A Study on a Dual-Electromagnetic Sensor System for Weld Seam Tracking of I-Butt Joints

J.-W. Kim and J.-H. Shin

Abstract

The weld seam tracking system for arc welding process uses various kinds of sensors such as arc sensor, vision sensor, laser displacement sensor and so on. Among the variety of sensors available, electro-magnetic sensor is one of the most useful methods especially in sheet metal butt-joint arc welding, primarily because it is hardly affected by the intense arc light and fume generated during the welding process, and also by the surface condition of weldments. In this study, a dual-electromagnetic sensor, which utilizes the induced current variation in the sensing coil due to the eddy current variation of the metal near the sensor, was developed for arc welding of sheet metal I-butt joints. The dual-electromagnetic sensor thus detects the offset displacement of weld line from the center of sensor head even though there's no clearance in the joint. A set of design variables of the sensor was determined for the maximum sensing capability through the repeated experiments. Seam tracking is performed by correcting the position of sensor to the amount of offset displacement every sampling period. From the experimental results, the developed sensor showed the excellent capability of weld seam detection when the sensor to workpiece distance is near less than 5 mm, and it was revealed that the system has excellent seam tracking ability for the I-butt joint of sheet metal.

Key Words : Dual-electromagnetic sensor, Weld seam tracking, Electromagnetics, Eddy current, Induced voltage, Exciting current, Sensor to workpiece distance, Permeability, Scanning range, Butt joint.

1. Introduction

The modern robotic or mechanized welding machine, in its many shapes and forms, has become commonplace in the automobile and heavy machinery manufacturing scene. Utilizing the latest computer and machine technology, today's welding robots provide efficiency. Despite these significant achievements, the modern welding robot is ultimately a limited mechanism, handicapped by its inability to perceive its surroundings. To teach an industrial robot to weld, for example, a human operator must move the robot's torch along the path of a joint. The robot records the motions of the torch and can repeat them when so commanded by the operator [1]. Theoretically, if all the conditions encountered on an assembly line are taught during the training session, the robot will carry out the task flawlessly. In practice, however, quality welds are difficult to achieve.

A major drawback of robotic welding is that custom-built fixtures must be used to position parts during an industrial welding operation. If the fixturing fails to place a part's joint in the exact position and orientation expected, the robot will weld in the wrong place, resulting in a rejected part [1]. Additionally, if a new part is to be produced, new fixture must be designed and installed. As a result, robotic welding isn't economically feasible unless a large number of identical parts are to be produced.

Several sensing techniques have been investigated to overcome these limitations. These sensors track dynamic variations in the position of the joint from the preprogrammed path. Torch path is then altered to position the weld on the joint. Currently, joint tracking systems with laser stripping [2,3] and through-the-arc sensing techniques are commercially available [4,5]. Our research team investigated a joint tracking concept that usages an electro-magnetic sensor [6]. The electro-magnetic sensor, which utilizes the induced current variation in the sensing coil due to the eddy current variation of the metal near the sensor, determines the positioning imperfections by sensing the induced current variation during scanning the sensor across the sheet metal butt-joints. In this study, a dual-electromagnetic sensor is proposed, which is able to detect the offset displacement of weld line from the center of sensor head without scanning motion even though there's no clearance in the joint.

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2. Design of a dual-electromagnetic sensor

2.1 Principle of dual-electromagnetic sensor

An alternating current (I_1) of the exciting (upper) coil in the sensor head, generates a magnetic flux (ϕ_1) as shown in Fig. 1(a) [6,7]. Let the sensor move onto the plate of the conducting material, the magnetic flux (ϕ_1) induces an eddy current (I_2) in the plate and a magnetic flux (ϕ_2) is also generated in such a direction that it opposes the flux from the coil, as shown in Fig. 1(c). This phenomenon is known as "Lenz's law" [8,9]. The opposite magnetic flux (ϕ_2) resulting from the eddy current decreases the magnetic flux (ϕ_1) in magnitude. Consequently, the final magnetic flux of the coil is defined as ϕ_3 which is smaller than the original magnetic flux (ϕ_1), as shown in Fig. 1(d). Therefore, the induced voltage on the sensing (lower) coil in the sensor head decreases, i.e., $V_1 > V_2$, and depends on the distance between the sensor and the metal, shape, continuity, conductivity, permeability of the metal, etc [10,11]. Considering this principle, it is possible to detect the weld line of the butt joints.

