Weld Quality Assessment Method for Short-Circuit Mode in GMAW

J. M. Kim and C. D. Yoo

Abstract

A weld quality assessment method is proposed in this work, which can be applied to the short-circuit mode in GMAW. Information about the welding signal trajectory, distribution of the signal duration at each sub-regions and short-circuit frequency is used to evaluate the weld quality. The weighted penalty, which is determined experimentally, is imposed for each abnormal signal. Performance of the proposed method is compared with the Simpson's method under the conditions of shielding gas reduction, workpiece surface contamination and joint gap in the butt and fillet welds. Although the proposed method predicts the weld quality with reasonable accuracy, further modification and extension to other metal transfer modes are needed as a further study.

Key Words : Weld quality assessment, Short-circuit mode, GMAW, Signal trajectory, Short-circuit frequency, Weighted penalty

1. Introduction

The arc welding process has been automated to enhance productivity using the robot. One of the important issues of arc welding automation is the capability of weld quality monitoring in real-time. Although several methods were proposed to assess weld quality, they are applicable to the limited conditions or lack of reliability. Therefore, the arc weld quality assessment method, which can be utilized to general circumstances, has not been developed. In this work, a weld quality assessing method is presented, which can be applied to the short-circuit mode in gas metal arc welding (GMAW). The proposed method is tested under the conditions of shielding gas, surface contamination and presence of the joint gap. Performance of this method is compared with other method using similarity of the arc signal.

Since welding current and voltage signals include information about arc stability, many researchers attempted to monitor weld quality by analyzing current and voltage signal. Another advantage of the arc sensor is that it does not require external sensors such as the CCD camera and is independent of directionality. In most cases, statistical methods were employed to determine weld quality such as the mean, deviation and frequency of the welding current or voltage signals by assuming that the stable arc will produce high quality weld. Ludewig[1)] and Kilty[2)] evaluated the weld quality using the deviation, short-circuit frequency and rate change of welding current or voltage. Quinn[3,4)] used arc resistance as well as current and voltage, and Adolfsson[5)] analyzed the current and voltage signals for weld quality monitoring. Wang[6)] detected weld defects from the short-circuit frequency and signal variation. Mita[7)] proposed the index representing weld quality, which consists of various factors such as the arcing time, short-circuit time and deviation of welding current. Kang[8)] also proposed an arc stability index, which relates to spatter generation. Recently, Simpson[9)] compared the patterns of reference and real signals in the two-dimensional graph, and weld quality was evaluated through similarity between two signals as shown in Fig. 1.

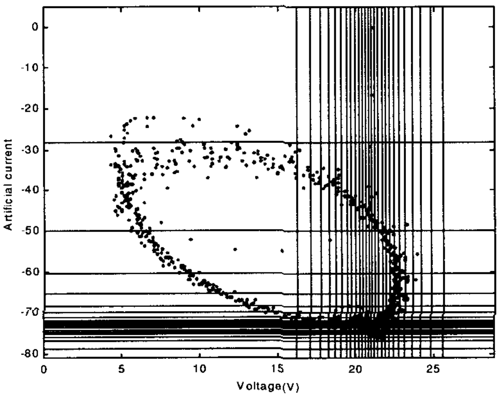

Fig.1 Simpson's method to assess weld quality

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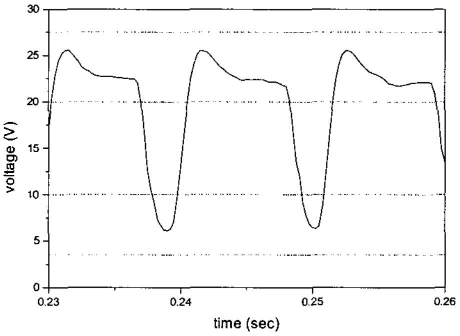
In this work, the working range of welding current and voltage is divided into several sub-regions, and the short-circuit signal is evaluated through its trajectory, duration of trajectory at each sub-region and short-circuit frequency. Weld quality index is calculated in real-time based on the features of the short-circuit signal. This method is tested experimentally and the results are compared with those of the Simpson's method.

