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Characteristics of Welding and Arc Signal in Narrow Groove Gas Metal Arc Welding Using Electromagnetic Arc Oscillation

Experiments produce optimum parameters for obtaining uniform and sufficient groove face penetration

BY Y. H. KANG AND S. J. NA

ABSTRACT. Narrow groove welding is an important technique for increasing productivity in the manufacture of thick-walled components. The nature of the process demands an automated approach and precise control to ensure consistently high weld quality. The most important objective of narrow groove welding is to maintain uniform and sufficient penetration at both groove faces. Several different approaches, such as wire bending technique and wire rotating method, have been adopted in an attempt to minimize the incomplete fusion in the narrow groove GMAW process. In this study, a welding system using electromagnetic arc oscillation was developed for narrow groove welding. The electromagnet for applying a magnetic field to the welding arc was designed from the electromagnetic analysis results. This paper shows the arc and head characteristics in narrow groove GMAW using electromagnetic arc oscillation. Based on the results, the appropriate welding and oscillation conditions were selected to satisfy high weld quality. Consequently, magnetic arc oscillation resulted in uniform and sufficient penetration to both groove faces. Arc signal characteristics for automatic joint tracking were also investigated. The periodic change of welding current in electromagnetic arc oscillation was examined by experiments and numerical analysis. To establish the mathematical model of the arc sensor, some assumptions were needed to calculate the arc length. Analytical results using these assumptions showed good agreement with experimental ones. The periodic signal was adopted to develop an automatic joint tracking system in narrow groove GMAW.

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Introduction

A magnetic field externally applied to a welding arc deflects the arc by electromagnetic force (Lorentz force) in the plane normal to the field lines. The magnetic field exerts the force on the electrons and ions within the arc, which causes the arc to be deflected away from the normal arc path. The welding arc can be deflected forward, backward, or sideways with respect to electrode and welding direction, depending upon the direction of the external magnetic field. A transverse magnetic field deflects the arc in the welding direction, whereas a longitudinal magnetic field deflects the arc perpendicular to the bead. If a unidirectional magnetic field is applied to an AC arc, or an alternating field is applied to a DC arc, then the arc can be oscillated in the position normal to the direction of welding, and this has been used to improve the arcs with both gas tungsten arc welding (GTAW) and gas metal arc welding (GMAW) (Ref. 1). Oscillating the arc sideways with respect to the welding direction could be used for strip cladding and welding of materials that are sensitive to hot cracking because this gives a wide bead and uniform and shallow penetration (Refs. 2, 3). Subjecting the welding arc to transverse magnetic fields increases the welding speed several times, at which rate undercut-free and no-porosity welds can be made (Ref. 4). Also, magnetic arc oscillation could be applied to high-speed joint tracking because the magnetically oscillating arc possesses virtually no inertia (Ref. 5).

KEY WORDS

Narrow Groove Welding
GMA Welding
Electromagnetic Arc Oscillation
Automated Welding
Arc Sensor
Joint Tracking

Narrow groove welding is an important technique for increasing productivity in the manufacture of thick-walled components. Narrow groove welding has many advantages such as high productivity and quality, minimal distortion, and all-position capability. But incomplete fusion into groove faces is the most frequent defect in narrow groove GMAW due to the low heat input and small molten weld pool. In order to improve the weld quality, an arc weaving technique has to be used. Arc length control and weld joint tracking are also needed because the weld quality is sensitive to any disturbance of the arc. Therefore, the nature of the process demands an automated approach and precise control to ensure consistently high weld quality. The most important objective of narrow groove welding is to maintain uniform and sufficient penetration at both groove faces. Several different approaches have been adopted in an attempt to minimize the incomplete fusion in the narrow groove GMAW process (Refs. 6–9). To improve the groove face fusion, the electrode may be oscillated by adopting a wire bending technique in which the bending direction is periodically changed,

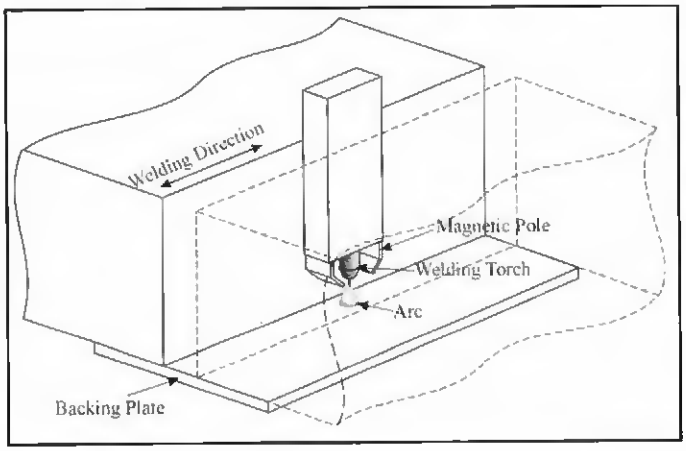

Fig. 1 — Narrow groove welding using electromagnetic arc oscillation.

