Study on Suppression of Bead-Meandering of Pure Ar-MIG Arc Welding using External Magnetic Field*

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Gas metal arc welding is typically performed by adding a minimal amount of oxygen to the shielding gas to protect the arc; this affects the toughness of the welded joints. This can be avoided by employing pure argon gas as the shielding environment. However, this leads to bead-meandering because the cathode spot on the base metal moves past the molten pool in search of O₂ outside the shielding gas. In this study, we propose a method for controlling the cathode spot by using an external magnetic field for suppressing bead-meandering, the proposed method does not require changing the electrode wire or the shielding gas. Horizontal and vertical external magnetic fields are obtained when using DC and AC external magnetic fields, respectively. A bead-on-plate welding experiment is performed by applying an external magnetic field and using pure Ar as the shielding gas. The effect of the external magnetic field on the stability of the arc, shape of the bead, and penetration depth is evaluated, and the effectiveness of pure Ar-MIG arc welding using external magnetic field is examined.

Key Words: Gas metal arc welding, MIG arc welding, Pure Ar shielding gas, Electromagnetic force, Bead-meandering

1. Introduction

In the existing process of gas metal arc (GMA) welding, which employs an electrode wire, a minimal amount of oxygen (O₂) is added to the shielding gas to protect the arc. The arc is stabilized due to the formation of iron oxide, which emits electrons on the surface of the base metal, that is welded using O₂. However, when this O₂ mixes with the molten metal, the toughness of the welded joint decreases. This toughness of the joint can be improved by reducing the mixing ratio of O₂ with the shielding gas. Generally, the use of pure argon as a shielding gas (pure Ar-MIG arc welding) is preferred. However, the use of pure argon leads to bead-meandering because the cathode spot on the base metal moves past the molten pool in search of O₂ outside the shielding gas 1. Previous studies have focused on improving the welding strength and quality using techniques such as the application of an external magnetic field to the current flowing in the molten pool/arc, leading to the generation of an electromagnetic force. Examples of such studies employing an external magnetic field in the horizontal direction are as follows. Wang et al. reported that the humping bead can be suppressed by generating an external magnetic field in a horizontal direction, because an electromagnetic force, inhibits the backward flow in the molten pool 2. Matsuda et al. found that the penetration depth could be increased by generating an electromagnetic force along the direction of gravity in the molten pool; moreover, they suppressed the burn-through by generating an electromagnetic force in the opposite direction of gravity, for TIG welding 3, 4. In addition, Machida et al. reported that the blow-holes in galvanized steel sheet welding could be suppressed by applying vibrations in the molten pool, using an AC external magnetic field 5. Similarly, researchers have also used an external magnetic field in the vertical direction. Ohmae et al. concluded that metallurgical improvements such as grain refinement were possible by generating a rotation action using the electromagnetic force in the molten pool, for TIG welding 6. In addition, we suppressed the irregular beads in high speed welding employing pure argon as a shielding gas, by generating a rotation action using the electromagnetic force in the molten pool 7. In this study, we propose a method for suppressing bead-meandering by controlling the cathode spot using an electromagnetic force, this is achieved, without changing the electrode wire or shielding gas. The direction of the external magnetic field was observed to be horizontal and vertical when using DC and AC external magnetic fields, respectively. An experiment on bead-on-plate welding is conducted by applying an external magnetic field and using pure Ar as the shielding gas. The effectiveness of pure Ar-MIG arc welding using an external magnetic field is examined. Moreover, the effect of the external magnetic field on the stability of the arc, and the shape of the bead are evaluated based on the experimental results.

2. Bead-meandering suppression method

In this paper, we proposed two different methods for the suppression of bead-meandering using an external magnetic field in the horizontal direction and another external magnetic field in the vertical direction.
2.1 External magnetic field in horizontal direction

When an AC external magnetic field with the amplitude $B_{AC}$ and frequency $f$ is applied perpendicularly to the arc of the welding current $I$, an electromagnetic force $F_{AC}$ is generated per unit length along the outer product direction. This enables the arc to oscillate at a regular interval with the frequency $f$, as shown in Fig. 1. This leads to the suppression of bead-meandering caused due to the irregular fluctuation. As shown in Fig. 1, an AC external magnetic field is applied in the direction of welding, and the arc is oscillated in the left-right direction using electromagnetic force. It should be noted that oscillation in the front-back direction is also possible.

