Numerical Analysis on Influence of Electrical Conductivity of Wire on Droplet Temperature in Duplex Current Feeding MIG Welding*

by Shinichi Tashiro**, Manabu Tanaka**, Masaru Seto*** and Atsuhito Aoki***

MIG welding under pure argon shielding gas atmosphere (pure argon-MIG welding) is suitable to obtain a high-strength and high toughness welded joint. However, it is difficult to apply pure argon-MIG welding practically to welding structure because of arc instability. In order to perform stable pure argon-MIG welding, duplex current feeding MIG welding has been developed. The duplex current feeding MIG welding consists of primary MIG welding current by constant-voltage power source and secondary current by constant-current power resource. In previous experimental study, it was found that the temperature of a droplet by duplex current feeding MIG welding was higher than the conventional MIG welding. In this paper, influence of electrical conductivity of the wire on basic characteristics of duplex current feeding MIG welding are discussed by numerical analysis. Consequently, it was clarified that the increase in the droplet temperature in the duplex current feeding MIG welding was significant especially in case of a wire material with lower electrical conductivity.

Key Words: MIG Welding, Pure Argon Shielding Gas, Metal transfer, Duplex Current Feeding, Droplet Temperature, Numerical Simulation, Electrical Conductivity

1. Introduction

In order to guarantee safety of a high-strength steel structure or a steel structure for cryogenic temperature, it is necessary to achieve both high strength and toughness of the welded joint. However, the strength and the toughness tend to decrease due to contamination of the weld metal by oxygen or nitrogen during welding. Therefore, TIG welding stable also in pure inert gas shielding gas is employed in many cases for joining this type of steels. TIG welding has disadvantages such as lower welding efficiency, though it produce a high quality weld joint. On the other hand, MIG welding realizes higher welding efficiency but tends to be unstable in pure inert shielding gas, so that mixture of argon with oxygen or carbon dioxide is generally used as the shielding gas. In this case, the toughness is largely decreased due to the addition of only small amount of oxygen or carbon dioxide.

In order to solve this problem, it is required to develop MIG welding process in pure inert shielding gas with high stability and efficiency. MIG welding faces problems such as a meandering weld bead due to unstable arc caused by irregular behavior of cathode spots, convex welding bead due to high surface tension. Those problems lead to welding defects such as incomplete fusion between weld passes in multi-layer welding.

Tanaka et al have developed the plasma MIG welding process mainly to stabilize the arc. In this study, a deep weld penetration and high wettability of the weld bead were not achieved, although the arc was adequately stabilized.

It is pointed out that the convex welding bead produced in the conventional MIG welding is caused by the large surface tension of the low temperature weld metal. Hence, it is desirable to raise the droplet temperature for increasing the wettability. However, in the conventional MIG welding, it is difficult to increase the droplet temperature because of the unique relationship between the welding current and the wire feed speed.

This study aims to develop new MIG (GMA) welding process with duplex current feeding, which enables to control the welding current and the wire feed speed independently by feeding the secondary current near the wire tip in addition to the conventional MIG current. In the previous study, the equipment for the duplex current feeding MIG welding was developed. Furthermore, basic characteristics in several welding conditions were experimentally clarified and those were compared with the conventional MIG welding. Fig.1 shows a schematic diagram of the duplex current feeding MIG welding. As explained above, the additional feeding point (contact point) of the secondary current was established near the wire tip. The torch has the dual nozzle structure. The pure argon gas was introduced from both nozzle. The distance between the contact tip and the feeding point of the secondary current was 12mm. The duplex current feeding MIG welding has two sets of welding power sources and current feeding points. The primary current with constant voltage characteristics and the secondary current with constant current characteristics were fed from the primary and the secondary feeding point, respectively. Consequently, it was found that the droplet temperature in the duplex current feeding MIG welding...
was higher than the conventional MIG welding. The convex welding bead was remarkably solved.

Then, mechanism and basic characteristics of duplex current feeding MIG welding were also investigated by numerical simulation with a simplified duplex current feeding MIG welding model \(^7\). As a result, it was found that total welding current was largely increased by feeding the secondary current in addition to the primary MIG welding current under the same arc voltage and wire feed speed. Furthermore, the droplet temperature was also increased due to the increase in total welding current.

The characteristics of duplex current feeding MIG welding are expected to be strongly affected by various thermophysical properties of the wire depending on it’s chemical composition. In this paper, influence of electrical conductivity of the wire, which is considered to be the most effective property, on basic characteristics of duplex current feeding MIG welding is discussed by numerical analysis.

