Numerical simulation of arc plasma and molten metal behavior in gas metal arc welding process

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Abstract
In this study, to make clear the phenomena of the gas metal arc welding process more deeply, a simulation model including both the arc plasma and the metal transfer phenomena is constructed and influence of the arc current is numerically investigated. The simulation model used in this study considered the iron vapor generating from the high-temperature metal surface and surface deformation of the molten metal as the interaction between the arc plasma and the molten metal. The simulation result shows that the molten wire glows largely at the wire tip when the arc current is low. On the other hand, for the high arc current, small droplet detaches from the wire tip. These simulation results of the behavior of the molten metal show good agreement with the experimental results. The balance of the driving force acting on the molten metal at the wire tip is very important to determine the molten metal behavior, and when influence of the electromagnetic force becomes stronger than that of the surface tension, the transfer mode is changed. In addition, simulation and experiment are carried out using the same pulsed current, these results of the arc plasma and the molten metal show good agreement. Therefore, the simulation model constructed in this study can describe the phenomena depending on the arc current. These results show that there are possibilities to be able to predict the behavior in gas metal arc welding process and optimize the current profile by the simulation model for controlling the gas metal arc welding phenomena.

Keywords: Gas metal arc welding (GMAW), Numerical simulation, Arc plasma, Metal transfer, Transfer mode, Arc current, Pulsed current

Nomenclature

| Symbol | Description | Unit |
|--------|-------------|------|
| $\vec{v}$ | Velocity | m/s |
| $t$ | Time | s |
| $\rho$ | Density | kg/m$^3$ |
| $P$ | Pressure | Pa |
| $\tau$ | Viscous stress tensor | Pa |
| $\vec{g}$ | Gravitational acceleration | m/s$^2$ |
| $\vec{B}$ | Magnetic flux density | T |
| $\sigma$ | Electrical conductivity | S/m |
| $\mu_0$ | Permeability of free space | H/m |
| $\vec{F}$ | External force | N/m$^3$ |
| $\Delta F$ | Source term of the F value by metal vapor | 1/s |
| $F_{em}$ | Electromagnetic force | N/m$^3$ |
| $F_{st}$ | Equivalent volumetric force of capillary pressure of surface tension | N/m$^3$ |
| $H$ | Enthalpy | J/kg |
| $\kappa$ | Thermal conductivity | W/m/K |
| $\kappa_{cure}$ | Curvature | 1/m |
| $T$ | Temperature | K |
| $C$ | Mass fraction of metal vapor | |
| $Ra$ | Radiative loss | W/m$^3$ |
| $D$ | Diffusion coefficient | m$^2$/s |
1. Introduction

Gas metal arc welding (GMAW) process is an indispensable technology in various fields of industry. Schematic image of the process is shown in Fig. 1. In this process an arc plasma is ignited between the wire electrode and the base metal and used as an energy source. It melts a wire electrode and base metal. In GMAW process, a consumable wire electrode is used and it fed from wire feeding machine continuously. This is used as not only an electrode of the arc discharge but also a filler material of the gap in the base metal. During the process, the molten wire moves from the wire tip to the base metal, this is called “metal transfer phenomena”.

![Fig. 1 Schematic image of the gas metal arc welding process](image-url)

Since the molten wire tip is an electrode of the arc discharge during GMAW process, characteristics of the metal transfer are closely related to stability and quality of the overall process. The properties of the metal transfer depend on the welding parameters such as the arc current, the welding voltage and the shielding gas, and the transfer mode can be divided several patterns (Ruckdeschel, 1976). Figure 2 shows influence of the arc current on the metal transfer mode obtained by a high speed camera. Here, the material of the wire electrode is mild steel, and the shielding gas is Ar+20%CO₂. As shown in this figures, when the arc current is low, the molten wire glows largely at the wire tip, and this transfer mode is called “globular transfer”. On the other hand, for the high arc current, many small droplets are transferred to the base metal. This transfer mode is called “spray transfer”. Generally, the spray transfer is preferred to use because it is relatively stable phenomena and low spatter generation in industrial field.

