_b \) of the final layer. Since the weld shape in each layer was almost constant, narrow gap SAW can be performed under same welding conditions from the first layer to the final layer.

5. Conclusions

In this study, it is developed a program to control the weld shape for narrow gap SAW. Using the experimental results of bead on plate, welding conditions were optimized by the developed program, and verification tests were performed. The conclusions are as follows,

1) The program was developed for deciding welding conditions that obtain the target weld shape.
2) The prediction intervals of deposited metal area \( A_R \) and bead width \( W_b \) were estimated. It was confirmed that the prediction accuracy of the developed program was sufficient for practical use.
3) 1-pass per layer narrow gap welding under optimized welding conditions was conducted. It was confirmed that the developed program can sufficiently control \( A_R \) and \( W_b \) of the final layer with narrow gap welding.
4) It is difficult to predict melting width in the groove \( W_G \) from the experimental results of bead on plate. However, qualitative control such as to widen \( W_G \) is possible by maximizing \( W_b \).

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