Fig. 2 shows the schematic draw of dual-electromagnetic sensor, which is able to detect the offset displacement of weld line from the center of the sensor head without scanning motion. On corresponding the center position of sensor to the weld line, the induced voltages from sensing coil #1 and #2 are identical, thus the sensing voltage which is defined as the difference between the induced voltages results in 0 V. As the center position of the sensor gets aside from the weld line, however, the sensor results in output voltage which is proportional to the amount of the offset displacement, and the sign of the output voltage represents the direction of the displacement.

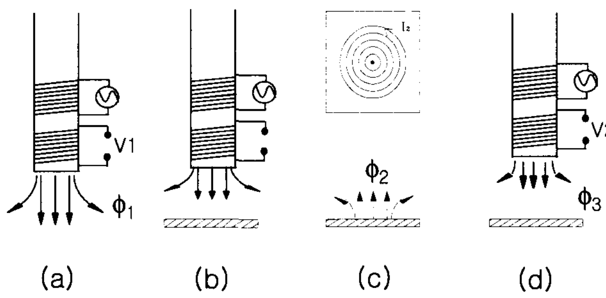

Fig. 1 Eddy current generation and change of induced voltage

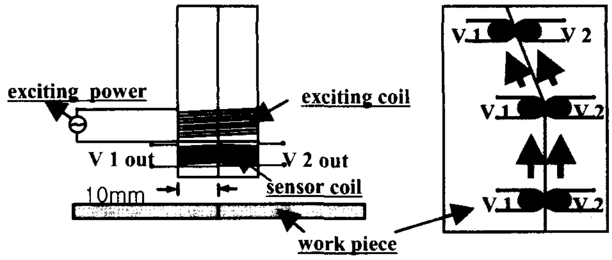

Fig. 2 Structure of dual-electromagnetic sensor

2.2 Output signal of the sensor

Since the induced output voltages from the sensing coils show very small magnitude of the order of several hundreds mV, the output signals are amplified with the factor of 13 times. The alternating output signals are rectified to the direct current (DC) signals, and then the signals are smoothed by a low-pass-filter with the cut-off-frequency of 15Hz to remove the noise [12].

Fig. 3 shows the output signals of left and right sensors during scanning the sensor head across the weld seam. It can be seen that the signal waves are symmetrical each other and the output voltages are identical at the weld seam. By using these signals, difference voltages of right sensor from left one ($V_L - V_R$) result in a useful signal as shown in Fig. 4. As the center of sensor head is coming on the weld line, the difference voltage is becoming zero. When the center of the sensor head is on the left side of weld line, the sign of the signal is negative, and on the right side the sign is positive. The negative or positive extreme value has been resulted when the right or left sensor is just on the weld line respectively. Therefore the position of weld seam can be detected by using the difference voltage of the dual-sensor when the weld line is located between the centers of the sensors. The amplitude of the dual-sensor signal, however, depends on the distance of sensor to workpiece. The signals, thus, have to be modified mathematically as a function of sensor to workpiece distance for extracting the exact position of weld seam from the sensor output.

2.3 Determination of the sensor design variables

To design the sensor, the following variables must be employed as the main set of factors;

1) core diameter of the sensor coil
2) number of windings

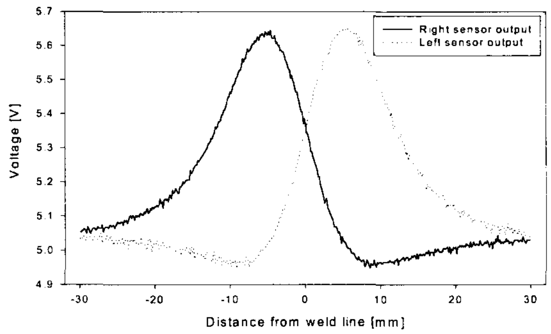

Fig. 3 Output signals of left and right sensing coils

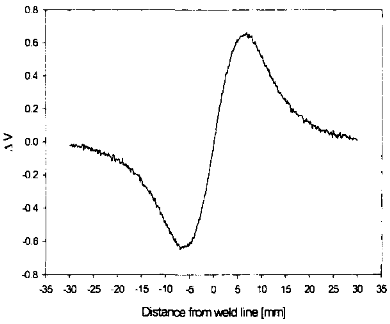

Fig. 4 Differentiation of right and left sensor output

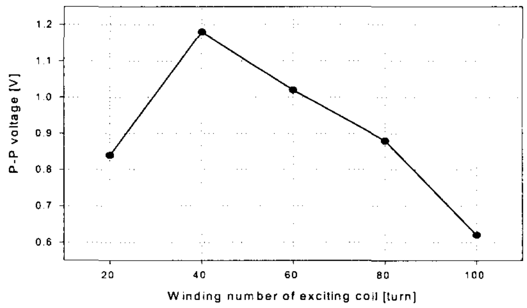

Fig. 5 P-P voltage relative to the winding number of exciting coil(Sensing coil = 40 turn)

