Three-Dimensional Simulation of Gas Metal Arc Welding Process Using Particle-Grid Hybrid Method*

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A gas metal arc welding phenomena simulator was developed, which simultaneously computed an arc plasma behavior and a weld pool formation process with the time evolution by alternately conducting the particle method and the grid method calculations. Also, the numerical simulation of this welding process was conducted. As a result, a weld pool was swelled up by the transportation of molten metal droplets with the time evolution and it was solidified after the heat source passed. The plasma temperature distribution in the welding direction temporally became asymmetry at the start of the welding. This was because the metal vapor evaporated from a wire surface was transported to forward, preferentially in the welding direction. Furthermore, the iron vapor concentration on the weld bead became lower than forward side because the radiation loss increased with increase in the iron vapor concentration. A few seconds after the start of the welding, the change of the arc plasma temperature distribution became smaller because a sufficient amount of a molten metal was supplied by the molten metal droplet transfer and the dent on the weld pool surface reduced.

**Key Words:** Gas Metal Arc Welding, 3-D Simulation, Particle Method, Grid Method

1. Introduction

A GMA (Gas Metal Arc) welding is one of welding processes, which uses consumable wire as an electrode. Although this process has high versatility and is widely used in the industry, many researches still have been conducted. This is because those welding phenomena are complicated and they are not clarified all yet. Recently, some three-dimensional simulations have been carried out to clarify those welding phenomena with developments of computational techniques and those GMA welding phenomena are gradually clarified. For example, Murphy et al. developed a three-dimensional numerical model of an arc plasma and a weld pool. They simulated the arc plasma behavior and the weld pool formation of a lap joint part simultaneously1). Moreover, they predicted the residual stress and the deformation of the weld part. In the study, a weld bead whose length was 50 mm was formed. A penetration shape and a concentration distribution of a droplet alloy in the weld bead showed good agreement with experiments.

Ogino et al. simulated molten metal droplet and arc plasma behaviors during a CO2 arc welding using a three-dimensional numerical model in which the plane symmetrical condition was assumed2). As a result, the lopsided iron vapor concentration distribution in the arc plasma was successfully simulated because a molten metal droplet was pushed up by an arc pressure and its shape became non-axisymmetric. In these grid methods, computational domains generally become cuboids. Therefore, the number of grids increases in three-dimensional when a base metal becomes longer by increasing the weld length. It indicates that many regions which are not important for welding phenomena have to be computed, hence, the computational costs dramatically increase. In this study, a particle method in which computational grids are not needed is focused on. This method is easy to discretize governing equations and also suitable for a numerical simulation with the parallelization. The particle method is used to simulate the behavior of molten metal. On the other hand, an arc plasma is solved by the grid method with the computational domain, limited around the arc plasma to reduce the computational costs. An objective of this study is the development of a GMA welding phenomena simulator that can simultaneously compute an arc plasma behavior and a weld pool formation process with the time evolution by alternately conducting the particle method calculation and the grid method calculation.

2. Computational methods

2.1 Governing equations of molten metal behavior

A molten metal behavior is simulated by an incompressible SPH (Smoothed Particle Hydrodynamics) method, a type of the particle method. The basic idea of this method is explained in the previous study 3). The velocity of a molten metal particle \( a \) is obtained by the Navier-Stokes equation which is written as 4)

\[
\frac{D\vec{u}_a}{Dt} = -\sum_b m_b \left( \frac{\rho_b}{\rho_a} \right) \nabla \vec{W}_{ab} - \frac{\delta }{\rho_a \rho_b } \sum_b m_b \left( \frac{\rho_b}{\rho_a} \right) \left( \vec{u}_b - \vec{u}_a \right) W_{ab} + \frac{\rho_b \vec{S}_{ab}}{\rho_a} + \vec{F}_a \tag{1}
\]

with \( u, t, b, m, p, \rho, W, \delta, \lambda, n, \mu \) showing the velocity, the time, particles within the evaluate radius \( h \) of \( a \), the mass, the
pressure, the density, the kernel function, the dimension number, the parameter, the number density and the viscosity coefficient, respectively. \( p_{\text{arc}} \) is the arc pressure, \( \vec{n} \) is the unit normal vector, \( S \) is the cross-section area of a particle, \( V \) is the volume of a particle. \( F \) is other external force including the Marangoni effect, the shearing force, the Lorentz force, the surface tension force in normal direction and the buoyancy. The temperature of the particle is calculated by the energy transfer equation, which is expressed as

\[
\frac{\partial T}{\partial t} = \frac{2\delta}{\rho \sigma C_p} \sum_b \frac{\kappa_b}{2} (T_b - T_a) W_{ab} + \frac{Q_a}{\rho_a C_a} - \frac{q_{\text{eva}}}{\rho_a V_a C_a}. \tag{2}
\]

