Numerical Simulation of Droplet Transfer with TiO₂ Flux Column During Flux Cored Arc Welding by 3D Smoothed Particle Hydrodynamics Method*

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A molten metal droplet transfer processes were simulated by a numerical model using a three-dimensional smoothed particle hydrodynamics method in order to clarify the flux column formation mechanism at the tip of a wire during a flux cored arc welding process. This study focuses on the flux cored arc welding with TiO₂ based wire. As a result, although the average droplet size obtained by the computation was larger than that by the experiment, the average length of the flux column obtained by the computation showed agreement with that by the experiment, which supports supported validity of this computational model. Moreover, the melting rate of the metal-pipe around flux was higher than flux. The flux column was formed at the tip of the wire. The simulations with different values of a specific heat and a thermal conductivity were performed to investigate the effect of the heat conduction in the wire on the flux column formation. The unmelted flux column was formed at the tip of the wire when the specific heat of the flux component was smaller and the thermal conductivity was higher than those of TiO₂. The result indicated that the heat conduction in flux played an important role in the flux column formation during flux cored arc welding.

Key Words: Flux Cored Arc Welding, Molten Metal Droplet Transfer, Flux Column, Smoothed Particle Hydrodynamics

1. Introduction

Flux cored arc welding (FCAW) is a welding process which uses a flux cored wire as an electrode. The flux cored wire consists of a metal pipe and flux filled in the pipe. The FCAW can be applied to all welding positions. Thus, this welding process has been utilized for various types of industry such as a shipbuilding and a construction¹⁾. Flux cored wires with various flux compositions have been developed and used. A flux column is formed at the tip of the wire under specific welding conditions during the FCAW. Then, molten metal droplets were transported to a weld pool along the flux column.

Several experimental investigations which focused on this flux column formation during the FCAW have been carried out. For example, Matsuda et al. performed the FCAW using wires with different flux compositions in order to investigate welding conditions under which the flux column was formed³⁾. They found that a length of the flux column became shorter as a proportion of iron powder in the flux component increased. Cheng et al. investigated the effect of the flux column formation on the molten metal droplet transfer process in a horizontal position welding using a pulse FCAW process⁴⁾. They clarified that the molten metal droplets whose size were uniform were transported into the weld pool in a specific direction when the flux column was formed.

Hosoi et al. observed the flux column formation process and discussed about the effect of the flux column on the molten metal droplet transfer process during a vertical upward welding⁵⁾. They clarified that the flux column was formed in the FCAW using wires whose component included TiO₂. They also concluded that the flux column was one of the factors which suppressed the defects generation in the weld metal during the vertical upward welding.

It is known that the flux column formation contributed to the uniform droplet transfer and the suppression of the defect generation^{4,5)}. However, flux column formation mechanisms during the FCAW have not been clarified because it is difficult to observe the inside of the wire by experiments.

In this study, the droplet transfer process is simulated by a numerical model using a three-dimensional Smoothed Particle Hydrodynamics (SPH) method in order to clarify the flux column formation mechanism during an FCAW process with a TiO₂ based wire. Moreover, simulations using different values of a specific heat and a thermal conductivity are performed to investigate the effect of the heat conduction in the wire on the flux column formation.

2. Computational method

2.1 Basic idea for SPH

In an SPH method, physical quantities such as the mass, the energy, and so on are transported by fluid particles. A physical quantity $\phi(r=r_a)$ at a certain position $\vec{r}_a$ is written as

$$\phi(\vec{r}=\vec{r}_a) = \sum_b \frac{m_b}{\rho_b} \phi_b W_{ab}, \quad (1)$$

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as the interactions with the adjacent particles b^6). Here, a and b are indices of particles, m is the mass, ρ is the density, W is the kernel function which is calculated according to the particle size and the distance between particles a and b . The M4-Spline function is used as the kernel function⁷).

