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Numerical simulation of molten metal droplet transfer and weld pool convection during gas metal arc welding using incompressible smoothed particle hydrodynamics method

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ABSTRACT

The weld pool convection and the bead formation in a gas metal arc welding were simulated by a three-dimensional incompressible smoothed particle hydrodynamics method. Moreover, the ensemble average processing was carried out to investigate dynamic changes of the velocity field of a weld pool. From these results, it was formed that the droplet transfer affected the velocity field of the weld pool, especially the region which was about 3 mm from a weld pool surface in the vertical direction and about ± 5 mm from center of the heat source in the horizontal direction.

1. Introduction

GMAW (Gas Metal Arc Welding) is one of the welding process in which an electrode wire is heated and melted. This process is widely used in industry because it can be applied to various materials and can be automated easily. In GMAW, its characteristics are significantly changed by operating conditions and materials of wires and base metals. Therefore, detailed mechanisms in GMAW should be clarified and understood to control its weld pool shape. However, it is difficult to investigate the processes in GMAW including molten metal transfers and weld pool convection by experiments. Because of experimental difficulties, numerical investigation using simulations have been carried out. For example, Cho et al. [1] simulated the humping and the melt through during a GMAW and investigated the effect of welding positions on velocity fields in a weld pool for V-groove joints. Hu et al. [2] simulated the sulfur concentration distribution and velocity fields in a weld pool. They also simulated the ripple deformation process on a weld bead. These computational models used grid systems to treat gas-liquid interface and gas-solid interface combining with VOF (Volume Of Fluid) method [3]. However, because the solid-liquid interfaces in the base metals were treated on grid points, the interface shapes were expressed as grid-like shapes.

On the other hand, SPH (Smoothed Particle Hydrodynamics) method and MPS (Move Particle Semi-implicit) method which are Lagrangian methods have been adapted to various welding processes in recent years because these methods can treat interfaces easier. For instance, Tong et al. [4] carried out to simulate a laser welding process in a two-dimensional domain. They calculated not only weld pool convection but also the flow and temperature of ambient atmosphere. They successfully computed a convection to the center of a weld pool, although their model considered only shear force and surface tension as a driving forces acting on a weld pool surface. Ito et al. [5,6] developed a computational model of GTAW (Gas Tungsten Arc Welding) for SUS304 stainless steel and investigated the effect of the sulfur content in a base metal on the weld pool convection and the penetration shape. They successfully simulate that weld pool convection and penetration depth were affected by the sulfur content in SUS304 using three-dimensional incompressible SPH method. Das and Cleary [7] simulated plastic strain and temperature distributions in a weld metal on V-groove joints made of aluminum alloy using three-dimensional SPH method. Although their model was a simple model in which the heat input from plasma and driving forces acting on a weld pool were not considered, they could visualized plastic strain, temperature and von Mises stress distribution around a weld part. However, there is still no study of the three-dimensional flow of a weld pool during a GMAW with molten metal droplet transfer.

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Hence, in this study, a three-dimensional model base on SPH method is developed to clarify the weld pool convection and mechanisms of bead formation in a GMAW process.

2. Incompressible SPH method

2.1. Density homogenizing algorithm

In this study, the density homogenizing algorithm is used in order to apply SPH method [8] that is originally used for compressible flows to incompressible flows such as weld pool convection. This algorithm is a computational technique which calculates a velocity field with the density homogenizing process using an iterative solution method based on a predictor-corrector method. The details of that density homogenizing algorithm are referred to the previous study [9]. That outline is described as follows. In the density homogenizing algorithm, at first, all fluid particles are moved according to their velocity predictors which are calculated by external forces and viscosity force obtained at the last time step. At this moment, the density field of the computational domain temporarily has a non-uniform distribution. To homogenize the density field, the predictors are corrected and all fluid particles are moved again according to these corrected predictors. This algorithm is a computational method to express the incompressible flow, in which the positions of particles are adjusted by these iterations until the density field in the whole region is homogenized.

2.2. Governing equations

In the SPH method, physical quantities such as mass, energy, and so on are transported by fluid particles. A physical quantity A_a at a certain position a is written as

$$A_a = \sum_b m_b \frac{A_b}{\rho_b} W_{ab}, \tag{1}$$

as the interactions with the adjacent particles b. Here, a and b are the indices of particles, m is the mass, ρ is the density, W is the kernel function. Using Eq. (1) and the Navier-Stokes equation which expresses the motion of fluid, the acceleration of a particle is written as

$$\frac{D\vec{u}_a}{Dt} = -\sum_b m_b \left(\frac{p_a}{\rho_a^2} + \frac{p_b}{\rho_b^2}\right) \nabla_a W_{ab} + \frac{2dim}{\lambda_a n_a \rho_a} \sum_{b \neq a} \frac{\mu_a + \mu_b}{2} (\vec{u}_b - \vec{u}_a) W_{ab} + \frac{\vec{F}_a}{\rho_a}, \tag{2}$$

where u is the velocity, t is the time, p is the pressure, dim is the dimension number, λ is the parameter of MPS method [10], n is the number density, μ is the viscosity and $\vec{F}$ is the external force vector.