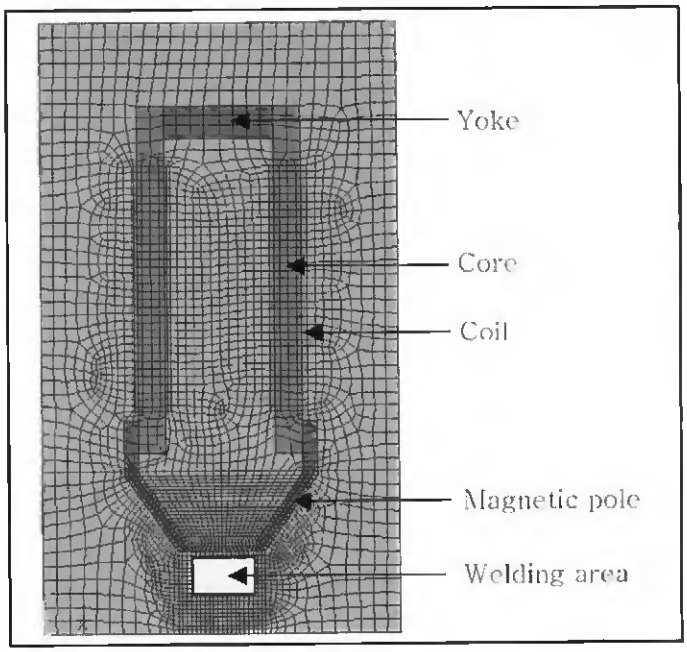

Fig. 2 — Finite element method model of the electromagnet.

or alternatively (Ref. 6), a wire rotating method in which an eccentric contact tip is rotated (Ref. 7). These systems are effective on penetration at both groove faces, but the former system is relatively complex; the number of oscillations is limited, and the wear resistance of the contact tip is low. In the case of the latter, the minimum root opening is often limited by the need to rotate the whole welding head, and the rotation of the eccentric contact tip may cause the welding head to vibrate, especially in deep groove welding.

In this study, a welding system using electromagnetic arc oscillation was developed for narrow groove welding. The welding arc was periodically oscillated by the electromagnetic force in the plane normal to the magnetic field lines when an alternating magnetic field is applied. With the magnetic arc oscillation method, it is easy to control the weaving width and frequency by controlling the magnitude and frequency of current applied to the electromagnet. The frequency of arc oscillation is the same as that of the controlling magnetic field. This paper shows the arc and bead characteristics in narrow groove GMAW using electromagnetic arc oscillation. Arc signal characteristics for automatic joint tracking were also investigated. The periodic change of welding current with electromagnetic arc oscillation was examined by experiments and numerical analysis and adapted to develop an automatic joint tracking system in narrow groove GMAW.

Development of Welding Head and Electromagnet

A schematic diagram of electromagnetic arc oscillation in narrow groove welding is shown in Fig. 1. The magnetic field is applied to the welding arc in parallel to the welding direction and the arc is deflected sideways with respect to the welding direction. If an alternating field is applied to the arc, it can be oscillated over the weld pool in a position normal to the direction of welding. The width of an arc oscillation is dependent upon the flux density of the applied magnetic field, the arc current, and the arc length (Refs. 4, 10).

Electromagnetic analysis was performed for the design of electromagnets used in narrow groove GMAW. Figure 2 shows the FEM model of the electromagnet composed of core, coil, yoke, and magnetic pole. The required maximum magnetic flux density in the welding area is about 200 gauss because flux density loss occurs in narrow groove welding of ferromagnetic materials such as mild steel. Figure 3 shows the analysis results under conditions of 450 coil turns and 1.2 A current on the coil. The magnetic flux lines are shown in Fig. 3A and the distribution of magnetic flux density in the welding area is shown in Fig. 3B. As can be seen from Fig. 3A, the loss of magnetic flux occurs at the side of the core because the distance between both cores is almost the same as that of both magnetic poles. But the density at the center of the welding area is more than 300 gauss (0.03 tesla), which is enough for arc oscillation, as shown in Fig. 3B. The electromagnet used in narrow groove welding could be designed from these results.

The narrow groove GMA welding head is shown in Fig. 4. The electromagnet is built into the welding head. The welding head is 6 mm thick, and the surface of the welding tip is coated with ceramic. Consequently, the body is insulated from the welding tip. The length and width of the welding head are 160 mm and 60 mm, respectively, while the length is dependent on the thickness of material welded. A welding tip made of copper with high thermal conductivity is cooled by forced water flow to prevent its temperature from rising above its melting temperature. Shielding gas is also supplied through side holes. The magnetic arc oscillation controller controls oscillation frequency and width.