![Fig. 2 Influence of the arc current on the metal transfer mode](image-url)

However, the behavior is not able to control completely, because the phenomena are very complicated and it is not understood completely. To make clear the phenomena, many experimental (Ludwig, 1957, Needham, et al., 1960, Rhee and Kannatey-Asibu, 1992) and numerical (Greene, 1960, Waszink and Graat, 1983, Nemchinsky, 1994) approaches are carried out and reported. In this study, numerical simulation is focused as a technique of visualization of the phenomena. There are some numerical models of the metal transfer phenomena based on computational fluid dynamics (CFD) (Choi, et al., 1998, Wang, et al. 2003). Especially, some numerical models including interactions between the arc plasma and the metal transfer phenomena are reported in recent years. For example, Hertel et al
reported detail of the structure of the arc plasma and summarized the role of the metal vapor generating from the wire tip (Hertel, et al., 2017). Ogino et al reported numerical investigation about influence of the shielding gas on the metal transfer phenomena, and revealed the current path near the wire tip is important to determine the metal transfer mode (Ogino, et al., 2016). Therefore, the numerical model is becoming very helpful tool to understand the phenomena in GMAW process, but few reports are available on numerical simulation including interactions between the metal transfer phenomena and arc plasma phenomena.

In this study, in order to make clear the phenomena of the GMAW process more deeply, influence of the arc current on the arc plasma and the metal transfer phenomena is numerically investigated. A numerical model including both the arc plasma and the metal transfer phenomena is used in this study. Deformation of the molten metal and metal vapor generates from the high temperature metal are considered as interactions between the arc plasma and the molten metal. In addition, influence of pulsed current on the metal transfer phenomena is also investigated and the numerical results are compared with the experimental result.

2. Numerical model

A simulation model that includes the interactions between the arc plasma and the metal transfer is constructed in this study. However, it is difficult to calculate these phenomena simultaneously because of the difference in the material properties and velocity scales. For this reason, the arc plasma and the molten metal were treated as two separate fluids in the model. The local thermodynamic equilibrium (LTE) is applied to the arc plasma and it is treated as an electromagnetic viscous fluid. In this study, the flow in both the arc plasma and the molten metal is treated as laminar flow. Detail of the model has been explained in authors’ previous paper (Ogino, et al., 2016). In this study, the behavior of the thermal and electromagnetic fluid is calculated by following equations:

\[
\nabla \cdot (\rho \vec{v}) = S \tag{1}
\]

\[
\frac{\partial (\rho \vec{v})}{\partial t} + \nabla \cdot (\rho \vec{v} \vec{v}) = -\nabla P + \nabla \cdot \tau + \rho \vec{g} + \vec{F} \tag{2}
\]

\[
\frac{\partial (\rho H)}{\partial t} + \nabla \cdot (\rho \vec{v} H) = -\nabla \cdot (-\kappa \nabla T) + W - Ra + S_E \tag{3}
\]

In the simulation, the electromagnetic force and the Joule heating strongly affect the behavior of the arc plasma and the molten metal. The electromagnetic force and the Joule heating can be calculated by the following equations:

\[
\vec{F}_{em} = \vec{j} \times \vec{B} \tag{4}
\]

\[
W = \frac{|\vec{j}|^2}{\sigma} \tag{5}
\]

\[
\nabla \cdot \vec{j} = 0 \tag{6}
\]

\[
\vec{j} = -\sigma \nabla \psi \tag{7}
\]

\[
\vec{B} = \nabla \times \vec{A} \tag{8}
\]

\[
\nabla^2 \vec{A} = -\mu_0 \vec{j} \tag{9}
\]

In this model, the metal vapor generating from the high-temperature metal surface is considered as an interaction of between the arc plasma and the molten metal. In this study, only the iron vapor is treated as the metal vapor. Its behavior is calculated by following equation:

\[
\frac{\partial (\rho C)}{\partial t} + \nabla \cdot (\rho \vec{v} C) = -\nabla \cdot (-\rho D \nabla C) + S \tag{10}
\]