\( T \) is the temperature, \( C \) is the specific heat and \( \kappa \) is the thermal conductivity. \( Q \) is the heat generation rate of a metal surface, in which the heat flux from a shielding gas, the emission loss, the cooling by the electron outflow, and the heating by the ion recombination are considered. \( q_{\text{eva}} \) is the heat flux by the evaporation. \( f_{\text{eva}} \) is the mass flux of metal vapor obtained by the Hertz-Kundsen-Langmuir equation, and \( h_{\text{eva}} \) is the latent heat of the evaporation.

### 2.2 Governing equations for arc plasma behavior

The current density in a computational domain and physical quantities of gas such as the temperature, the iron vapor concentration and the velocity are simulated by a grid method. The mass conservation equation and the momentum equation of gas are expressed as

\[
\nabla \cdot (\rho \vec{u}) = 0, \tag{4}
\]

\[
\nabla \cdot (\rho \vec{g}) = -\nabla p + \nabla \cdot [\mu (\nabla \vec{u} + (\nabla \vec{u})^T)] + \vec{j} \times \vec{B} + \rho \vec{g}. \tag{5}
\]

Here, \( j \) is the current density and \( g \) is the acceleration of the gravity. The temperature of gas is obtained by the energy transfer equation shown in Eq. (6) and the iron vapor concentration of gas is calculated by the transfer equation of iron vapor shown in Eq. (7).

\[
\nabla \cdot (\rho \vec{h}) = -\nabla \left( \frac{k}{c_p} \nabla \theta \right) + \frac{|\vec{j}|^2}{\sigma} + Q, \tag{6}
\]

\[
\nabla \cdot (\rho \vec{Y}) = -\nabla \cdot (\rho \vec{Y}) - \nabla \cdot (\rho \vec{f}_{\text{eva}} \vec{h}). \tag{7}
\]

\( h \) is the enthalpy, \( Y \) is the iron vapor concentration, \( c_p \) is the specific heat under constant pressure, \( \sigma \) is the electrical conductivity and \( \Gamma \) is the diffusion coefficient. In Eq. (6), the radiation loss of an arc plasma, heat fluxes on a cathode surface and an anode surface are considered as the heat generation rate \( Q \). The current density is obtained using the current conservation equation and the Ohm’s law which are described as

\[
\nabla \cdot \vec{j} = 0, \tag{8}
\]

\[
\vec{j} = \sigma \vec{E}. \tag{9}
\]

\( E \) is the electric field. The magnetic flux density \( B \) is calculated by Eq. (10) and Eq. (11).

\[
\nabla \times \vec{A} = \vec{B}, \tag{10}
\]

\[
\nabla \cdot \vec{A} = -\mu_0 j. \tag{11}
\]

\( A \) is the vector potential and \( \mu_0 \) is the magnetic permeability in the vacuum. These equations are discretized by a finite volume method and they are solved using the SIMPLE (Semi-Implicit Method for Pressure Linked Equations) algorithm. In this calculation, a region in which \( r' = \sqrt{x'^2 + y'^2} \) is smaller than a wire radius and \( z' \) is higher than the sum of the thickness of a metal arc and an arc length is regarded as the wire region. Metal shapes of a base metal, a weld pool, and a weld bead are obtained using the computational result of the SPH method at the same time. Metal region is decided by a function \( G \) which is described as

\[
G = \pi h^2 \sum_b W_{bc}. \tag{12}
\]

\( c \) is the grid point. When \( G \) is greater than or equal to 0.95, the control volume is regarded as a metal region. On the other hand, physical quantities of the arc plasma to calculate the Lorentz force, the shearing force and heat generation rates acting on a molten metal surface are obtained by the bilinear interpolation. These calculations of the heat source by the grid method are carried out every 50 ms to reduce computational costs.