Welding Characteristics of Electromagnetic Arc Oscillation

One feature of magnetic arc oscillation is the decentralized physical effects of the arc, which provides a wide bead and uniform and shallow penetration. This also can be obtained by mechanically rotating the arc. Therefore, uniform and sufficient penetration to both groove faces was obtained with this narrow groove welding process.

Arc Images

The magnitude of magnetic arc deflection was measured with a high-speed video camera. The welding experiments were made in a square-groove butt joint with a 10-mm root opening under the following conditions: a welding current of 280 A, welding voltage of 31 V, travel speed 22 cm/min, contact tip-to-workpiece distance 15 mm, and arc oscillation frequency 30 Hz. Figure 5 shows the images of the arc column during narrow groove welding at magnetic flux densities of 25 gauss, 50 gauss, and 75 gauss. Assuming oscillation width as the offset of the arc centerline, the oscillation width increases with in-

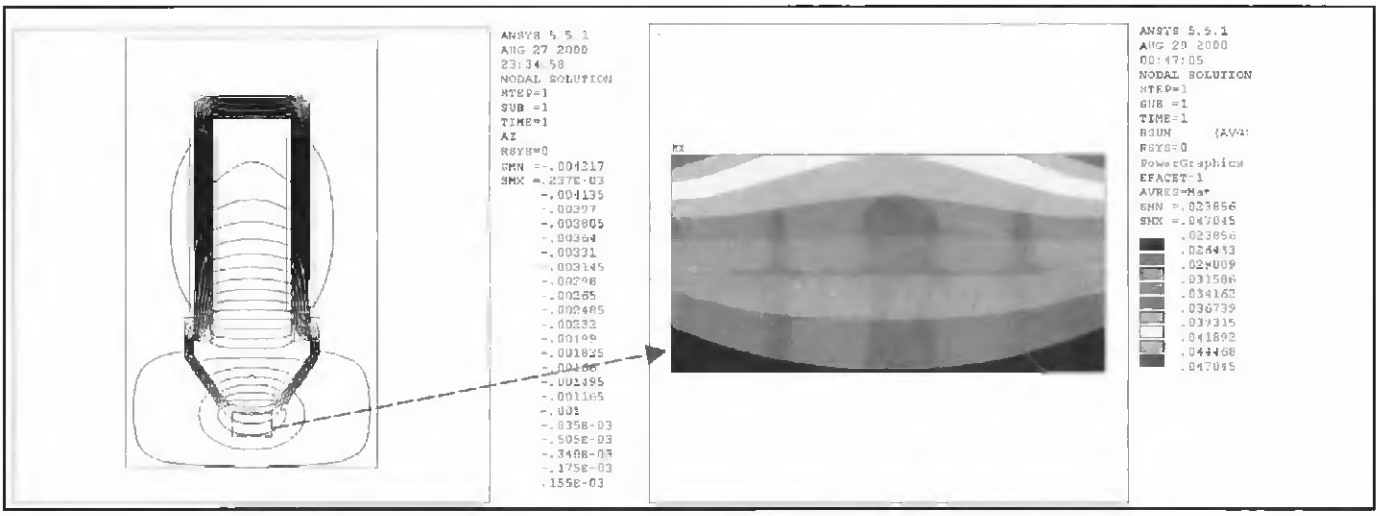

Fig. 3 — Magnetic flux lines and distribution of magnetic flux density in the welding area.

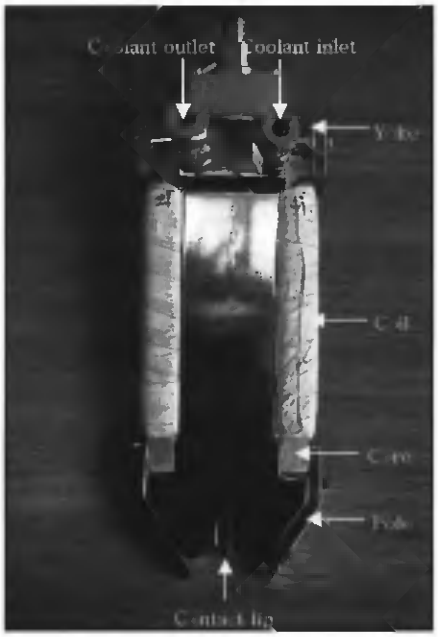

Fig. 4 — Narrow groove GMA welding head.