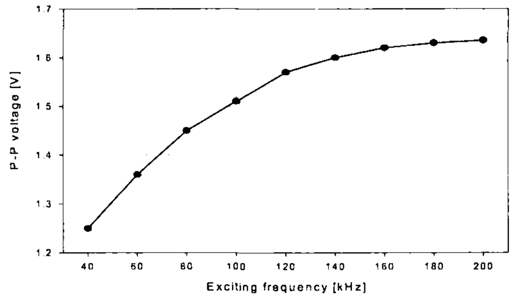

Fig. 6 P-P voltage relative to the exciting power frequency

3) frequency of exciting current

The detecting range of dual-sensor is set to the distance between the sensor coil centers. The diameter of the core was thus determined as 9.6 mm since the aiming detecting range was 10 mm in this study. Two ceramic ferrite cores which have 40 turns of sensing coil respectively are wound together with the exciting coil. Fig. 5 shows the peak-to-peak (p-p) voltages of the dual-sensor signal like as that in Fig. 4, according to the winding number of exciting coil. In this figure, p-p voltage shows its maximum at 40 turns of winding. However, since there was severe noise in the signals as the number of winding decreased, the winding number of exciting coil was determined as 60. Fig. 6 shows the p-p voltage according to the exciting current frequency and the p-p voltage becomes to be saturated with increasing the frequency. The frequency of exciting current power was set on 140 kHz.

2.4 Effect of sensor to workpiece distance

Fig. 7 illustrates the dual-sensor signals according to the sensor to workpiece distance of which range is from 1 mm to 5 mm. As the distance is decreased, the difference voltage and then the sensitivity of the sensor is growing. The p-p voltage according to the sensor to workpiece distance is shown in Fig. 8. From the figures, the small distance is better for increasing the accuracy of weld line detection. However, to get rid of collision of sensor head with bump of the workpiece or tack weld, 3 mm or longer sensor to workpiece distance is required.