This SPH method was originally developed for simulations of compressible flows⁸). When the SPH method is applied to an incompressible fluid, the motion cannot be expressed unless the time step is sufficiently small. Therefore, an enormous computational cost is required for the simulation. In this study, the density homogenizing algorithm is used to apply the SPH method to the incompressible flow with large time step. Details of this algorithm is written in the reference⁹).

2.2 Navier-Stokes equation for SPH

The velocity of a liquid particle a is calculated by the Navier-Stokes equation¹⁰), which is described in the SPH form as

$$\frac{D\vec{u}_a}{Dt} = -\sum_b m_b \left(\frac{p_a}{\rho_a^2} + \frac{p_b}{\rho_b^2} \right) \nabla_a W_{ab} + \frac{2D}{\lambda_a w_a \rho_a} \sum_b \frac{\mu_a + \mu_b}{2} (\vec{u}_b - \vec{u}_a) W_{ab} + \frac{\vec{F}_a}{\rho_a}, \quad (2)$$

where $\vec{u}$ is the velocity vector, t is the time, m is the mass, ρ is the density, p is the pressure, D is the dimension number, λ is the parameter¹¹), μ is the viscosity and $\vec{F}$ is the external force vector. The gravity, the surface tension and the Lorentz force are considered as the external force. w is described as

$$w_a = \sum_b W_{ab}. \quad (3)$$

2.3 Energy transfer equation

Temperature changes of all particles are calculated by an energy transfer equation, which is described as

$$\frac{DT_a}{Dt} = \frac{2D}{\rho_a \lambda_a w_a C_a} \sum_b \frac{\kappa_a + \kappa_b}{2} (T_b - T_a) W_{ab} + \frac{S_a q_a}{C_a m_a}, \quad (4)$$

where T is the temperature, C is the specific heat, κ is the thermal conductivity, S is the cross-section of a particle, q is the heat generation rate. In this model, the heat generation rate is described as

$$q_a = q_{\text{Arc}} - \varepsilon \alpha (T_a^4 - 300^4) + |\vec{j}_a| \varphi_a + \frac{|\vec{j}_a|^2 m_a}{S_a \gamma_a \rho_a}. \quad (5)$$

Here, q_{Arc} is the heat transfer from an arc plasma based on the Fourier's law, ε is the emission coefficient, α is the Stefan-Boltzmann constant, φ is the work function, $\vec{j}$ is the current density vector and γ is the electrical conductivity. The terms in the right-hand side show the heat flux from a shielding gas, the emission loss, the heating by the electron inflow and the Joule heating, respectively.

3. Computational conditions

Figure 1 shows the schematic illustration of a computational domain. The arc plasma has three-dimensional distribution. However, three-dimensional calculation of the arc plasma is difficult and requires more computational cost than two-dimensional calculation. The calculation for physical quantities of the arc plasma assumes a two-dimensional axisymmetric condition and a steady state. Physical quantities of the arc plasma are obtained by a calculation with a grid-based method¹²) using the initial shape of the wire. Therefore, a heat source distribution of the arc plasma does not change during a computation with the wire shape deformation. Physical quantities of the wire particles are obtained by a calculation with three-dimensional SPH method. The physical properties at each particle position are calculated using the bilinear interpolation¹⁰). A wire diameter is set to be 1.2 mm. A diameter of the flux region is set to be 0.54 mm. Material properties of TiO₂ which is the main component of flux are given to flux particles. Solid particles of the wire are supplied from the top of the computational domain. The wire feed rate is set to be 16 m/min. A base metal is not set in the computational domain of the SPH method. Table 1 shows other computational conditions. The surface tension coefficient, the viscosity coefficient and the emissivity are set to be equal for the metal pipe and the flux component. The surface tension coefficient is 1.0 N/m, the viscosity coefficient is 2.0×10^{-3} Pa·s and the emissivity is 0.4. Table 2 shows other material properties. Material property values at 300 K are used for the calculation. Temperature dependence of material property is not considered.