2. Weld quality assessing method

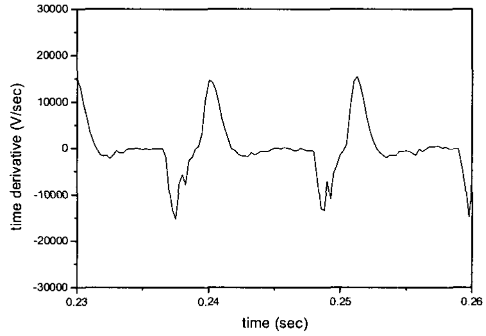
Welding current and voltage signals in the short-circuit mode are affected by welding conditions, and the short-circuit frequency exists between 50~100 Hz in the normal condition. In order to extract the features of the short-circuit mode, two-dimensional plot is used, which consists of the current or voltage value (V) in the horizontal axis and the rate change of the current or voltage value (dV/dt) in the vertical axis. The region of two-dimensional plot is divided into several sub-regions as shown in Fig. 2, and the point located each sub-region represents a measured voltage value and its time derivative at each sampling time. The sub-regions are determined based on the characteristics of the short-circuit mode. Information about the signal trajectory, distribution of points at each sub-region during one short-circuit period, short-circuit frequency and occurrence of instantaneous short-circuit is used to determine the weld quality index.

Fig. 2 shows the procedure to construct two-dimensional plot (V vs. dV/dt). Welding voltage in the short-circuit mode is measured for 0.5 second (Fig. 2(a)), and its derivative is calculated (Fig. 2(b)). The points in Fig. 2(c) represent the voltage and its time derivative at each sampling. The region of the plot consists of 6 sub-regions, and each sub-region has specific characteristics as follows: (R1) the arc is maintained, (R2) the arc length becomes short, (R3) the short-circuit occurs, (R4) the arc is regenerated, (R5) welding voltage becomes excessively high, and (R6) welding voltage is excessively low.

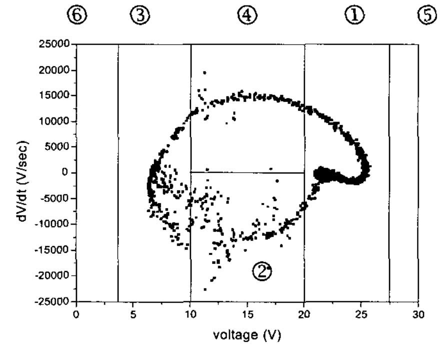
The point in Fig. 2(c) represents the voltage and its time derivative, and its path depends on the signal characteristics. Under the normal condition, the points should pass sequentially through sub-region 1, 2, 3 and 4, and more points exist at the sub-region 1 and 3 than the sub-region 2 and 4. However, the sequence and distribution of the points vary in the abnormal conditions, and the typical example of the abnormal conditions includes the instantaneous short-circuit and arc restart. In the case of the instantaneous short-circuit, the points pass through sub-region 1, 2 and 4 sequentially. When the arc is restarted (not a normal arc regeneration), number of points at sub-region 3 becomes excessive. When the points pass the sub-region 5 and 6, it implies the abnormal conditions.



(a) Welding voltage waveform



(b) Time derivative of voltage signal



(c) Plot of welding voltage and its time derivative with sub-regions

Fig.2 Procedure to construct two-dimensional plot

Weld quality is evaluated using the quality index as:

$$Q = 100 - \sum_{i=1}^{N} w_i - w_f \times D_f \qquad (1)$$

where, Q represents the weld quality index, N the number of abnormal signal, w_i the weighted penalty of abnormal signal, D_f the difference in short-circuit frequency between the reference and measured signal, w_f the weighted penalty of short-circuit frequency difference. When the measured signal is ideally normal, the penalty becomes 0 and the weld quality index is 100. The abnormal signal patterns and corresponding weighted penalties are determined experimentally.

3. Experiment

Experiments were carried out under various conditions using the GMAW system, which consists of the inverter-type power supply and three-axis rectangular manipulator. Bead-on-plate, butt and fillet welds were made on the 6mm steel plate using the 1.2mm wire and argon shielding. Travel speed was 32 cm/min, and the CTWD (Contact Tip to Workpiece Distance) was 20mm. Welding voltage and current were 22 V and 190 A, respectively, which produced the short-circuit mode. During welding, voltage and current signals were sampled at 4 kHz for each channel and the high frequency components above 150 Hz were attenuated using the low pass filter.