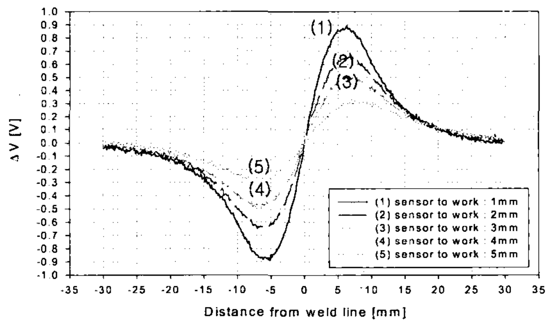

Fig. 7 Sensor output signals relative to the sensor-to-workpiece distance

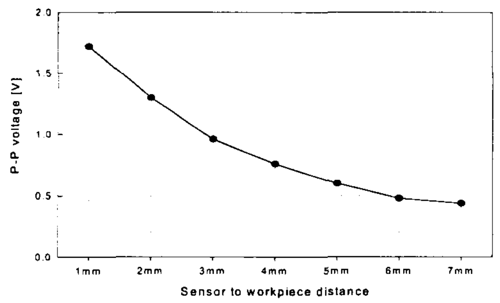

Fig.8 P-P voltage relative to the sensor-to-workpiece distance

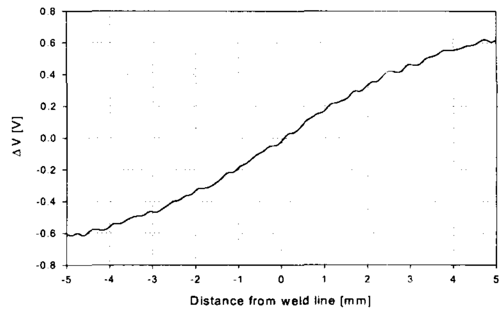

Fig. 9 Sensor output signals at the interesting range

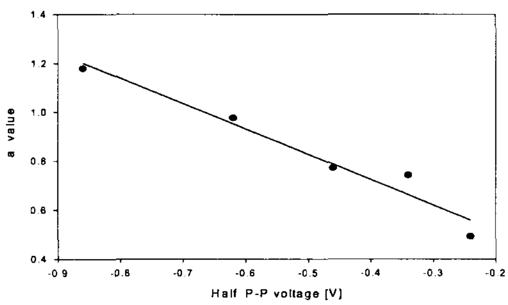

Fig. 10 Relationship between coefficient a and half of p-p voltage

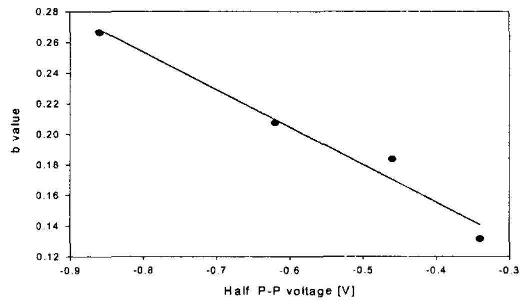

Fig. 11 Relationship between coefficient b and half of p-p voltage

3. Construction of the weld seam tracking system

3.1 Mathematical modeling

The detecting range of dual-sensor can be set to the distance between the sensor coil centers, and then the typical sensor output signal in the range is shown in Fig. 9. The curve in Fig. 9 can be represented as a exponential function, thus fitted to the equation (1) where y is the distance from weld line.

$$\Delta V = a \cdot (1 - \exp(-b \cdot y)),\ 0\ \text{mm} \le y \le 5\ \text{mm} \qquad (1)$$

where the constants a and b can be determined according to the sensor to workpiece distance. The relationship between the sensor to workpiece distance and p-p voltage is as shown in Fig. 8, Thus the relationship between a or b and p-p voltage could be derived as the equation (2) by using the curve fitting method.

$$a = -0.8921 \cdot (\text{p-p voltage} / 2) + 0.4092$$
$$b = -0.2452 \cdot (\text{p-p voltage} / 2) + 0.0574 \qquad (2)$$

These relations are shown in Fig. 10 and 11. Finally, the weld line position (y) can be obtained by using the following equation and the sensor output (ΔV).

$$y = -1 / b \cdot \ln (1 - \Delta V / a) \qquad (3)$$

3.2 Weld seam tracking system

The deviation of sensor position from the weld line can be estimated from the sensor output by using the equation (3) and compensated by moving the sensor position as much as derived deviation, The system consists of the sensor device for detecting the weld line, the servo control device for driving the sensor movement, and a personal computer. The personal computer is used as a system controller which includes sensor signal processing. And pulse generator which controls the servo motors was connected to the personal computer. The sensor head moves at constant speed in X-direction, and the position is compensated for tracking in Y-direction at every sampling time. The system sampling time was set to 0.05 sec and the block diagram of the system is illustrated in Fig. 12.

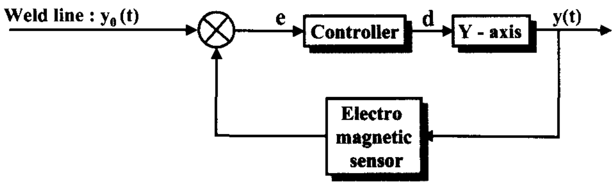

Fig. 12 Block diagram of the weld seam tracking system

4. Result of weld seam tracking

The experiments are carried out by using the butt joint of a slant weld line with an angle of 8.5° after straight weld seam of 80 mm along the X-axis. Fig. 13 shows the weld seam tracking result in the case of X-axis speed of 7 mm/s and sensor to workpiece distance of 3 mm. The excellent seam tracking result can be seen from the figure and the tracking errors are within ±0.3 mm. Fig. 14 shows the result in the case of sensor to workpiece distance of 5 mm. Comparing to the case of 3 mm sensor to workpiece distance, it shows deteriorated tracking performance due to the lower sensitivity according to the longer sensor to workpiece distance. The tracking errors in this case are within ±0.7 mm.

Fig. 15 shows the tracking result in the case of X-axis speed of 10 mm/s and sensor to workpiece distance of 3 mm. It shows worse tracking performance than that in the case of 7 mm/s traverse speed. The tracking errors in this case are within ±0.5 mm, however the result shows better tracking performance than that in the case of 5 mm sensor to workpiece distance.