Fig. 1 Schematic illustration of the computational domain.

Table 1 Computational conditions for the FCAW model.

Time step	1.0×10^{-5} s
Diameter of particles	ϕ 0.05 mm
Welding current	300 A
Polarity	Direct current electrode positive
Shielding gas	Pure Ar
Gas flow rate	20.0 L/min

Table 2 Material properties for the FCAW model.

	Flux	Metal pipe
Melting point	1870 K ⁽¹³⁾	1511 K ⁽¹⁴⁾
Thermal conductivity	11.8 W/(m·K) ⁽¹⁵⁾	67.0 W/(m·K) ⁽¹⁵⁾
Specific heat	688 J/(kg·K) ⁽¹⁵⁾	460 J/(kg·K) ⁽¹⁵⁾
Density	4210 kg/m ³ ⁽¹³⁾	7850 kg/m ³ ⁽¹⁴⁾
Work function	5.96 eV ⁽¹⁶⁾	4.50 eV ⁽¹⁴⁾

4. Results and discussion

4.1 Validity of the numerical model

Computational results and experimental results were compared in order to verify the present numerical model. Table 2 shows the experimental conditions. DW-100 (JIS Z3313 T 49J 0 T1-1 C A-U) which included TiO₂ in the flux component was used as a wire. SS400 (JIS G3101) was used as a base metal. Droplet transfer processes were observed using a high-speed video camera (MIRO.eX, VisionResearch).

Figure 2 shows the experimental result and the computational result immediately after a droplet was detached. Figure 2 (b) shows the vertical cross-section along the center of the wire. In Fig. 2 (b), dark gray particles and light gray particles represent a metal pipe and flux, respectively. The flux column was formed at the tip of the wire in both of the experimental result and the computational result. The droplet size and the length of the flux column immediately after droplet detachment from the wire tip was measured. Figure 3 shows the definition of the length of the flux column and the droplet diameter. The end of the wire was defined as the lower end of the flux column. The top of the arc plasma was defined as the upper end of the flux column. The average length of flux column was obtained by averaging 10 measurements. The distance between the left edge and the right edge of the droplet immediately after detachment was defined as the droplet diameter. The average droplet size was obtained by averaging 10 measurements. Figure 4 shows the droplet sizes and the lengths of the flux columns obtained from the experimental results and the computational results. Solid triangle and solid circle represent average values obtained from experimental results and computational results, respectively. Error bars represent the 95%

confidence interval for the average values. The 95% confidence interval is written as

$$\left[\bar{x} - 1.96 \frac{\sigma}{\sqrt{n}}, \bar{x} + 1.96 \frac{\sigma}{\sqrt{n}} \right], \quad (6)$$

where $\bar{x}$ is the average value of the samples, σ is the standard deviation and n is the sample size. σ is written as

$$\sigma = \sqrt{\frac{1}{n-1} \sum_{i=1}^n (x_i - \bar{x})^2}, \quad (7)$$

where x_i is the individual value of samples.

In terms of the droplet size, the computational results did not agree with experimental results within the 95% confidence interval. This is because the calculation model assumes that the current density distribution of an arc plasma does not change during the computation. In an actual molten metal droplet transfer process, a current path in the arc plasma changes with the wire deformation. With constriction of the wire shape, the current density in the constricted wire increases, which causes the increase of the Lorentz force in it. Thus, it is considered that the droplets were detached from tip of the wire because of the increase of the Lorentz force on the top of the droplet⁽¹⁷⁾. However, the Lorentz force does not increase on the top of the droplet during this computation since the current density distribution does not change. It takes a longer time for the droplets to detach compared with the experiments. Therefore, the droplet in this computation grows and its size was larger than the experiments.

In terms of the length of the flux column, the computational results show agreement with the experimental results within the 95% confidence interval. This study focuses on the mechanism of flux column formation. Therefore, the present model can be used validly for the simulation.