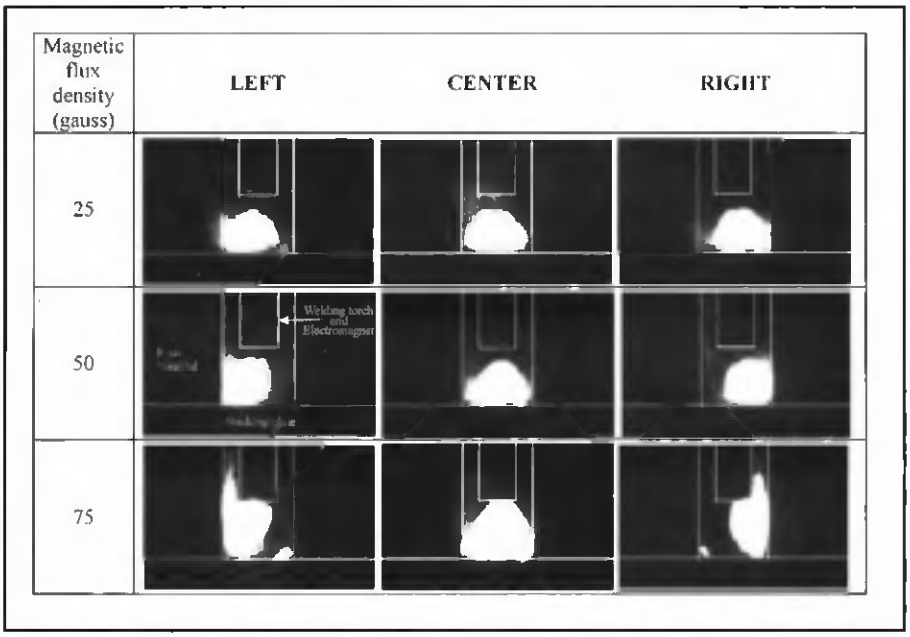

Fig. 5 — Arc column images for various oscillation widths during narrow groove welding.

creasing flux density. The oscillation width was small at a density of 25 gauss, and oscillation effect could not be expected. At 75 gauss, the width was too large and undercut at the groove face could be expected. The deflected arc is directed toward the corner between the weld material and the backing plate at a density of 50 gauss.

Figure 6 shows images of the arc column for root openings of 8 and 10 mm. Despite operating under the same welding conditions and with the same magnetic flux density, the arc shape and oscillation width are very different from each other if the root opening decreases from 10 to 8 mm. In the 8-mm root opening, the deflected arc occurred between wire tip and groove wall.

Formation of Weld Bead

The influence of welding parameters on weld bead formation using electromagnetic arc oscillation was investigated. The examined parameters were oscillation frequency and magnetic flux density (or oscillation width) applied in the welding area. Macrosections of weld beads under various oscillation frequencies from 0 to 50 Hz are shown in Fig. 7. The figure clearly indicates the side penetration P with arc oscillation is deeper than without oscillation. Side penetration P slightly increased and the penetration H decreased with increased arc oscillation frequency.

The relationship between magnetic flux density and bead formation was investigated. The density was varied from 0 to 75 gauss by changing current applied to the electromagnet. The oscillation frequency was fixed at 30 Hz, and the other welding conditions were the same as in previous experiments. Macrosections obtained from this experiment are shown in Fig. 8. Increased density caused increased oscillation width, as mentioned previously. The penetration to groove faces, therefore, increased with increased magnetic flux density. In conventional straight welding without magnetic arc oscillation, the side penetration P was especially small, while the penetration H was very large. But at a density of 75 gauss, undercut occurred at both groove faces. The maximum magnetic flux density would be limited to 50 gauss under the welding conditions in this experiment with a 10-mm

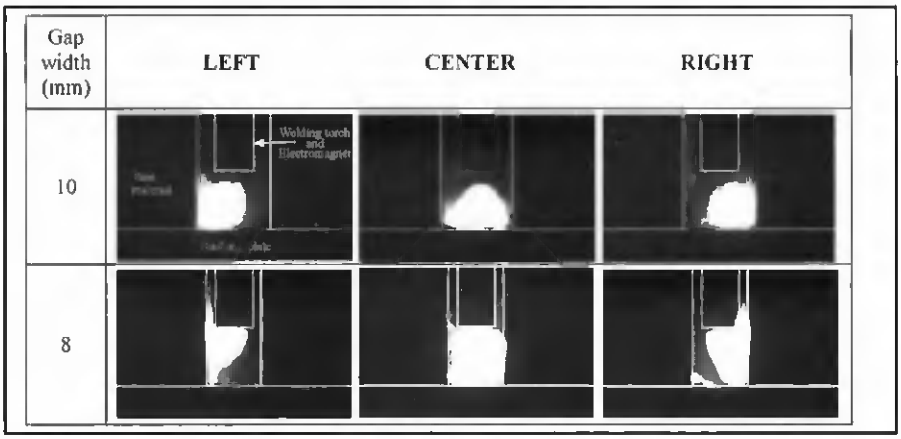

Fig. 6 — Arc column images for various root opening widths during narrow groove welding.