Fig. 16 is the result in the case of a weldment which has mismatched weld seam and the same sensor to workpiece distance and speed with Fig. 13. The heights of weldment surface at the both ends are the same, but there is 2 mm height difference at the middle of weld seam (X = 70 mm). This is for modifying the situation of thermal distortion during welding and mismatching at weldment set-up. However the mismatched weld seam hardly affects to the weld seam tracking performance of the sensor system. This is considered due to the fact that mismatch affects to the p-p voltage but not to the position of weld line.

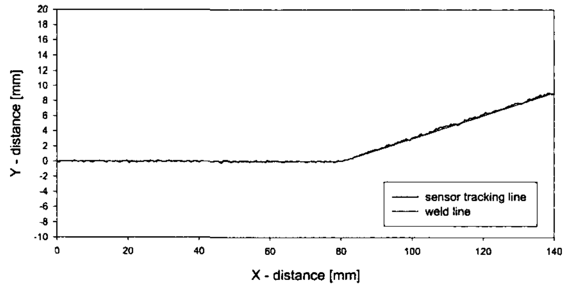

Fig. 13 Weld seam tracking result
(sensor-to-workpiece distance; 3mm, speed; 7mm/s)

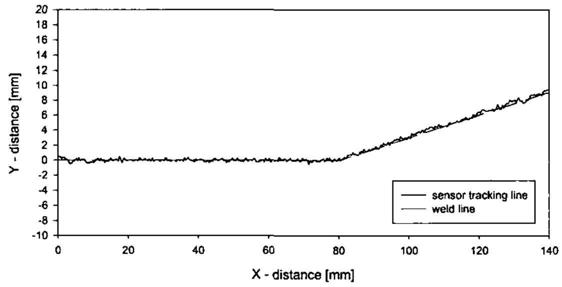

Fig. 14 Weld seam tracking result
(sensor-to-workpiece distance; 5mm, speed; 7mm/s)

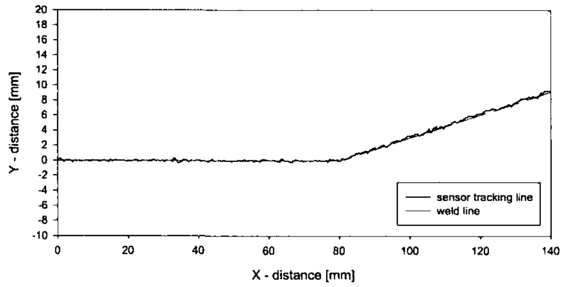

Fig. 15 Weld seam tracking result
(sensor-to-workpiece distance; 3mm, speed; 10mm/s)

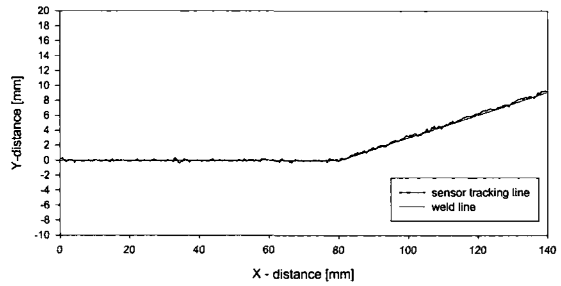

Fig. 16 Weld seam tracking result
(mismatch of weld joint; 2 mm)

5. Conclusion

A dual-electromagnetic sensor system for weld seam tracking was designed and constructed, by which the deviations of sensor position from weld line were detected and automatic weld seam tracking was implemented. The followings are concluding summaries:

1) Through a series of experiments, the detection capabilities of the weld line depending on the design parameters of the dual-electromagnetic sensor are evaluated. And then the winding number of exciting and sensing coils were set to 60 and 40 respectively, and the frequency of the exciting current power was set to 140 kHz as the optimum design values.
2) A dual-electromagnetic sensor was proved to be able to detect the deviation of sensor from weld line without scanning motion, and an equation for the relation between the deviation of sensor from weld line and the sensor output was derived by using the mathematical modeling
3) It was revealed that the tracking capability depends mainly on the sensor to workpiece distance but hardly on mismatch of weld seam. Thus, this system is considered to be suitable for the butt weld joint of thin plate which has no gap or irregular gap.
4) The automatic seam tracking system developed in this study showed an excellent seam tracking capability in the case of sensor to workpiece distance of 3 mm, thus it is considered that the system can be applied to the production lines of arc welding processes.

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