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Citation	Transactions of JWRI. 39(2) P.11-P.13
Issue Date	2010-12
Text Version	publisher
URL	http://hdl.handle.net/11094/3719
DOI	
rights	
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Three-dimensional simulation of a flow in an arc weld pool by SPH method†

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KEY WORDS: (SPH) (Arc welding) (Weld pool) (Penetration shape) (Marangoni effect)

1. Introduction

To optimize an arc welding process, precise prediction and evaluation of weld penetration are indispensable. However, it is extremely difficult to measure and directly observe the molten-metal flow in the weld pool [1]. Furthermore, the modeling approach is also arduous because conventional grid-based numerical methods require a tangled algorithm to simulate the complicated flow in a weld pool which includes deformation of its free surface and movement of the solid-liquid interface due to the phase transition.

In this study, to overcome that problem, an SPH (Smoothed Particle Hydrodynamics) method is adopted for simulating the thermofluid behavior during an arc welding process, taking into account four dominant flow-driving forces: the gradient of the surface tension (Marangoni effect), the gas drag at the surface, the buoyancy, and the electromagnetic force (Lorentz force). The numerical calculations are carried out to demonstrate the individual effects of those forces on the flow behavior. Also, the simulation of a weld pool is performed including all of those forces and the phase transition. In addition, the influence of the sulfur content on the flow behavior and the weld penetration is presented.

2. Model Description

The SPH method is a gridless Lagrangian technique that expresses the fluid motion by particles that move according to Navier-Stokes equation. Additionally, even a solid region can be represented by particles that do not move. Hence, SPH method offers high adaptability to processes with large interface deformation such as a flow in an arc weld pool. In this method, the mass of each particle is given as a continuous function of Kernel W, so that the equation of motion is written as

$$\frac{\partial \boldsymbol{u}_a}{\partial t} = -\sum_b m_b \left(\frac{p_a}{\rho_a^2} + \frac{p_b}{\rho_b^2} \right) \nabla_a W_{ab} + \frac{\boldsymbol{F}_a}{m_a}, \qquad (1)$$

where a and b denote the particle indices, $\boldsymbol{u}$ is the velocity, t is the time, p is the pressure, m is the mass of a particle, ρ is the density at the position of a particle, and $\boldsymbol{F}$ is the external driving force. The first term of the right hand side in Eq.(1) represents the pressure gradient. In this paper, although the viscosity term is neglected, the fluid behaves like a viscous flow because of the numerical viscosity. The detailed model description is found in Ref. [2].

3. Computational Condition

The computational domain is a cylindrical anode with the diameter of 50 mm and the height of 10 mm. The domain is discretized by 27,504 particles with the diameter of 1.0 mm. At the side and bottom of the domain, two-particle layers are set as a solid wall which does not melt. It is assumed that the position of the cathode is above the cylinder along the central axis. The physical properties of SUS304 are given to all the particles. The 300K uniform temperature distribution is given to the entire area as an initial condition. The wall temperature is also fixed at 300K. The top surface of the anode is heated in the arc welding. The heat flux from an arc to the anode surface is calculated based on the temperature distribution numerically obtained by Tanaka et al. [3], which affects the surface particles. The time step is set to be 1.0 ms.

Table 1 Computational conditions.

Case	Force	Phase
1	–	Liquid
2	Marangoni (with low sulfur)	Liquid
3	Marangoni (with high sulfur)	Liquid
4	Gas drag on surface	Liquid
5	Buoyancy	Liquid
6	Lorentz force	Liquid
7	All forces (with low sulfur)	Solid+Liquid
8	All forces (with high sulfur)	Solid+Liquid

4. Results and Discussion

In this study, eight cases of computation are performed as presented in **Table 1**. Case 1 is to see the effect of heat transfer only. Cases 2-6 are carried out against molten metal in order to check whether the SPH method can handle convective flows driven by the four forces: namely, the gradient of surface tension (Marangoni effect), the gas drag on the surface, the buoyancy, and the electromagnetic force (Lorentz force). **Figure 1** presents the computational results of the half domain at t = 2.0 s. Each particle is colored according to its temperature. White corresponds to 2500 K.

† Received on 30 September 2010.
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Transactions of JWRI is published by Joining and Welding Research Institute, Osaka University, Ibaraki, Osaka 567-0047, Japan

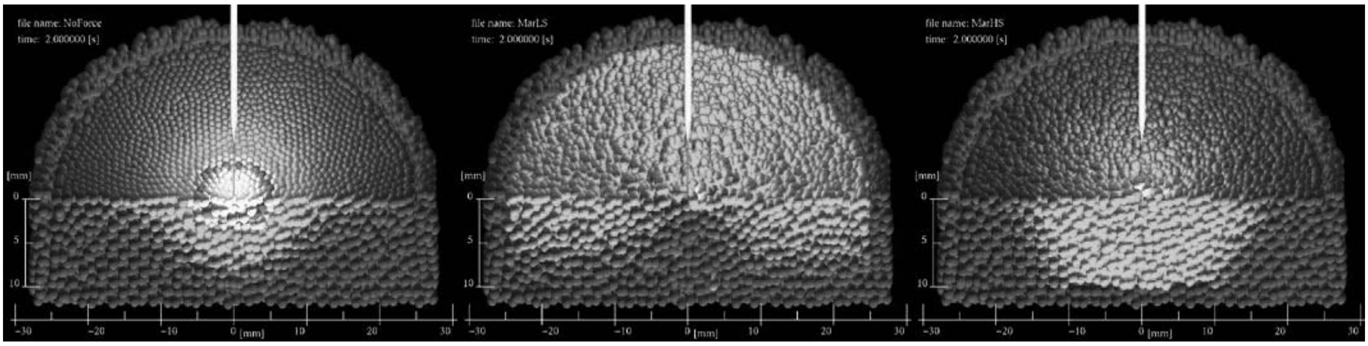
In Case 2, the fluid heated at the center on the surface spreads outward, while in Case 3, the heated fluid is transported downward. These results derive from the difference in the direction of the surface tension gradient. It is known that Marangoni effect shows two different tendencies depending on the sulfur content in SUS304, i.e. the surface tension increases with temperature when the sulfur content is low, while it decreases when the sulfur content is high [4]. In the present computation, the specific data of Ref. [4] is used.