In order to determine the weighted penalty and evaluate performance of the proposed method, several conditions were tested where the defects and corresponding abnormal signals were produced. They consist of shielding gas reduction, contamination of the workpiece surface using the grease, and predefined joint gap of the butt and fillet welds. The boundaries of sub-regions were selected in this work as 27.5 V, 20.0 V, 10.0 V, and 3.5 V, and weld quality was evaluated at every 0.5 second. The reference signal was collected during initial 0.5 second, and information from the initial signal was used to select the reference values of the short-circuit frequency, distribution of points at the sub-regions.

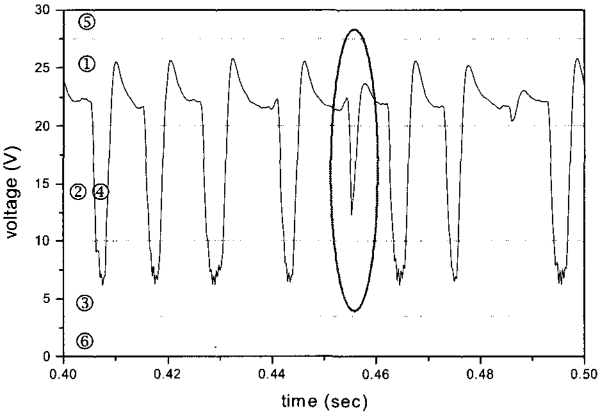
4. Results and discussion

4.1 Determining weighted penalty

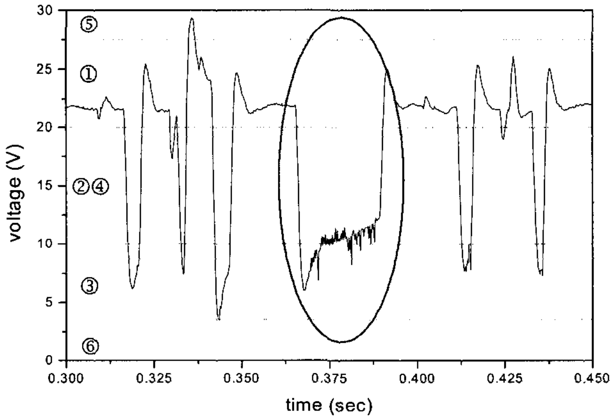
The weighted penalties in equation (1) are determined experimentally, and various abnormal signals affecting weld quality and arc stability need to be defined. Examples of the abnormal signals such as the instantaneous short-circuit and arc start are illustrated in Fig. 3. For the instantaneous short-circuit (Fig. 3(a)), the point does not pass the sub-region 3, and the weighted penalty is selected to 2.5. When the number of points at sub-region 3 is smaller than the reference value by $2\sigma_3$, the penalty becomes 2. Fig. 3(b) shows the signal similar to arc start condition, and the number of points at sub-regions 3 and 4 becomes much larger than that of the reference signal. When the number of points at sub-regions 3 and 4 is greater than $4\sigma_3$and $4\sigma_4$, the high penalty of 5 is given because this case affects weld quality significantly. When welding voltage becomes excessively high or low, the signal trajectory passes through the sub-region 5 or 6, and the penalties are given as 2 and 1, respectively. For other cases of abnormal signals, the penalties are 1 in general. Effects of variation in the short-circuit mode are considered by imposing the weighted penalty of 2. Theses weighted penalties are used to predict the weld quality index in equation (1).

4.2 Assessment of weld quality

In order to evaluate performance of the proposed method, weld defects are made intentionally by reducing the flow rate of shielding gas, deteriorating the surface condition of the workpiece and machining the joint gap. The results are compared with those of Simpson's method.



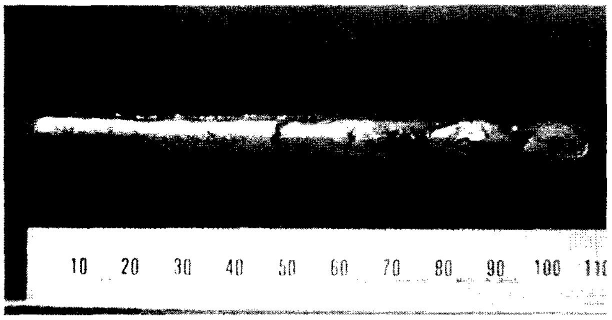
(a) Waveform of instantaneous short circuit