![Fig. 1 Schematic diagram of duplex current feeding MIG welding.](image)

2. Simulation model

In this study, mechanism and basic characteristics of duplex current feeding GMA welding are investigated by numerical simulation with a simplified duplex current feeding MIG welding model. Fig.2 shows an axisymmetric two-dimensional simulation domain \((r,z)\) with a radius of 30mm and a height of 30mm consisting of an arc region and a wire region assuming stationary welding for simplicity. The height is the same as CTWD used in our previous experiment \(^6\). Sizes of meshes are approximately 0.1mm. Regions for a contact tip, a shielding gas inlet and a nozzle are defined on the top boundary. The outer diameter of the contact tip and the inner diameter of the shielding gas inlet are 2.4mm and 14mm, respectively. On the axis, the wire region with the diameter of 1.2mm and the extension of 25mm corresponding to arc length of 5mm is defined. In this model, the energy transport in the wire due to the wire feed and the energy loss due to the metal transfer are considered although the wire is assumed to be in solid phase and change in the wire extension and detachment of the droplet are ignored. The side boundary is pressure outlet. The bottom boundary corresponds to the surface of the base metal. The region inside the base metal are not calculated.

The primary current and the secondary current are in constant voltage characteristic and constant current characteristic, respectively. Although pulsed current was used for the primary current in the previous experiment, the direct current is used for the both current for simplicity. The primary current is fed from the wire region on the top boundary and changes by 0.01A in each iteration to match the applied voltage to the setting voltage. The secondary current of 50A is fed at the point below 12mm from the contact tip. The bottom boundary is set to be 0V. In this model, distributions of temperature, velocity and so on are obtained by solving the following equations assuming steady state.

Mass conservation:
\[
\nabla \cdot \left( \rho \vec{u} \right) = 0
\]  

Momentum conservation:
\[
\nabla \cdot \left( \rho \vec{u} \vec{u} \right) = -\nabla p + \nabla \cdot \vec{t} + \rho \vec{g} + \vec{j} \times \vec{B}
\]  

Energy conservation:
\[
\nabla \cdot \left( \rho h \vec{u} \right) = \nabla \cdot \left( \frac{k T \nabla T}{V_S} + \vec{J} \cdot \vec{E} - \vec{R} + Q_s - Q_{\text{csv}} \right)
\]  

\[
Q_s = \left( \frac{j_1 \phi - \varepsilon \alpha T^4}{V_s} \right) S_m / V_c
\]  

\[
Q_{\text{csv}} = \rho h \frac{u_w}{V_d}
\]  

Mass conservation of metal vapor:
\[
\nabla \cdot \left( \rho Y \vec{u} \right) = \nabla \cdot \left( \rho D \nabla Y \right) + Q_v
\]  

\[
Q_v = \left( \frac{m}{2 \pi k_b T_s} P_v \right) S_m / V_c
\]  

Current conservation:
\[
\nabla \cdot \sigma \nabla \Phi = 0
\]  

Ohm’s law:
\[
\vec{j} = -\sigma \nabla \Phi = \sigma \vec{E}
\]  

Vector potential:
\[
\nabla^2 \vec{A} = -\mu_0 \vec{j}
\]  

Magnetic field:
\[
\vec{B} = \nabla \times \vec{A}
\]  

Where \( \rho \): mass density, \( \vec{u} \): velocity, \( p \): pressure, \( \vec{t} \): viscus
stress tensor, $\vec{\sigma}$: gravity, $\vec{J}$: current density, $\vec{B}$: magnetic field, $h$: enthalpy, $k$: thermal conductivity, $T$: temperature, $\vec{E}$: electric field, $R$: arc radiation, $Q_e$: electron condensation and surface radiation on the wire surface, $Q_{\text{loss}}$: energy loss in the wire due to metal transfer, $\phi$: work function of the wire, $\tau$: surface emissivity, $\alpha$: Stephan Boltzmann constant, $S_a$: surface area of wire surface cell, $V_a$: volume of wire surface cell, $h_d$: enthalpy of the droplet, $u_w$: wire feed speed, $V_c$: volume of the droplet, $Y$: mass fraction of metal vapor, $D$: diffusion coefficient of metal vapor, $Q_v$: evaporation rate of metal vapor, $m$: atomic mass of metal vapor, $k_B$: Boltzmann constant, $T_e$: surface temperature of the wire, $P_c$: saturation vapor pressure, $S_c$: surface area of cell, $V_c$: volume of cell, $\sigma$: electrical conductivity, $\Phi$: electric potential, $\vec{A}$: vector potential.