In Case 4, the gas drag, which is a frictional force by the shielding gas flow on the surface of the weld pool, is calculated from the velocity distribution obtained in Ref. [3]. Because the drag acts outward to the surface particles, the high temperature region at the surface spreads.

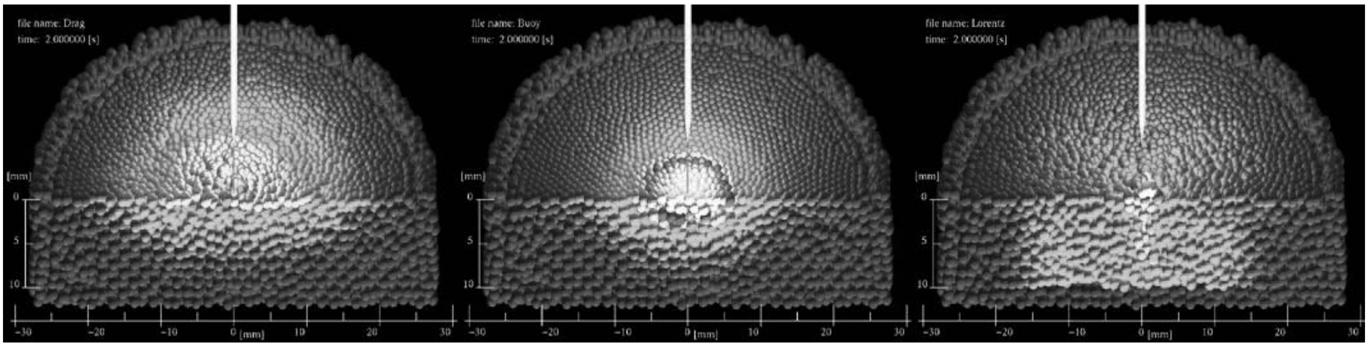
In Case 5, the buoyancy caused by the non-uniform temperature distribution in a weld pool are taken into account. The force is calculated using the Boussinesq approximation and is given to all liquid particles. As a result, the high temperature region is observed only on the surface.

Case 6 shows that the fluid heated at the surface flows downward. During the arc welding, the electromagnetic field is generated, and consequently, the Lorentz force acts on the fluid inside of the weld pool. In this study, the axisymmetric Lorentz force is calculated from the electric current density distribution obtained in Ref. [3].

Figure 2 depicts the computational results when all the forces and the phase transition are taken into account, at t = 20.0 s. For the phase change, the latent heat is treated. The red particles are at the melting point, 1750 K. The depth of penetration is approximately 4 mm in Case 7, meanwhile the penetration has reached about 8 mm in Case 8. This difference is obviously attributed to the difference in the sulfur contents.

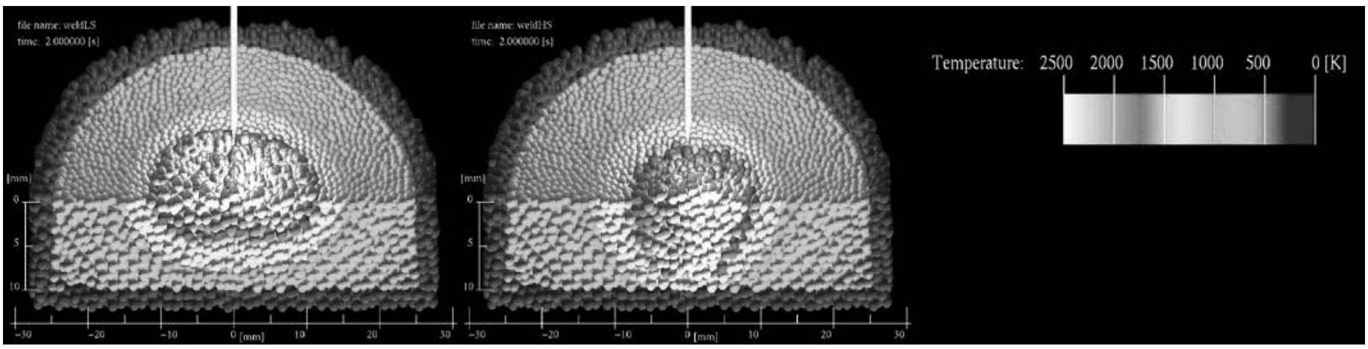


Case 1 Case 2 Case 3



Case 4 Case 5 Case 6

Fig. 1 Temperature distributions caused by flow driven with only a force (t = 2.0 s).



Case 7 Case 8 Color legend of the images

Fig. 2 Temperature distributions including all the forces and phase transition (t = 20.0 s).

5. Conclusions

In this study, the SPH method was applied to a simulation of the thermofluid behavior during an arc welding process, taking four dominant flow-driving forces into account. The numerical calculations presented the effect of each force on the temperature distribution inside the weld pool. Also, the simulation of a weld pool was conducted including all the forces and the phase transition. The influences of the sulfur content on the flow behavior and the weld penetration were shown. The penetration shapes of the present computation showed a tendency similar to Ref. [3]. Here, we can conclude that SPH method is a method suitable for a thermofluid simulation of an arc weld pool.

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