3. Modeling of the metal droplet transfer

3.1. Driving forces acting on the wire

A computational model developed by Tsujimura et al. [11,12] is used in this study as a heat source. This model is a simple model, which did not consider molten metal droplet transfer phenomena but only heat energy transferred by molten metal droplets, and gave the energy to a certain area on the base metal surface around the center of a heat source. Therefore, it is difficult to calculate parameters of a molten metal droplet such as velocity, mass, diameter and transfer frequency from that computational result. In this study, as a preliminary simulation for the main simulation of a weld pool with the molten metal droplet transfer, the formation and detachment processes of molten metal droplets at the tip of a wire during a GMAW are computed by the incompressible SPH method to determine the velocity of a molten metal droplet to the weld pool. The obtained velocity is used in the main simulation of the weld pool. Moreover, using these results and the energy balance obtained by the previous study [11], the frequency and temperature of a molten metal droplet are calculated. These parameters are also used in the main weld pool simulation. During a GMAW, pressure and shearing force which are caused by shielding gas, gravity, surface tension, Lorentz force as driving forces [13]. Among these driving forces, the forces caused by plasma or shielding gas are calculated using the computational results of the previous study [11]. However, the directions of the pressure and shearing force are changed by the position and shape of molten metal droplets. It is difficult to determine these two driving forces from the simple arc model [11]. In this study, these two driving forces on a droplet are merged and treated as a drag force given by shielding gas. The external force in Eq. (2) acting on particle a is given

$$\vec{F}_a = \vec{j} \times \vec{B} + \vec{F}_a^{\mathrm{L}} + \vec{F}_a^{\mathrm{LS}} + \vec{F}_a^{\mathrm{D}} + \rho_a \vec{g}, \tag{3}$$

where j and B are the current density and the magnetic flux density at the particle position, respectively. The first term means the Lorentz force obtained from the previous study [11] using the bilinear interpolation. V is the volume, F^{L}, F^{LS} are the surface tension forces which are calculated using the attractive force model [5]. In this attractive force model, each force can be written as

$$\vec{F}_a^{\mathrm{L}} = \frac{1.2(1-\psi)\gamma h}{V_a} \sum_b f_{ab}^{\mathrm{attract}} \bigg|_{a,b \in \mathrm{Liquid}} \tag{4}$$

$$\vec{F}_a^{\mathrm{LS}} = \frac{1.2\psi\gamma h}{V_a} \sum_b f_{ab}^{\mathrm{attract}} \bigg|_{a,b(\mathrm{Liquid} \cup \mathrm{Solid})}, \tag{5}$$

ψ is the parameter to determine the contact angle and the surface tension coefficient γ is set to be 1.0 N/m. $f_{ab}^{\mathrm{attract}}$ is the weighted function that is decided by the distance between particle a and b, which is expressed as

$$f_{ab}^{\mathrm{attract}} = \begin{cases} \frac{|\vec{d}_{ab}|}{h} & \left(0 \leqslant \frac{|\vec{d}_{ab}|}{h} < 1\right) \\ 2 - \frac{|\vec{d}_{ab}|}{h} & \left(1 \leqslant \frac{|\vec{d}_{ab}|}{h} < 2\right) \end{cases}, \tag{6}$$

$\vec{d}_{ab}$ is the relative distance vector between particle a and b. h is the evaluate radius. F^{D} is the drag force caused by shielding gas obtained assuming that a droplet is a hard sphere [14]. $\vec{g}$ is the acceleration vector of gravity, which is set to be -9.8 m/s^2.

3.2. Computational conditions for the wire model

In this calculation, the diameter of a wire is 1.2 mm and it consists of particles with the diameter of 0.1 mm. Moreover, the temperature change of a particle is not considered for simplification and solid particles which are parts of the wire are changed to liquid particles when they move under the solid-liquid interface whose height equals to that of the wire tip at $t = 0.0$ s. This is reasonable because the solid-liquid interface is assumed to keep a constant height since a wire feed rate balances with the wire melting speed [13]. In this study, the welding current, the wire feed rate and the welding speed are set to be 300 A, 7.9 m/min and 5.0 mm/s based on the previous study [11] for a spray transfer. In addition, the density of a particle is 7850 kg/m^3 and the viscosity coefficient is