The conservation equations of mass and momentum are solved only in the arc region. The source term $\vec{R}$ is defined only in the arc region. The source terms $Q_e$ and $Q_{\text{loss}}$ are defined only in the wire region. The wire feed speed is given to the advection term in the energy conservation equation for considering the energy transport by the wire feed. It is assumed that the droplet is formed in the wire region above 1mm from the wire tip. The temperature of each cell in the droplet is replaced to an averaged value in the entire droplet in each iteration assuming very large energy transport caused by convection. $Q_{\text{loss}}$ is uniformly subtracted from the droplet.

The thermodynamic and transport properties of the arc under the LTE assumption are calculated as functions of temperature and metal vapor concentration $g$. Diffusion coefficient of metal vapor is taken from Ref. 9. Only iron is assumed for metal vapor composition. The thermodynamic and transport properties of mild steel are used for the wire $^{10,11}$.

Table 1 summarizes boundary conditions. Where $u_{\text{gas}}$ is the gas velocity corresponding to the shielding gas flow rate and $j_1$ is the current density of the primary current. In order to consider evaporation of metal vapor from the weld pool surface, temperature on the base metal is assumed to be 1800K for $r<=5\text{mm}$ and 300K for $r>5\text{mm}$ $^{12}$. $P_{\text{atm}}$ is an atmospheric pressure.

The wire feed speed is 8m/min. The composition of the shielding gas is pure argon and the flow rate of that is 10L/min. The setting voltage is 21.75V on the contact tip on the top boundary. The calculation is done with ANSYS Fluent 16.1.

Table 1 Boundary conditions

| Boundary | Mass and momentum | Mass fraction of metal vapor | Energy | Electric potential | Magnetic potential |
|----------|-------------------|------------------------------|--------|--------------------|--------------------|
| AB (Wire wire)| $-\infty$ | 1000 | $\delta_{j1}(\text{wire})$ | $\delta_{\Phi}(\text{wire})$ | $\delta_{B}(\text{wire})$ |
| BC (Contact tip)| $0$ | $\delta_{j1}(\text{wire})$ | 3000 | $\delta_{\Phi}(\text{wire})$ | $\delta_{B}(\text{wire})$ |
| CD (Gas inlet)| $0$ | $\delta_{\Phi}(\text{wire})$ | 0 | $\delta_{\phi}(\text{wire})$ | $\delta_{B}(\text{wire})$ |
| DE (Nozzle)| $0$ | $\delta_{\Phi}(\text{wire})$ | 1000 | $\delta_{\phi}(\text{wire})$ | $\delta_{B}(\text{wire})$ |
| EE (Gas outlet)| $P_{\text{atm}}$ | $\delta_{\Phi}(\text{wire})$ | 0 | $\delta_{\phi}(\text{wire})$ | $\delta_{B}(\text{wire})$ |
| FG (Base metal)| $0$ | $\delta_{\Phi}(\text{wire})$ | 1800K ($r<=5\text{mm}$) | $\delta_{\phi}(\text{wire})$ | $\delta_{B}(\text{wire})$ |
| GH (Base)| $A_{\text{wire}}$ | $\delta_{\Phi}(\text{wire})$ | 1800K ($r>5\text{mm}$) | $\delta_{\phi}(\text{wire})$ | $\delta_{B}(\text{wire})$ |

3. Results and Discussion

First, basic characteristics of the conventional MIG welding and the duplex current feeding MIG welding assuming electrical conductivity of $7.7 \times 10^5\text{ S/m}$, and $4.1 \times 10^5\text{ S/m}$ are compared. Fig.3 shows distributions of electric potential. It was seen that the electric potential was 21.75V on the contact tip on the top boundary which was the same as the setting voltage. In the duplex current feeding MIG welding, the electric field decreased above the feeding point of the secondary current but it conversely increased below that due to the secondary current compared with the conventional MIG welding. In case of $7.7 \times 10^5\text{ S/m}$, the current was 212A in the conventional MIG welding. On the other hand, the current density increased below the feeding point of the secondary current due to the addition of the secondary current in the duplex current feeding MIG welding. Consequently, it was found that the total current increased to 253A which was larger.
than that of the conventional MIG welding, although the primary current decreased to 203A. As a result, the droplet temperature was 2096K in case of the conventional MIG welding. The droplet temperature in duplex current feeding MIG welding increased to 2324K which was larger than that of the conventional MIG welding by approximately 230K, because of greater Joule heating in the wire and heating by electron condensation on the wire surface caused by the increase in the current. In contrast, increase in the total current compared with the conventional MIG welding was only 8A in case of $4.1 \times 10^6$ S/m.

