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Analysis of submerged arc welding process by three-dimensional computational fluid dynamics simulations

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ABSTRACT

The effect of torch angle and current polarities on the convection heat transfer in single wire submerged arc welding is analyzed. To develop arc models such as arc heat flux, arc pressure and electromagnetic force, this study adopts the Abel inversion method with CCD camera images for direct and alternating current polarities. The heat transfer by molten slag from the flux consumption is considered as an additional boundary heat source in the numerical simulation. The variation of arc forces, the direction of droplet flight with polarity and the torch angle significantly affect the molten pool flow and the resultant weld beads. The simulated weld pool profiles are validated with corresponding experimental results and found to be in good agreement.

1. Introduction

Submerged arc welding (SAW) is a very complex process that includes physical and chemical reactions. Moreover, it is very difficult to investigate the whole SAW process using numerical simulations. However, the molten zone and heat-affected zone (HAZ) could be estimated using the finite element method (FEM) and considering just the conduction heat transfer. Wen et al. (2001) modeled multi-wire SAW of thick-wall line pipe and calculated the thermal distributions under various welding conditions. Mahapatra et al. (2006) predicted the temperature distributions and angular distortions in single-pass butt joints using three-dimensional simulations. Sharma et al. (2009) suggested and validated a volumetric heat source model of twin-wire SAW by using different electrode diameters and polarities. Kiran et al. (2010) simulated a three-dimensional heat transfer of a V-groove tandem SAW process for various welding conditions using FEM. However, these studies with FEM only considered the heat conduction transfer in the welding process, which is insufficient to explain the curve weld bead such as fingertip penetration.

To overcome these disadvantages, computational fluid dynamics (CFD) is widely used to investigate molten pool flows and final weld beads because it makes it possible to approach the welding process more realistically (Kim and Na, 1994). Considering the importance of weld pool convection in the welding process, numerous researchers have attempted to analyze the heat transfer and fluid flow. Kim et al. (2003) calculated the convective heat transfer and resultant temperature distributions for a filet gas metal arc welding (GMAW) process. Kim et al. (1997) obtained the thermal data and analyzed the molten pool flows for various driving forces in stationary gas tungsten arc welding (GTAW). However, these studies assumed that the welding process was in a quasi-steady-state. Thus it was very difficult to approximate the droplet impingent and arc variation with alternating current (AC).

Therefore, it is necessary to apply a transient analysis to the welding simulation because it can detect the free surface variation during the simulation time. One transient analysis method is the volume of fluid (VOF) method, which can track the molten pool surface; therefore, the variable models from arc plasma could be implemented in the simulations. Cho et al. (2013a) calculated the electromagnetic force (EMF) with mapping coordinates in V-groove GTAW and GMAW, and then applied it to the numerical simulation to obtain the dynamic molten pool behavior and final weld bead using the commercial software, Flow-3D. With the advantage of VOF transient simulation, Cho et al. (2013c) could calculate unstable molten pool flow patterns such as humping and overflow in V-groove positional GMAW. Cho et al. (2013b) obtained the heat flux distribution of the arc plasma in gas hollow tungsten arc welding (GHTAW) using the Abel inversion method and applied it to the VOF model to predict the molten zone area. Additionally, a

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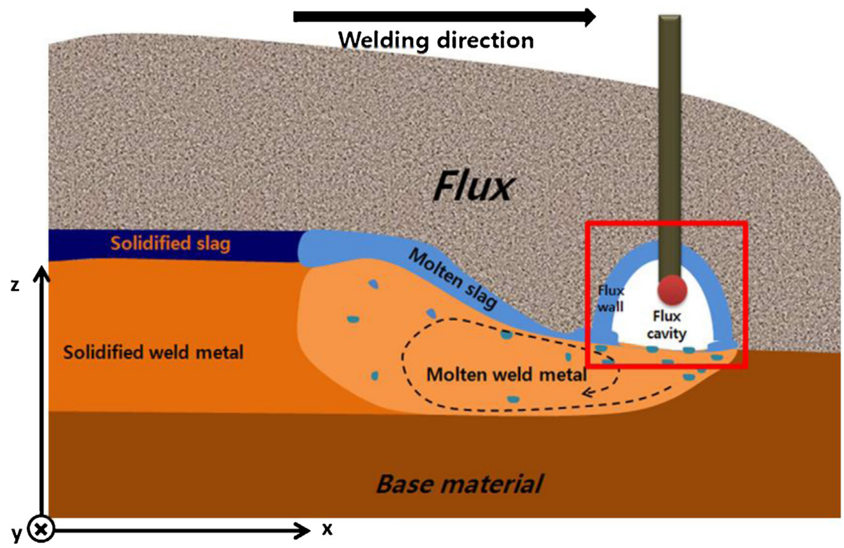