The iron vapor is generated according to the Hertz-Knudsen-Langmuir equation and transferred by the convection in the arc plasma and diffusion. The diffusion coefficient used in the model is calculated according to Wilke’s report (Wilke, 1950). The shape of the molten metal is changed continuously. In this model, the free-surface of the molten metal is tracked by volume of fluid (VOF) method (Hirt and Nichols, 1981). In VOF method, the shape of the fluid is described by fluid occupancy so-called F value in each calculation cell. According to the velocity field, the free-surface deformation can be calculated by following equation:

\[
\frac{\partial F}{\partial t} + (\vec{v} \cdot \nabla) F = \Delta F \tag{11}
\]

The surface tension force is important to determine the shape of the molten metal. In this model, it is calculated using continuum surface force (CSF) model (Brackbill, et al., 1992). The capillary pressure of surface tension force
can be expressed as a volume force in the surface region by CSF model. The equivalent volume force of the capillary pressure by surface tension force can be calculated as follows:

\[ \vec{F}_{st} = \gamma \kappa \text{curv}\vec{n} \]  

(12)

These equations are solved in two-dimensional axially-symmetric geometry by our own computer code. A schematic image and the boundary conditions for the model are shown in Fig. 3. Here, the wire electrode is anode, and the base metal is cathode. The arc current is provided from the top of the wire electrode. In this model, the droplet detached from the wire electrode is treated as an electrical insulator material, since the cathode spots which should be observed when the droplet is an electrical conductor are not observed at the droplet surface in experiment. It is thought that the higher energy is required to form the cathode spots than to form the current path in the surrounded arc plasma. The wire electrode is fed from the top of calculation domain by constant feeding speed, and its temperature at the top boundary is set to 300 K. The shielding gas is flows from the top of the calculation domain. The temperature of the bottom surface of the base metal is set to 300 K and grounded. In this study, the wire electrode and the base metal is mild steel, and the shielding gas is Ar+20\%CO\textsubscript{2}. This shielding gas is generally used for the welding of the carbon steel. The material properties of the arc plasma including its temperature dependence and influence of iron vapor used in this study is taken from the reports by Murphy (Murphy, 2010). When the iron vapor mixes in the arc plasma, the material properties of the arc plasma is changed. Especially, the electrical conductivity and the radiation loss are significantly changed by the small amount of the iron vapor as shown in Fig. 4. These changes in material properties strongly affect on the current path and temperature distribution in the arc plasma.

Fig. 3 Schematic image and boundary conditions for the model

![Fig. 3 Schematic image and boundary conditions for the model](image)

(a) Electrical conductivity
(b) Radiation loss

Fig. 4 Influence of the iron vapor on the material properties of the arc plasma

![Fig. 4 Influence of the iron vapor on the material properties of the arc plasma](image)
3. Simulation results

Figure 5 shows calculation results by our model. In this figure, the temperature distributions of the arc plasma (right) and metal region (left) are shown. Here, the arc current is set 220 and 290 A to investigate its influence, and these figures show the temperature distributions at before and after the droplet detachment from the wire tip. As shown in this figure, the transfer mode is changed depending on the arc current. When the arc current is 220 A, the molten wire glows up largely at the wire tip and a large droplet detaches as shown in Fig. 5(a). This transfer mode can be classified the globular transfer. In this case, the electromagnetic force is not much strong and the molten wire is supported by surface tension force due to low arc current, and main driving force to detach from the wire tip is gravity force. On the other hand, when the arc current is 290 A, as shown in Fig. 5(b), small droplets detach from the wire tip. This transfer mode can be classified the spray transfer. In this case, the electromagnetic force is enough strong and facilitates the molten wire to detach from the wire tip due to high arc current. Focusing on the arc temperature, it becomes low at the center of the arc plasma as shown in Fig. 5(b). This temperature distribution is closely related to the existence of the iron vapor generates from the wire tip. Figure 6 shows the iron vapor concentration distribution in the arc plasma. At the center, a large amount of the iron vapor exists. When the iron vapor mixes in the arc plasma, the radiation loss of the arc plasma significantly increases (Schnick, et al., 2010). Consequently, the arc temperature at the center is decreases. The metal vapor is very important to determine the temperature distribution of the arc plasma in GMAW process. Since the temperature distribution of the arc plasma determine the current path and distribution of the electromagnetic force, it is very important to consider the behavior of the metal vapor for understanding the phenomena of the GMAW process.