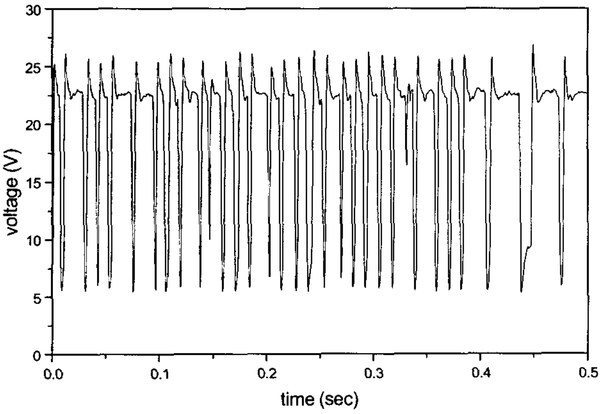
(b) Waveform of arc start

Fig.3 Abnormal voltage waveforms

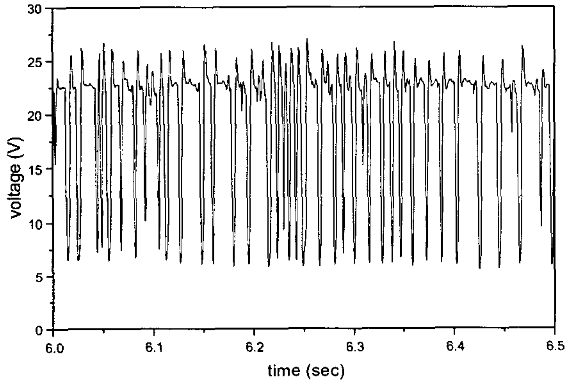
Fig. 4 shows the bead shape and voltage signals when the shielding gas is reduced from 20 l/min to 5 l/min. The irregular bead shape is obtained with reduced gas flow rate due to lack of shielding. The voltage signal with 20 l/min flow rate fluctuated more regularly than that with 5 l/min flow rate. The processing results are illustrated in Fig. 5 where the mean value, standard deviation, weld quality indices using Simpson's and the proposed methods are compared. Gas flow rate is reduced after 6 seconds, and the weld quality index is predicted at every 0.5 second. When gas flow rate is reduced at 6 seconds, the mean and standard deviation vary in large magnitude, which implies that the mean and deviation can provide some information about weld quality. While the weld quality index decreases a little using Simpson's method, it drops abruptly using the proposed method, and the index value of 75 is selected in this work as the criterion to judge proper weld quality based on the experimental results. Although the proposed method appears to predict more accurately than the Simpson's method, the trends of weld quality indices using both assessment methods become similar. It is noted that the parameters of the Simpson's method may not be optimized.