![Fig. 1](image1.png)

**Fig. 1** Bead-meandering suppression on application of external magnetic field in horizontal direction. (left-right oscillation)

2.2 External magnetic field in vertical direction

As shown in Fig. 2, when an external magnetic field with the magnetic flux density $B$ is applied to the arc of the welding current $I$ in the vertical direction, an electromagnetic force $F$ is generated per unit length counterclockwise to the direction of welding. This electromagnetic force generates a rotational motion in the molten pool, thereby suppressing bead-meandering. In addition to the DC external magnetic field, an AC external magnetic field is examined. Using an AC external magnetic field with the frequency $f$, the direction of the rotational motion in the molten pool can be periodically changed thus enabling the arc to oscillate at regular intervals at the frequency $f$. An AC excitation current with an amplitude in the positive electrode (bias-AC) is generated when a DC bias current is added to the AC excitation current. The electromagnetic force is only applied in one direction, this leads to stirring of the molten pool and oscillation of the arc at regular intervals.

3. Welding experiment

As shown in Fig. 3(a), a small electromagnet, which is capable of welding in all position is installed at the tip of the welding torch. (four electromagnets are placed around the torch.) An external magnetic field is applied to perform the bead-on-plate experiment. The bead width is measured at multiple points for single bead and the meandering is evaluated the average and the standard deviation values. Table 1 lists the welding conditions.

![Fig. 2](image2.png)

**Fig. 2** Bead-meandering suppression on application of external magnetic field in vertical direction.

![Fig. 3](image3.png)

**Fig. 3** Electromagnet

| Table 1 | Welding conditions. |
|---------|---------------------|
| Base metal (thickness [mm]) | SS400 (3.2) |
| Electrode wire (diameter [mm]) | DS1A (1.2) |
| Shielding gas | 100%Ar |
| Gas flow [L / min] | 23 |
| Welding speed $v$ [m / min] | 0.8 |
| Welding current $I$ [A] | 300–350 |
| Welding voltage $V$ [V] | 32 |
| Power supply characteristics | Constant voltage characteristics |
4. Experimental results

Table 2 Electromagnet conditions.

| External magnetic field in horizontal direction |  |
|-------------------------------------------------|---|
| Front-back oscillation AC electromagnet current \(I_{EM}[A]\) (peak-to-peak) | 1, 2, 3 |
| Left-right oscillation AC electromagnet current \(I_{EM}[A]\) (peak-to-peak) | 0.5, 1, 1.5 |
| AC electromagnet current frequency \(f[Hz]\) | 30, 50, 100 |

| External magnetic field in vertical direction |  |
|-----------------------------------------------|---|
| DC electromagnet current \(I_{EM}[A]\) | 0.5, 1, 1.5, 2, 2.5 |
| AC electromagnet current \(I_{EM}[A]\) (peak-to-peak) | 1, 2, 3, 4, 5 |
| Bias-AC electromagnet current \(I_{EM}[A]\) (maximum) | 1, 2, 3, 4, 5 |
| AC and bias-AC electromagnet current frequency \(f[Hz]\) | 30, 50, 100 |

4.1 External magnetic field in horizontal direction

The electromagnet conditions are listed in Table 2. In the case of an external magnetic field in the horizontal direction, bead-meandering is suppressed under several conditions, irrespective of the direction of oscillation of the arc. It is observed that the width of the bead width decreases during the front-back oscillation; however, this width increases during the left-right oscillation.

During the front-back oscillation, the arc can oscillate in the forward and backward directions with respect to the direction of welding. A higher frequency of the magnetic flux density leads to faster oscillations, because the arc oscillates at the same frequency as the magnetic flux density. When a small magnetic flux density is applied, the arc is strongly deflected in the forward direction. Contrarily, a minute deflection in the arc was observed when the magnetic flux is applied in the backward direction. During the left-right oscillation, the arc oscillates at a regular interval in the lateral direction, when an external magnetic field is applied. This oscillation is only concentrated around the electrode wire.