### 2.3 Computational domains and computational conditions

Figure 1 and Fig. 2 show computational domains for a particle method and a grid method. A red dash line in Fig. 1 shows the center of a wire at a start of a calculation and a white dash line in the figure describes a weld line. An origin point in the computational domain of the grid method corresponds to the lower end of the red dash line in Fig. 1. The computational domain for the SPH method is a cuboid whose size is 50×100×9 mm consisting of 360,000 particles. The computational domain for the grid method is also the cuboid whose size is 50×50×24 mm consisting of 41×41×61 grids. A size of a minimal grid is 0.2×0.2×0.2 mm. The material properties of a mild steel are given to a base metal, a weld pool, and a weld bead are obtained using the computational result of the SPH method at the same time. Metal shapes of a base metal, a weld pool, and a weld bead are obtained by the bilinear interpolation. These calculations of the arc plasma to calculate the Lorentz force, the shearing force and heat generation rates acting on a molten metal surface are obtained by the bilinear interpolation. These calculations of the heat source by the grid method are carried out every 50 ms to reduce computational costs.

The current density in a computational domain and physical quantities of gas such as the temperature, the iron vapor concentration and the velocity are simulated by a grid method. The mass conservation equation and the momentum equation of gas are expressed as

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\nabla \cdot (\rho \vec{h}) = -\nabla \left( \frac{k}{c_p} \nabla \theta \right) + \frac{|\vec{j}|^2}{\sigma} + Q, \tag{6}
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\( h \) is the enthalpy, \( Y \) is the iron vapor concentration, \( c_p \) is the specific heat under constant pressure, \( \sigma \) is the electrical conductivity and \( \Gamma \) is the diffusion coefficient. In Eq. (6), the radiation loss of an arc plasma, heat fluxes on a cathode surface and an anode surface are considered as the heat generation rate \( Q \). The current density is obtained using the current conservation equation and the Ohm’s law which are described as

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\( E \) is the electric field. The magnetic flux density \( B \) is calculated by Eq. (10) and Eq. (11).
physical quantities. At the top of the domain, the gas flow rate as a shielding gas is set vertically downward inside of a nozzle. A temperature of the shielding gas is set to be 300 K. Other regions at the top are set to be Neumann conditions for all physical quantities. Table 1 shows other computational conditions.

![Fig. 1 Computational domain of particle method.](image1)

![Fig. 2 Computational domain of grid method.](image2)

3. Results and discussion

Figure 3 shows the temperature distribution of a molten metal for each time calculated by an SPH method. This figure is a bird’s eye view with the color of particles showing their respective temperatures. When a temperature of particles is smaller than a melting point of a mild steel, the particles are colored by the gray. Other particles are colored by a range from the blue to the red depending on their temperature. In the Fig. 3, the red dash line shows the center of a wire at that time. As time passes, a weld pool is swelled up by the transportation of molten metal droplets and is solidified after the heat source passes (Fig. 3(a) ~ Fig. 3(c)). The increase of the temperature on the weld pool surface is suppressed by the evaporation of the metal vapor and maximum temperature of the surface becomes about 2,350 K. Figure 4 shows the temperature distribution of an arc plasma. The left side and the right side of Fig. 4 show the vertical and perpendicular cross-sections along a weld line ($x' = 0.0$ m) and to the line ($y' = 0.0$ m) respectively. Gray regions for each figure signify metals. At the start of a welding, the arc plasma temperature distribution is approximately symmetric for each cross-section because the base metal surface is flat (Fig. 4(a)).

Then, the arc plasma temperature distribution becomes asymmetry in both of $x'$-$z'$ direction and $y'$-$z'$ direction (Fig. 4(b)). This is because a weld pool is largely deformed by the molten metal droplet transfer and the weld pool convection. Figure 5 shows the velocity distribution, the Peclet number distribution and the iron vapor concentration distribution at $t = 0.8$ s, respectively. In Fig. 5(a), the color shows a scalar of the gas velocity and vectors show the flow direction on the $y'$-$z'$ plane. The color in Fig. 5(b) shows the iron vapor concentration. Furthermore, the color in Fig. 5(c) shows the Peclet number which is described as