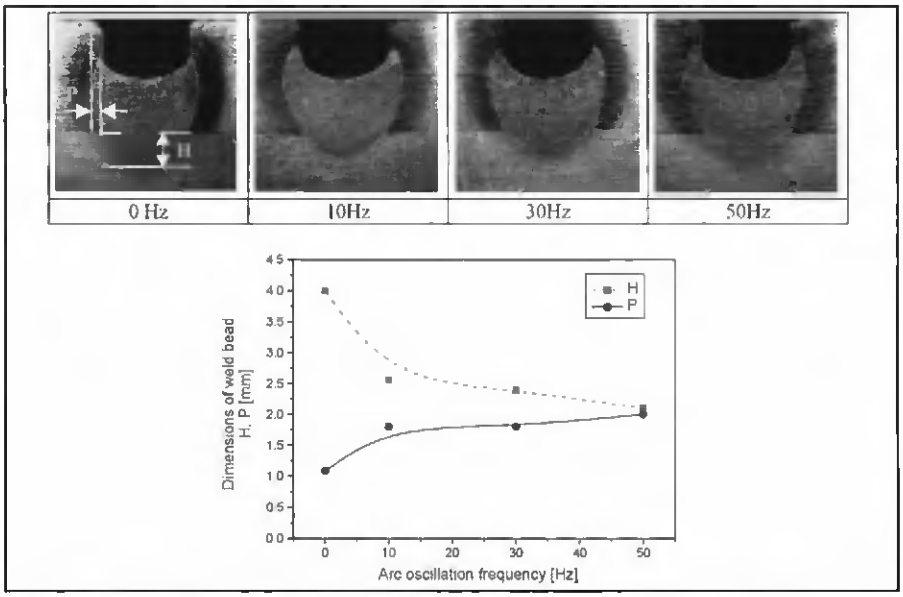

Fig. 7 — Effect of oscillation frequency on bead shape (magnetic flux density = 50 gauss).

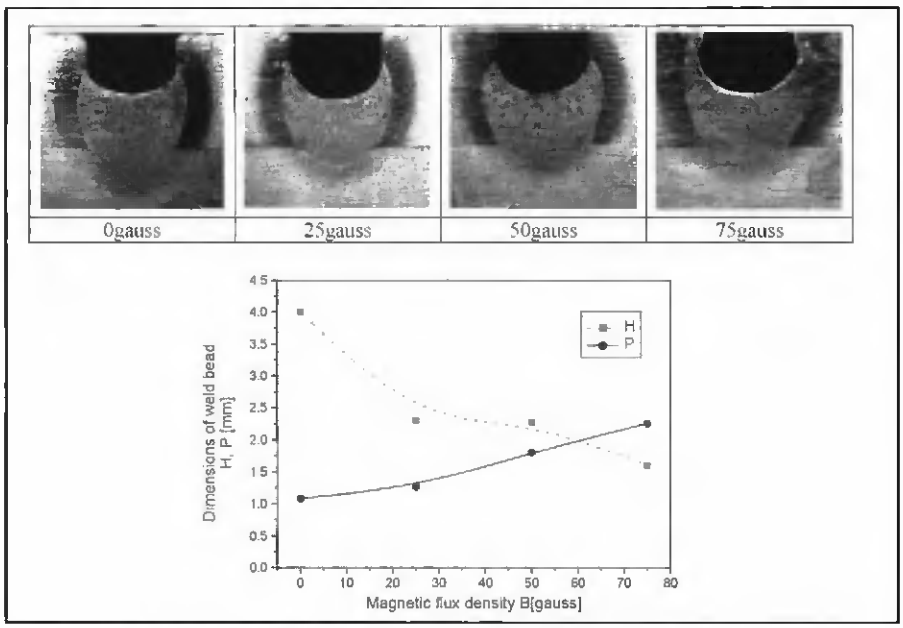

Fig. 8 — Influence of magnetic flux density on bead shape (oscillation frequency = 30 Hz).

root opening for a square groove weld. The same results could be obtained by investigating the images of the arc column — Fig. 5.

Figure 9 shows a macrosection of a thick plate. The thickness of the plate is 22 mm with a 10-mm root opening. A deposition of 4–5 mm per pass was obtained at 280 A, 31 V, and 22-cm/min welding speed. An average depth of side penetration was about 1.7 mm. A stable uniform penetration into the groove faces was secured by using magnetic arc oscillation.

Arc Signal Characteristics for Automatic Joint Tracking

In narrow groove welding, the deviation of the welding wire from the center line of the deep groove directly affects the weld quality. Since the arc sensor system does not need any external sensing device and senses the position of the arc itself, it is preferable for narrow groove welding.

Magnetic arc oscillation leads to a change of arc length, which in turn periodically changes the welding current and voltage. An alternating parallel magnetic field causes the arc to oscillate in a position normal to the direction of welding, which has an effect like mechanical weaving. Welding current variation was investigated during narrow groove GMA welding using magnetic arc oscillation.