Fig. 1. Schematic diagram of SAW.

more complex welding process can also be calculated by VOF. Cho and Na (2006) conducted a laser welding simulation that included the multiple reflection and keyhole formation. Moreover, Cho and Na (2009) conducted the three-dimensional laser-GMA hybrid welding, which adopted the laser welding and GMAW. Han et al. (2013) compared the driving forces for the weld pool dynamics in GTAW and laser welding. The VOF method could also be applied to describe the alloying element distributions and pore generation in the laser-GMA hybrid welding process (Cho et al., 2010, 2012). This paper considers the heat transfer by molten slag as a heat input and suggests a new way to describe the molten pool flows in a single-electrode SAW process using CFD.

2. Characteristics of SAW

Fig. 1 shows a schematic diagram of SAW to allow the following characteristics to be understood: (a) flux and molten slag cover the overall weld bead, and (b) the fabricated flux wall protects the flux cavity.

Although it is very difficult to observe the metal transfer of SAW, some previous studies succeeded in capturing the motion of a droplet in SAW. Franz (1965) and Van Adrichem (1966) observed the metal transfer through a ceramic tube using a X-ray cinematography and found that drops travel in free flight to the weld pool, or they may project sideways to collide with the molten flux wall. This metal transfer in SAW is the so-called flux-wall guided (FWG) transfer, as shown in Fig. 2.

During the SAW process, a small portion of the flux is melted and consumed. Chandel (1998) found that the flux consumption relies upon three sources: (a) conduction from the molten metal, (b) radiation from arc and (c) resistance heating of the slag. However, their individual contributions to flux consumption are still unclear. In any case, the total flux consumption can be calculated by measuring the mass of the flux used. Renwick and Patchett (1976) analyzed the relations between welding parameters and the flux consumption and found that flux consumption initially increased with increasing current, reached a maximum, and then decreased. Chandel (1998) also measured the flux consumption of SAW with various welding parameters and showed that the flux consumption reached a peak value at 500 A and decreased at higher currents, as shown in Fig. 3(a). This decrease at a high current is a result of the increasing current causing the droplet size to decrease. Therefore, the contact area between the droplet and the flux-wall could be decreased, as shown in Fig. 3(b). In short, FWG transfer is difficult to observe at high current and the spray mode of transfer can be expected to be considered in high current SAW (Pokhodnya and Kostenko, 1965).

3. Mathematical formulations

To accurately describe the volume of a droplet, previous studies have used at least 4 meshes for the droplet diameter (Cho and Farson, 2007 and Cho et al., 2013c). Thus, this paper used a mesh density of as 0.4 mm/mesh to sufficiently describe the droplet volume and molten pool flow. In the simulations, welding started at 1.5 cm in x-direction.

3.1. Governing equations

The governing equations in the CFD simulations of a weld pool involve the mass conservation equation, momentum conservation equation (Navier–Stokes equations), and energy conservation equation. The commercial package Flow-3D was used for the simulation with a VOF equation. The material properties and variables are given in Table 2.

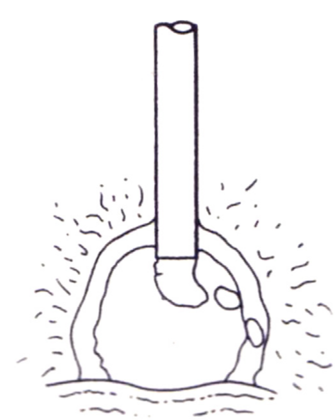

Fig. 2. FWG transfer in SAW (Lancaster, 1986).