Difference of the metal transfer behavior calculated by the simulation model shows good agreement with experimental observation shown in Fig. 2. Therefore, the simulation model constructed in this study can calculate the arc plasma and the metal transfer behavior appropriately. Figure 7 shows influence of the arc current on the transfer frequency of the metal transfer. As shown in this figure, the transfer frequency suddenly increases at 270 A. This means the transfer mode changes from the globular transfer to spray transfer at 270 A. The balance of the driving force acting on the molten wire at the wire tip is very important to determine the transfer mode, and this figure shows influence of the electromagnetic force becomes stronger than that of the surface tension force at 270 A.
Fig. 5 Influence of the arc current on the arc plasma and metal temperature distributions

(a) Arc current: 220 A

(b) Arc current: 290 A

Fig. 6 Iron vapor concentration distribution in the arc plasma
Next, the simulation model is applied to pulsed current welding process. Pulsed current is used in industry to control the metal transfer behavior and the heat input into the base metal. When the appropriate current profile is used, the behaviors of the arc plasma and the molten metal are synchronized with the current. Many kinds of the pulsed current profile are suggested, but the optimum condition is determined through many trials and errors. Figure 8 shows the current profile used in this study. This current profile is obtained by the experiment in advance, and the behavior of the arc plasma and the molten metal are very stable in experiment. Here, this pulsed current is used in the simulation and the results are compared with experiment.

Figure 9 shows the comparison between the simulation results and the experimental results. The simulation results show temperature distribution of the arc plasma (right) and the metal region (left). The experimental results are obtained by a high speed camera. The legends (A)-(H) shown in Fig. 9 correspond with the timing of (A)-(H) shown in Fig. 8. Just before the current increases as shown in (A), due to the low arc current, the temperature of the arc plasma is low, and the luminescence of the arc plasma cannot obtained in experiment. After the pulse starts, and the arc current increases, the temperature of the arc plasma also increases as shown in simulation results of (B)-(E). However, the temperature of the arc plasma at the end of the high current duration shown in (E) is lower than that at the beginning shown in (B), even though these current are almost same. In the high current duration, the temperature of the molten wire tip also increases, and a large amount of the iron vapor is generated and flows into the arc plasma. Consequently, the temperature of the arc plasma becomes low at the end of the high current duration. As shown in experimental results, the luminescence of the arc plasma also becomes stronger in high current duration. After the high current duration, the molten metal at the wire tip becomes a necking shape and detaches from the wire tip as shown in (G). As shown in these figures, the simulation result of the molten metal behavior shows good agreement with the experimental result during the pulsed welding process. Therefore, the simulation
model constructed in this study can calculate the behaviors of the arc plasma and the molten metal depending on the current profile. This result shows that there is a possibility to be able to optimize the current profile by the simulation model for controlling the GMAW phenomena.

![Simulation](image1)

![Experiment](image2)

Fig. 9 Comparison between the simulation and experimental result of the arc plasma and the molten metal behaviors using pulsed current

4. Conclusion

In this study, to make clear the phenomena of the GMAW process more deeply, influence of the arc current on the arc plasma and the metal transfer phenomena is numerically investigated. A simulation model including both the arc plasma and the molten metal behaviors is constructed. Deformation of the free-surface of the molten metal and the iron vapor generating from the surface of the high-temperature metal is considered as interactions between the
arc plasma and the molten metal. The simulation result shows difference of the transfer mode depending on the value of the arc current and it shows good agreement with experimental result. In addition, pulsed current is applied to the simulation model, and the calculated behaviors are very similar with the experimental results. Therefore, the simulation model constructed in this study can calculate the arc plasma and the molten metal behaviors depending on the current profile. These results show that there are possibilities to be able to predict the behavior in GMAW process and optimize the current profile by the simulation model for controlling the GMAW phenomena.

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