Numerical analysis of the arc sensor in narrow groove GMAW was carried out for theoretical prediction. A conventional welding power source can generally be considered equivalent to a constant U_s source with an output resistance K_s and inductance L_s. The welding cable is also characterized by its resistance R_c and inductance L_c. The arc voltage, U_a consists of voltage drops in the anodic zone, cathodic zone, and arc column. Based on the experimental results, it is characterized by a constant component u_{ao}, resistance R_a, and the electric field intensity $E_a(= E_{al} + E_{ai}I)$ of the arc column. E_{al} and E_{ai} represent a constant component of E_a and the component of E_a proportional to current, respectively. Thus, the voltage equations for the whole loop of the welding circuit can be written as follows (Ref. 11):

$$\frac{dI}{dt} = \frac{U_s - u_{ao}}{L_s + L_c} - \frac{K_s + R_c + R_a + R_c}{L_s + L_c} I - \frac{E_{al} + E_{ai}I}{L_s + L_c} L_a \quad (1)$$

where I is the welding current, L_a is the arc length, and R_c the electric resistance of the welding wire extension. The dynamic melt-

ing model of the welding wire is as follows:

$$\frac{dL_e}{dt} = V_f - \frac{AI}{1 - BJ_e} \quad (2)$$

where V_f is the wire feed rate, A and B the coefficients in the wire melting model, and J_e the quantity of Joule heat at the wire tip, as shown in Equation 3.

$$J_e = \int_{t-\Delta t}^{t} I^2(\tau)d\tau \quad (3)$$

As shown in Fig. 10, the arc length L_a is expressed by the geometrical relationship of the deflection angle θ, the contact tip to workpiece distance L_t, the wire extension length L_e, and the distance between the electrode wire and groove face W. Thus, the arc length L_a can be written as follows:

$$(L_t - L_e)\tan\theta \le W \rightarrow L_a = \frac{L_t - L_e}{\cos\theta} \quad (4)$$

$$(L_t - L_e)\tan\theta > W \rightarrow$$

$$L_a = \frac{L_t - L_e}{\cos\theta} - \frac{(L_t - L_e)\tan\theta - W}{\sin\theta} \quad (5)$$

The arc shape and oscillation width vary depending on the root opening width, as mentioned before. Consequently, the arc length changes according to the width. Therefore, the following assumptions were used for calculating the arc length:

a. $W \le Wc$
  1. $La > W \rightarrow$ *Arc length* $= W$
  2. $La \le W \rightarrow$ *Arc length* = *Equations 4 or 5*

b. $W > Wc \rightarrow$ *Arc length* = *Equations 4 or 5*

where Wc is the critical root opening width

The critical root opening width was introduced to calculate the arc length change according to the applied root opening width. The critical width is the critical value that decides whether the arc is influenced by the groove face or the backing plate.

If the distance between the welding wire and groove face W is less than the critical width Wc and if the calculated arc length La is longer than W, the arc occurs between the wire tip and groove wall. If the calculated arc length is smaller than W, however, the arc length is determined by Equations 4 or 5. If W is longer than Wc, the arc length is determined also by Equations 4 or 5.

Waveforms of the welding current were monitored to investigate the relation with the distance between the welding wire and groove faces. Experiments were carried out on a specimen with a single groove face at the right side, as shown in Fig. 11, where the applied magnetic flux density was 50 gauss. In this case, the critical width Wc was determined to be between 4 and 5 mm from the simulation and the experimental results. The peak-to-peak values of welding current increased with decreased distance W because the shortest length of the arc during oscillation was the same as the distance W. If W is less than Wc and the arc is deflected toward the groove face, it is assumed to occur between the wire tip and the groove face. Therefore, flat parts in welding current waveforms were observed at the distance W of 3 and 4 mm. The magnitudes as well as waveforms of welding current in simulation showed a fairly good agreement with the experimental results. In the case of 75 gauss magnetic flux density, for which the critical width Wc was between 5 and 6 mm, the simulation results were also similar to experimental ones, as shown in Fig. 12.

Fig. 9 — Example of macrosection of thick plate welded by NGW using magnetic arc oscillation (thickness 22 mm, root opening 10 mm).

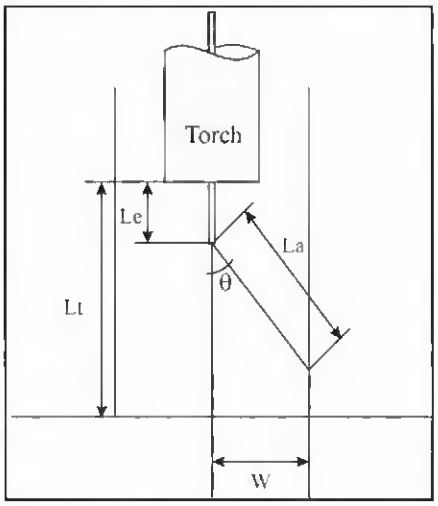

Fig. 10 — Arc length in narrow groove welding.