Second, influences of electrical conductivity of the wire are discussed. Fig.4 shows dependence of the electrical conductivity of the wire on the total current. It was found that increase in the total current compared of the duplex current feeding MIG welding (DCF) compared with the current of the conventional MIG welding gradually decreased with the electrical conductivity of the wire. Fig.5 shows dependence of the electrical conductivity of the wire on the droplet temperature. Consequently, it was clarified that the increase in the droplet temperature in the duplex current feeding MIG welding was significant especially in case of a wire material with lower electrical conductivity such as the iron compared with the aluminum.

![Fig. 3 Distributions of electric potential.](image)

![Fig. 4 Dependence of electrical conductivity of wire on total current.](image)

![Fig. 5 Dependence of electrical conductivity of wire on droplet temperature.](image)

4. Conclusions

In this paper, influence of electrical conductivity of the wire on basic characteristics of duplex current feeding MIG welding were discussed by numerical analysis. Consequently, it was clarified that the increase in the droplet temperature in the duplex current feeding MIG welding was significant especially in case of a wire material with lower electrical conductivity.

Reference

1) S. Terashima and K. K. D. H. Bhadeshia: “Change in toughness at low oxygen concentrations in steel weld metals”, Science and Technology of Welding and Joining, 11, 5 (2006), 509-516
2) T. Nakamura, K. Hiraoka: “GMA Welding of 9% Ni steel in the pure Argon shielding gas using coaxial multi-layer solid wire”, Quarterly J. Japan Welding Soc., 30, 3 (20012), 254-261
3) S.A.David, T.Debroy, J.M.Vitek: “Phenomenological Modeling of Fusion Welding Process” MRS Bulletin, 10, 1 (1994), 29-35
4) M. Tanaka, T. Tamaki, S. Tashiro, K. Nakata, T. Ohnawa, T. Ueyama : “Characteristic of ionized gas metal arc processing”, Surface & Coating Technology, 202 (2008), 5251-5254
5) K. Yamazaki, E. Yamamoto, K. Suzuki, F. Koshiishi, K. Waki, S. Tashiro, M.Tanaka, K. Nakata: “The Measurement of Metal Droplet Temperature in GMA Welding by Infrared Two-Color Pyrometry”, Quarterly J. Japan Welding Soc., 26, 3 (2008), 214-219
6) M. Seto, A. Aoki, M. Tanaka, S. Tashiro, T. Era: “Study on new welding process with duplex current feeding”, Quarterly J. Japan Welding Soc., 34, 2 (2016), 150-157
7) S. Tashiro, M. Seto, A. Aoki, M. Tanaka: “Numerical simulation of new GMA welding process with duplex current feeding”, IWW Doc. 212-1434-16 (2016)
8) M. Tanaka, K. Yamamoto, S. Tashiro, K. Nakata, E. Yamamoto, K. Yamazaki, K. Suzuki, A. B. Murphy and J. J. Lowke: “Time-dependent calculations of molten pool formation and thermal plasma with metal vapour in gas tungsten arc welding”, J. Phys. D: Appl. Phys., 43 (2010), 434009 (11pp)
9) M. Schnick, U. Fuessel, M. Hertel, A. Spille-Kohoff, and A. B. Murphy: “Numerical investigations of arc behaviour in gas metal arc welding using ANSYS CFX”, Front. Mater. Sci., 5, 2 (2011), 98-108
10) M. Hertel, A. Spille-Kohoff, U. Fuessel and M. Schnick: “Numerical simulation of droplet detachment in pulsed gas-metal arc welding including the influence of metal vapour”, J. Phys. D: Appl. Phys., 46 (2013), 224003 (11pp)
11) Y. Ogino, Y. Hirata, A. B. Murphy: “Numerical simulation of GMAW process using Ar and an Ar-CO2 gas mixture”, Weld World, (2016), DOI 10.1007/s40194-015-0287-3
12) K. Yamazaki, E. Yamamoto, K. Suzuki, F. Koshiishi, S. Miyazako, S. Tashiro, M. Tanaka, K. Nakata: “The Surface Temperature Measurement of Weld Pool by Infrared Two-Color Pyrometry”, Quarterly J. Japan Welding Soc., 27, 1 (2009), 34-40
13) Y. Tsujimura, S. Kanemaru and M. Tanaka: “An Engineering Model for Numerical Simulations of GMA Welding”, Quarterly J. Japan Welding Soc., 30, 1 (2012), 60-67