Table 2 Experimental conditions for FCAW.

Welding current	316 A
Arc voltage	31.5 V
Polarity	Direct current electrode positive
Shielding gas	100% Ar
Gas flow rate	20.0 L/min.
Welding speed	5 mm/s
Filter	ND-8×2
Aperture	F45
Lens	Nikon, AF Micro-NIKKOR 200 mm 1:4 D
Camera	VisionResearch, MIRO.eX
Exposure time	20 μs

(a) Experimental result (b) Computational result
Fig. 2 Comparison of experimental and computational results.

Fig. 3 Definition of the length of the flux column and the droplet diameter.

(a) Droplet diameter (b) Length of flux column
Fig.4 Experimental and computational results.

4.2 Mechanism of flux column formation

Simulations with different values of the specific heat and the thermal conductivity are performed to investigate the effect of the heat conduction in a wire on the flux column formation. Figure 5

and Fig. 6 show the computational results. Both of them show the vertical cross-sections along the center of the wire at $t = 35$ ms. Figures 5(a) and 5(b) show the particle state and temperature distributions when the specific heat and the thermal conductivity of TiO_2 are given to flux. Moreover, Figures 6(a) and 6(b) show the particle state and temperature distributions when the specific heat and the thermal conductivity of a metal pipe are given artificially to flux. In the particle state distributions, red particles, blue particles, yellow particles and light blue particles represent a solid metal pipe, a molten metal, solid flux and a molten flux, respectively. In the temperature distributions, particles are shown by the color range from blue to red depending on their temperatures.

The flux temperature at point A ($z = 3.5$ mm) is lower than the melting point of flux (Fig. 5 (b)). On the other hand, the flux temperature at point A ($z = 3.5$ mm) in Fig. 6 is higher than the melting point, and flux is melted. The material properties of the flux are equal except for the specific heat and the thermal conductivity in Fig. 5 and Fig. 6. The specific heat of the flux is higher and the thermal conductivity is lower in Fig. 6 compared to Fig. 5. Figure 7 shows an enlarged view of the region B ($-0.5 < y < 1.5$, $2.0 < z < 3.0$) in Fig. 6. Figure 7(a) and 7(b) show the particle state and the temperature distribution, respectively. Energy is hardly conducted in the flux column because of the low thermal conductivity of TiO_2 . Temperature of the flux column hardly rises compared to the metal pipe because of the high specific heat of TiO_2 . Then, temperature inside the flux is lower than the surface of the flux column (Fig. 7(b)). These results suggest that the flux column is formed because of the high specific heat and the low thermal conductivity of the flux component TiO_2 .

5. Summary

Molten metal droplet transfer processes were simulated by a numerical model using a three-dimensional SPH method in order to clarify the flux column formation mechanism during FCAW. Although the average droplet size obtained by the computation was larger than that by the experiment, the average length of the flux column obtained by the computation showed agreement with that by the experiment, which supported validity of this computational model. Furthermore, simulations with different values of the specific heat and the thermal conductivity were performed to investigate the effect of the heat conduction in the wire on the flux column formation. The unmelted flux column is formed at the tip of the wire when the specific heat of the flux component was smaller and the thermal conductivity was higher than those of TiO_2 . The result indicate that the flux column is formed because of the high specific heat and the low thermal conductivity of the flux component TiO_2 . The behavior of the droplet with flux and heat

source distribution of the arc plasma should be discussed in order to understand the droplet transfer process in FCAW in more detail. Temperature dependence of the material properties and three-dimensional distribution of the arc plasma should be considered in a future work

(a) Particle state distribution (b) Temperature distribution
Fig. 5 Computational results when the specific heat and the thermal conductivity of TiO₂ are given to flux.

(a) Particle state distribution (b) Temperature distribution
Fig. 6 Computational results when the specific heat and the thermal conductivity of the metal pipe are given to flux.

Fig. 7 Enlarged view of the region B in Fig. 5

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