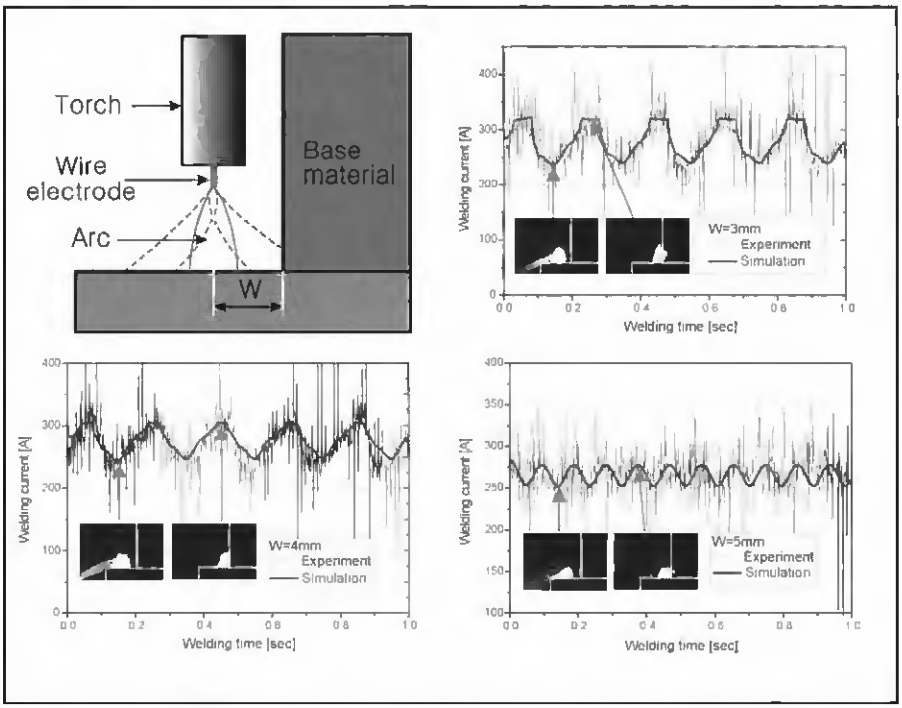

Fig. 11 — Welding current waveforms under various distances between welding wire and groove face at a magnetic flux density of 50 gauss.

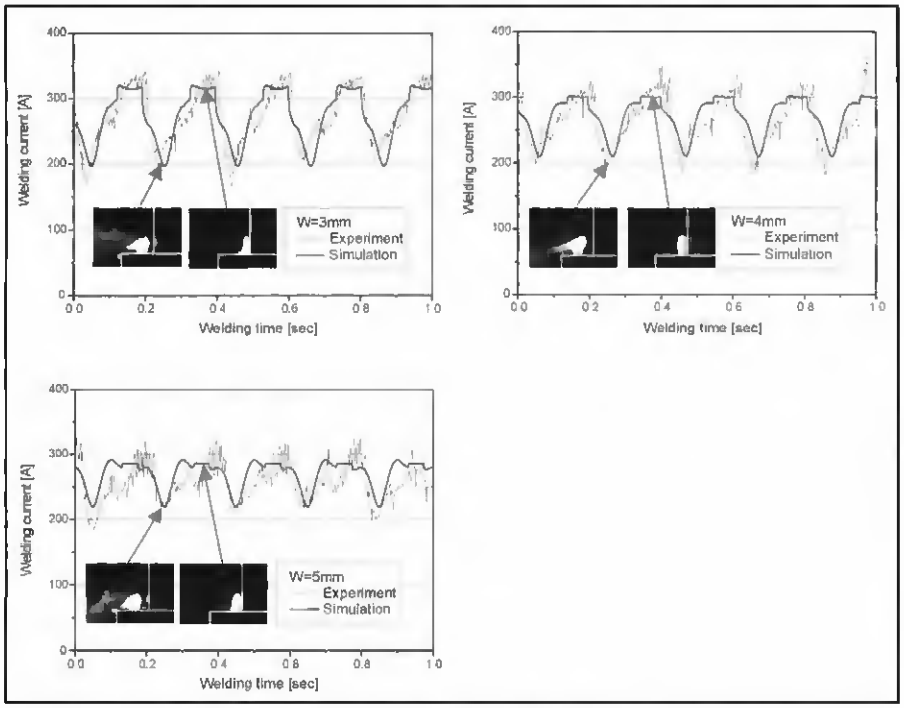

Fig. 12 — Welding current waveforms under various distances between welding wire and groove face at a magnetic flux density of 75 gauss.

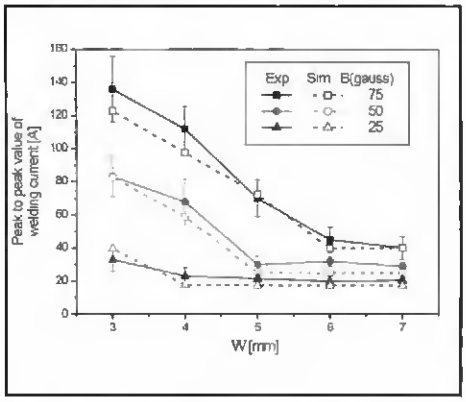

Fig. 13 — Peak-to-peak value of welding current under various distances between welding wire and groove face and various magnetic flux densities.