$$Pe = \frac{\rho |U| \Delta x}{\rho \tau}, \tag{13}$$

$\Delta x$ is the characteristic length and it is set to be a length which equals to the nozzle inner diameter. A weld bead at backward of a wire is swelled up by the molten metal droplet transfer and the weld pool surface under the wire tip is dented by an arc pressure. The current density at backward of it increases because the distance between the wire tip and the weld pool surface at backward of a wire becomes shorter than forward of it by the weld bead formation. So, the current density at the backward of the wire increases. This causes an increase of the Lorentz force at that region. The gas velocity at the backward of the wire is accelerated by the Lorentz force and Peclet number becomes bigger. It means that the effect of the convection on the metal vapor transportation is larger than the diffusion. Therefore, metal vapor evaporated from a wire surface is transported forward preferentially in the welding direction, and the iron vapor concentration on the weld bead becomes lower than forward. The arc temperature at forward side of the wire decreases because the radiation loss increases with increasing of the iron vapor concentration.

A few seconds later, the change of the arc plasma temperature distribution becomes smaller because a sufficient

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**Table 1** Computational conditions.

| Parameter                        | Value                      |
|----------------------------------|----------------------------|
| Particle diameter                | 0.5 mm                     |
| Wire diameter                    | 1.2 mm                     |
| Time step                        | 0.1 ms                     |
| Viscosity                        | Metal: $1.50 \times 10^{-3}$-$1.15 \times 10^{-3}$ Pa·s $\rightarrow$ $2.43 \times 10^{-4}$-$2.63 \times 10^{-4}$ Pa·s |
| Thermal conductivity             | Metal: 30.0~73.0 W/m/K $\rightarrow$ Gas: 9.72~8.09 W/m/K |
| Specific heat                    | Metal: $4.40 \times 10^{-1}$-$1.04 \times 10^{0}$ J/kg/K $\rightarrow$ Gas: $4.03 \times 10^{-1}$-$3.80 \times 10^{0}$ J/kg/K |
| Electrical conductivity          | Metal: $8.00 \times 10^{-2}$-$7.69 \times 10^{0}$ A/V/m $\rightarrow$ Gas: $1.00 \times 10^{-2}$-$1.20 \times 10^{0}$ A/V/m |
| Density                          | Metal: $7.85 \times 10^{3}$ kg/m$^3$ $\rightarrow$ Gas: $3.38 \times 10^{-1}$-$2.27$ kg/m$^3$ |
| Melting point                    | 1750 K                     |
| Latent heat of melting($^{11}$)  | 250 kJ/kg                  |
| Latent heat of evaporation       | $6.09 \times 10^{2}$ kJ/kg |
| Gas flow rate                    | 20 L/min                   |
| Welding current                  | DCEP 300 A                 |
| Welding speed                    | 5 mm/s                     |
amount of a molten metal is supplied by the molten metal droplet transfer and the dent on the weld pool surface reduces (Fig. 4(c)).

As stated above, the numerical model developed in this study successfully simulated the arc plasma behavior and the molten metal simultaneously. The plasma temperature simulated in this simulation showed the same tendency compared with the actual GMA welding phenomena\textsuperscript{12).}

![Fig. 3 Temperature distribution of molten metal.](image)

![Fig. 4 Temperature distribution of arc plasma in vertical cross-section (left) and cross-section (right) along weld line.](image)
4. Conclusions

In this study, a GMA welding phenomena simulator was developed, which could simultaneously compute an arc plasma behavior and a weld pool formation process with the time evolution by alternately conducting the particle method and the grid method calculations. Then, the numerical simulation of a GMA welding process was conducted. Conclusions of this study are summarized as follows:

(1) A weld pool was swelled up by the transportation of molten metal droplets with the time evolution and it was solidified after the heat source passed.

(2) The plasma temperature distribution in the welding direction temporally became asymmetric at the start of a welding. This was because the metal vapor evaporated from a wire surface was transported forward preferentially in the welding direction. Then, the iron vapor concentration on the weld bead became lower than the forward side. Therefore, the arc temperature at forward of the wire became lower than backward because the radiation loss increased with increasing of the iron vapor concentration.

(3) A few seconds later after the start of the welding, the change of the arc plasma temperature distribution became smaller because a sufficient amount of a molten metal was supplied by the molten metal droplet transfer and the dent on the weld pool surface reduced.

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