(a) Bead shape with reduction in gas flow rate

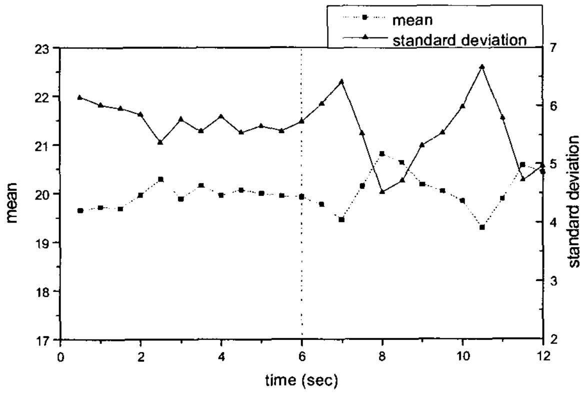


(b) Voltage signal with gas flow rate of 20 l/min

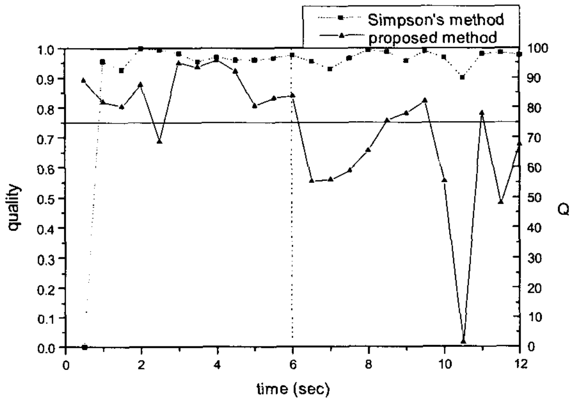


(c) Voltage signal with gas flow rate of 5 l/min

Fig.4 Bead and voltage signal with reduction of gas flow rate



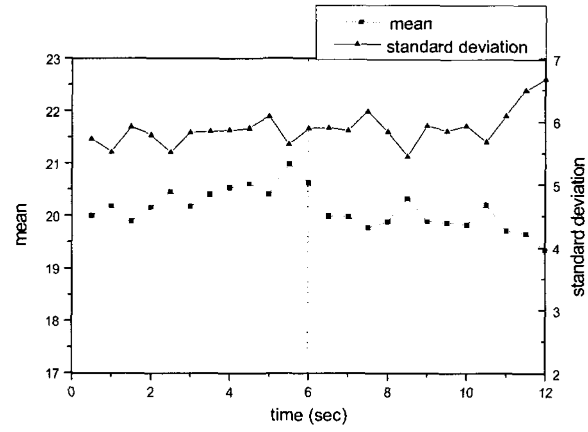
(a) Mean value and standard deviation



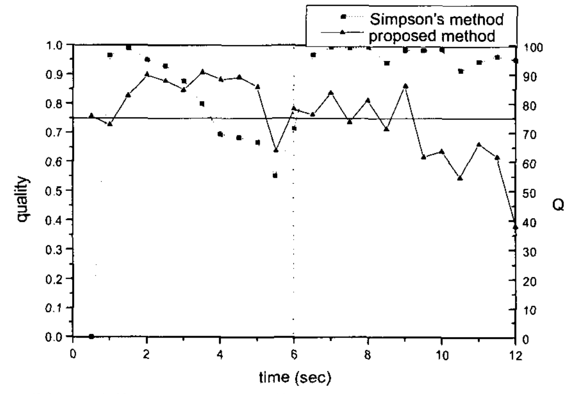
(b) Weld quality indices using Simpson's and proposed methods

Fig.5 Comparison of weld quality assessment method for shielding gas reduction

When the bead-on-plate welds were made on the specimen whose surface was contaminated using the grease, the signal processing results are illustrated in Fig. 6. After 6 seconds, the arc passes through the contaminated region. As seen in Fig. 6(a), the mean and standard deviation do not vary significantly, and it is difficult to determine weld quality from these values. The Simpson's method does not produce the consistent results (Fig. 6(b)) because similarity is affected by the mean value. The quality index of the proposed method decreases at 5.5 seconds, and it drops below 75 at 8.5 seconds. Based on the results, the proposed method predicts weld quality more accurately than the Simpson's method.



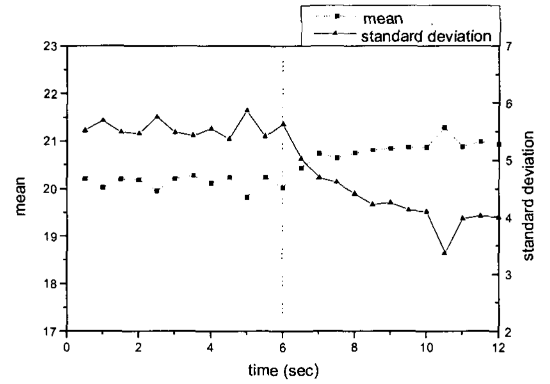
(a) Mean value and standard deviation of the voltage



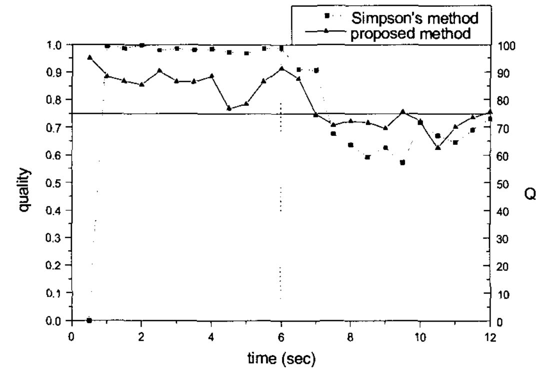
(b) Welding quality indices using Simpson's and proposed methods

Fig.6 Comparison of weld quality assessment methods for contaminated surface

Fig. 7 shows the results when the butt joint has a 2mm gap after 6 seconds. After 6 seconds, the mean welding voltage increases because the arc length is increased due to sagging of the weld pool. As the short-circuit frequency decreases, the standard deviation is reduced in Fig.7(a). Both Simpson's and proposed methods show the similar trends in Fig.7(b), and predict the weld quality with reasonable accuracy.