Fig. 4 and Fig. 5 compare the bead obtained via the addition of \(O_2\) and the bead obtained using the proposed method, respectively, when an AC external magnetic field is applied, with front-back oscillations. The black dotted line represents the values of the bead obtained by adding \(O_2\). For the addition of \(O_2\), the standard deviation of the bead width is closer when \(I_{EM} = 3\) A and \(f = 30\) Hz, which indicates an effective suppression of bead-meandering, as shown in Fig. 4. However, the average bead width decreases, as shown in Fig. 5. Fig. 6 and Fig. 7 compare the bead obtained via the addition of \(O_2\) and the bead obtained using the proposed method when an AC external magnetic field is applied, with left-right oscillations. The standard deviation in the width of the bead is found to be greater than that of the previous condition. Moreover, the suppression of bead-meandering is inferior when \(I_{EM} = 1\) A and \(f = 100\) Hz. The average bead width is similar to that when \(O_2\) is
added, this width is maintained at a constant value.

### 4.2 External magnetic field in vertical direction

When an external magnetic field is applied in the vertical direction, bead-meandering is suppressed under several conditions, and the width of the bead remains almost unchanged. It is observed that the DC magnetic field and the bias-AC magnetic field is suppressed to a greater extent than the AC magnetic field in the vertical direction.

In the DC magnetic field, the arc column decreases owing to the increase in the electromagnet current. In the AC and bias-AC fields, fluctuations are observed when the direction of rotation of the arc is changed. However, an occasional forward movement is observed in the arc under all three external magnetic fields; this could not be suppressed completely.

Fig. 8 and Fig. 9 compare the bead obtained via the addition of O₂ and the bead obtained using the proposed method when a DC external magnetic field is applied. The standard deviation in the width of the bead is similar to the values for the bead obtained by adding O₂ when \( I_{EM} = 2.5 \, \text{A} \), which suppresses bead-meandering, as shown in Fig. 8. Moreover, the average width of the bead is maintained, as indicated in Fig. 9.

Fig. 10 and Fig. 11 compare the bead obtained via the addition of O₂ and the bead obtained using the proposed method when a bias-AC external magnetic field is applied. The standard deviation in the width of the bead is similar to the values for the bead obtained by adding O₂ when \( I_{EM} = 5 \, \text{A} \), which suppresses bead-meandering, as shown in Fig. 10. In addition, the average width of the bead width remains the same, as shown in Fig. 11.
4.3 Appearance of beads and cross section

Fig. 12 presents a comparison of the appearance of the bead when a magnetic field is applied and the appearance of the bead when a magnetic field is not applied. In the case of front-back oscillation, bead-meandering is effectively suppressed despite the thinner beads, as indicated in Fig. 12 (b). The bead width remains constant during the left-right oscillation, as shown in Fig 12 (c). In the case of the DC, AC, and bias-AC magnetic field, bead-meandering is effectively suppressed, and the bead width remains constant as shown in Fig. 12 (d), (e) and (f), respectively.

Fig. 13 depicts a comparison of the cross section of the bead when a magnetic field is applied in vertical direction and the cross section of the bead when a magnetic field is not applied. As shown in Fig. 13, the point at which deepest penetration occurred moved towards the center due to the application of the external magnetic field. However, it is also evident that the depth of penetration decreased owing to the application of this magnetic field. Moreover, it is also confirmed that a slightly deeper penetration occurs when a bias AC magnetic field is applied, as compared to when the DC and AC magnetic field are applied.

5. Conclusions

In this paper, we proposed a method for the suppression of bead-meandering in pure Ar-MIG arc welding, using an external magnetic field. The effectiveness of the proposed method was verified using a bead on plate experiment, based on the application of external magnetic fields. However, it was confirmed that the penetration depth decreased due to the application of a vertical external magnetic field. Therefore, further studies are required to establish a method of applying external magnetic fields while maintaining the penetration depth.

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