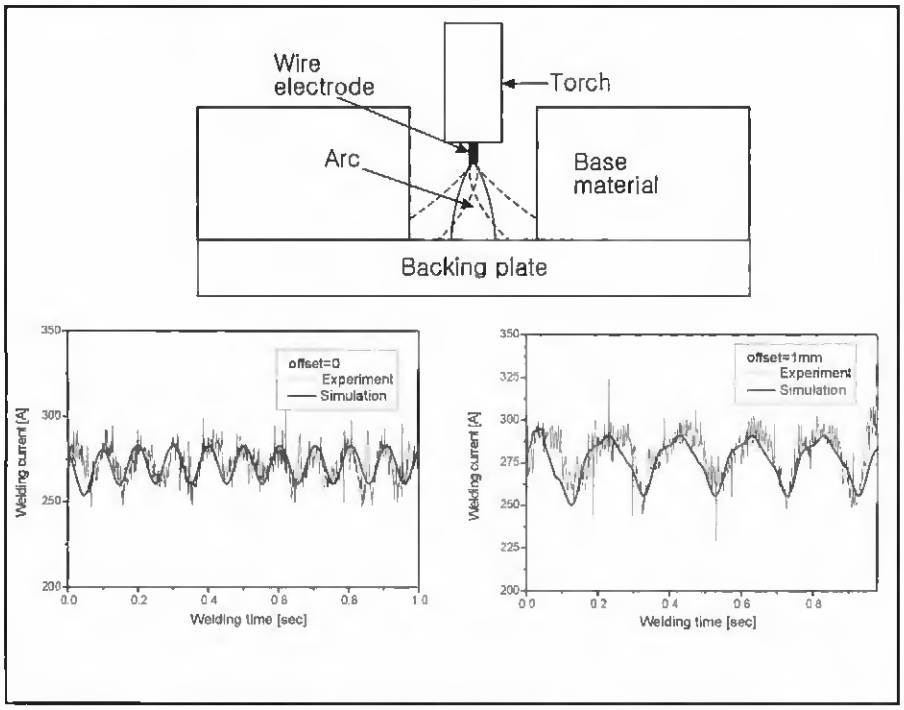

Fig. 14 — Welding current waveforms in narrow groove welding using magnetic arc oscillation (oscillation frequency = 5 Hz).

From the previous experimental and simulation results, it is clearly indicated that by increasing W, the peak-to-peak value of welding current decreased rapidly, up to a distance of 5 mm in 50 gauss and 6 mm in 75 gauss, as shown in Fig. 13. This implies the welding current is seriously affected by the groove face at distances less than the critical width. At 25 gauss, the groove face has almost no effect on the variation of welding current.

The experiments were carried out on a specimen with both groove faces, as shown in Fig. 14. The waveforms of the welding current were monitored under magnetic flux density of 50 gauss and arc oscillation frequency of 5 Hz with a 10-mm root opening for a square-groove weld. Figure 14A shows a welding current waveform for no deviation between the welding head and groove center. Figure 14B shows a waveform that indicates a deviation of the welding head to the right side by about 1 mm. A waveform frequency of 10 Hz showed no deviation. Two similar waveforms of welding current were obtained in one period of arc oscillation. The waveform frequency was 5 Hz for the 1-mm deviation. This periodic change of welding current can be used as the output signal for an arc sensor for automatic joint tracking in narrow groove GMA welding.

Conclusions

Arc shape and bead formation in narrow groove GMA welding were investigated. Based on the results, appropriate welding and oscillation conditions were selected to maintain high weld quality. Magnetic arc oscillation resulted in sufficient penetration to the groove face. The penetration increased slightly with increased arc oscillation frequency. Increased magnetic flux density applied in the welding area caused increased oscillation width. The penetration to the groove face also increased with increased magnetic flux density. But at a density of 75 gauss, undercut occurred at both groove faces. Consequently, the magnetic flux density was limited to 50 gauss under the welding conditions used in this experiment, which included a 10-mm root opening for a square-groove weld.

Magnetic arc oscillation resulted in a change of arc length, which in turn caused the welding current signals to change periodically. Although the signals included

the high-frequency noise of the welding power source, the welding current fluctuation — the basic signal component — produced by magnetic arc oscillation was clearly shown. Basic signal components can be used as the output signal of the arc sensor for automatic joint tracking in narrow groove GMA welding.

Numerical analysis of the arc sensor was also carried out for theoretical prediction. The arc shape and oscillation width varied depending on the root opening width. Some assumptions in establishing the mathematical model of the arc sensor were needed to calculate the arc length. Analytical results using these assumptions showed fairly good agreement with experimental ones.

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