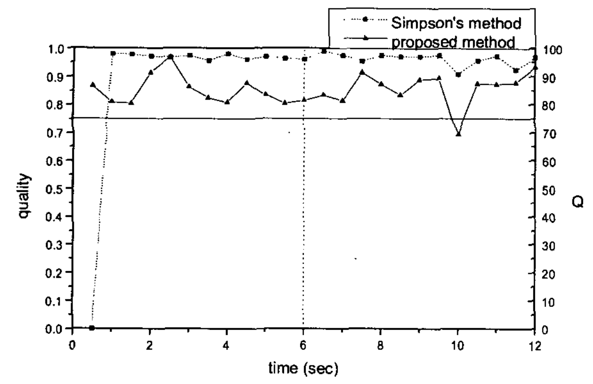
(a) Mean value and standard deviation



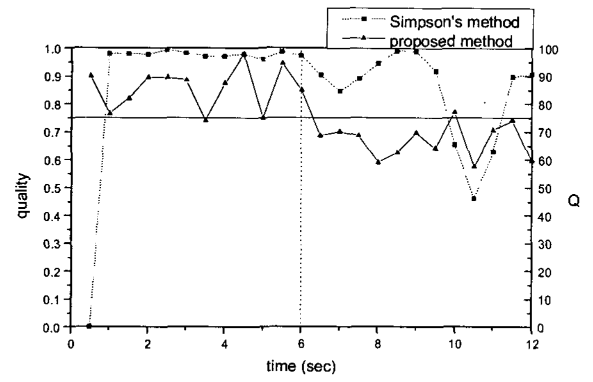
(b) Welding quality indices using Simpson's and proposed methods

Fig.7 Comparison of weld qualtiy assessment methods for butt joint having 2mm gap

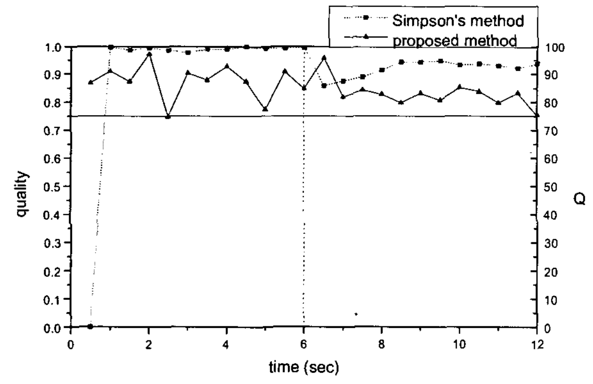
In the case of the fillet joint using the specimens having the gap of 2, 4 and 5mm, the results of the Simpson's and proposed methods are compared in Fig. 8. For 2mm gap, both methods predict that the weld quality is acceptable in Fig. 8(a). When the gap is increase to 4mm, the indices predicted by both methods decreases to indicate the improper weld quality. However, both methods predict the acceptable weld quality for 6mm gap. In this case, the bead-on-plate welds were made instead of the fillet welds because of large gap, and both methods are not able to recognize the difference between the welding voltage signals of fillet and bead-on-plate welds.



(a) Results of fillet joint for 2mm gap



(b) Results of fillet joint for 4mm gap



(c) Results of fillet joint for 5mm gap

Fig.8 Comparison of weld quality assessment methods for fillet joint

Based on the experimental results, the proposed method predicts the weld quality more accurately than the Simpson's method though the latter may not be fully optimized. Comparing the processing time, the proposed method is much faster than the Simpson's method by 15 times because it requires only simple subtraction to calculate the time derivatives of voltage signal.

5. Conclusion

A weld quality assessment method is presented in this work, which can be applied to the short-circuit mode in GMAW. Information about the welding signal trajectory, distribution of the signal duration at each sub-regions and short-circuit frequency is used to evaluate the weld quality. Performance of the proposed method is compared with the Simpson's method experimentally, and the proposed method predicts the weld quality with reasonable accuracy in real time. Further modification and extension to other metal transfer modes are needed as a further study.

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