Journal of Materials Processing Tech. 251 (2018) 251–261

Contents lists available at ScienceDirect

Journal of Materials Processing Tech.

journal homepage: www.elsevier.com/locate/jmatprotec

Research paper

Numerical simulation of the transition of metal transfer from globular to spray mode in gas metal arc welding using phase field method

Yangyang Zhao, Hyun Chung*

Department of Mechanical Engineering, Korea Advanced Institute of Science and Technology (KAIST), 291 Daehak-ro, Yuseong-gu, Daejeon, 34141, Republic of Korea

ARTICLE INFO

Keywords:
Gas metal arc welding (GMAW)
Globular transfer
Spray transfer
Magnetohydrodynamics
Phase field method

ABSTRACT

A numerical model is constructed based on the solution of the magnetohydrodynamic equations within the framework of phase field algorithm to simulate the metal transfer process and investigate the mechanism of the transition of metal transfer from globular to spray mode. Surface tension is the strongest driving force acting on the pendent droplet in globular transfer, while the governing force shifts to the electromagnetic pinch force in spray transfer. Driving force balance in the axial direction could be the indicator of detachment in globular transfer, while that force balance doesn't exist in spray transfer. The condition for the transition from globular to spray transfer is that the local pressure at the root of the droplet caused by the electromagnetic pinch force exceeds the surface tension pressure at the droplet tip corresponding to a droplet radius equals to the wire radius. Compared with volume of fluid method, phase field method shows a more physically realistic estimation of the current path from the drop to the arc plasma and leads to a better agreement with experimental data.

1. Introduction

Gas metal arc welding (GMAW) is a long-established welding process and has been used to join a wide range of metallic materials in many industrial fields. In GMAW, an arc plasma is established between a consumable filler-metal electrode wire and the workpiece in the atmosphere of shielding gas. The arc melts the wire resulting in the formation of molten droplets which are detached and transferred from the wire to the workpiece. At lower currents, the droplet with a diameter larger than the wire diameter is termed as "globular transfer", while at a high enough current, the droplet would have a diameter smaller than the wire diameter, which is called "spray transfer" (Lancaster, 1986). The capability and quality of the GMAW process is strongly affected by the characteristics of the metal transfer, such as droplet size and frequency of transfer (Lancaster, 1986). Therefore, extensive endeavors have been made to build a better understanding of the metal transfer behavior and its mechanism.

Among several theoretical models proposed to analyze metal transfer, the static force balance model (SFBM) (Waszink and Graat, 1983) and the pinch instability theory (PIT) (Allum, 1985a,b) are of particular relevance. The force balance model calculates the attaching and detaching forces acting on the pendent droplet in the axial direction, and can estimate the droplet size with good accuracy in the globular transfer mode. The pinch instability theory focuses on the radial forces to predict the droplet size in the spray transfer. However, both the SFBM and PIT do not predict the transition from globular transfer to spray transfer (Lowke, 2009).

More recently, numerical investigations calculating the dynamic development of drops have been reported. Choi et al. (1998a,b) used Volume of Fluid (VOF) method to simulate the dynamic characteristics of the globular and spray transfer. However, in the early simulations, the electromagnetic field is analyzed by assuming a uniform (Choi et al., 1998a,b), linear (Fan and Kovacevic, 1999) or Gaussian (Wang et al., 2003) distribution of current density on the surface of the droplet. The accuracy of the modeling result is strongly affected by the assumption of current density distribution on the droplet surface. Moreover, unified models considering both the metal and arc plasma have been reported. Hu and Tsai (2007a,b) developed a unified electrode-arc-workpiece model to simulate the transport phenomena occurring during the GMAW process using a constant welding current. Hertel et al. (2013) presented a numerical simulation of arc and droplet transfer in pulsed GMAW of mild steel in argon shielding gas. Ogino et al. (2016) have investigated the effect of shielding gas composition on droplet transfer behavior using a constant current. Zhao and Chung (2017) built a unified arc-droplet model coupled with electromagnetic-thermal-fluid dynamic analysis to investigate the metal transfer and heat transfer behavior in variable polarity GMAW. These advanced numerical models significantly improve our understanding on the interaction between the molten metal and arc plasma. However, due to the complexity and considerable calculation time of those models, the

* Corresponding author.
E-mail addresses: zhaoyangyang@kaist.ac.kr (Y. Zhao), hyunny92@kaist.edu (H. Chung).

http://dx.doi.org/10.1016/j.jmatprotec.2017.08.036
Received 25 April 2017; Received in revised form 24 August 2017; Accepted 26 August 2017
Available online 30 August 2017

range of welding current in most of these aforementioned simulation models is quite limited. In order to investigate the transition of metal transfer behavior, a broad range of welding current is needed to cover both the globular transfer and spray transfer regime.

Moreover, the interface tracking method would strongly affect the accuracy of the predicted droplet shape as a function of time. Most of the published results are obtained based on the VOF method assuming a sharp interface with zero thickness. Recently, phase field method (Provatas and Elder, 2011) is increasingly popular due to its ability to accurately model two phase flow problems involving sophisticated moving interfaces and complex topologies. Phase field method treats the interface as a thin diffusive layer separating the two fluids. Therefore, the two fluid phases and their interface can be treated in a unified manner. Besides, phase field method incorporates the two phases and interface into the free energy function of the system. It means that it not only transports the interface with the flow but ensures that the total energy of the system is minimized correctly, which is considered to be more physically realistic for small scale interfacial problems (Yang et al., 2017), while a sharp interface method (*e.g.* VOF method) represents a mathematical idealization of the interface. However, application of phase field method to simulate the GMAW process is rarely reported.

In this regard, a numerical model is constructed based on the solution of the magnetohydrodynamic equations within the framework of phase field algorithm to understand the mechanism of the transition of metal transfer from globular transfer to spray transfer. The dynamic characteristics of the drop transfer in globular and spray mode are analyzed and compared. The influence of the driving force in different transfer modes is investigated quantitatively, and the criterion for the transfer mode transition is therefore determined. Moreover, the simulation results using phase field method and volume of fluid method are compared and discussed.

2. Numerical modeling

2.1. Basic assumptions

This study focuses on understanding the mechanism of the transition of drop transfer from globular to spray mode with an emphasis on the magnetohydrodynamic analysis by clarifying the driving forces acting on the pendent liquid droplet and the resultant detaching behavior, the heat transfer analysis is therefore not considered. Due to the symmetry of the GMAW system, the metal transfer behavior can be simplified to a 2D axisymmetric system, as shown in Fig. 1. The dashed box shows the computational domain of this study. The droplet size are calculated by averaging the computed results for 10 droplets, therefore a special boundary condition is set to the bottom of the computation domain that the detached droplet can leave the computational domain through that boundary. Besides, the following assumptions are made in order to simplify the calculation:

(a) Solid-liquid phase transformation of the wire is not considered. The metal is treated as liquid flowing into the computational domain at the wire feeding rate which is assumed to be equal to the wire melting rate calculated by empirical equation.
(b) The liquid metal and shielding gas are treated as two immiscible and incompressible electromagnetic fluid phases. And the fluid flow of both the liquid and gaseous phase are assumed to be laminar flow (Hu and Tsai, 2007a,b).
(c) Driving forces acting on the liquid metal are simplified as gravity, surface tension, and electromagnetic force. The viscous drag force and arc pressure are neglected based on the result presented by Haidar (1998) and Waszink and Graat (1983) that the arc pressure and viscous drag force are only of the order of 10% of the surface tension, and these two forces are largely self-canceling for an argon arc.

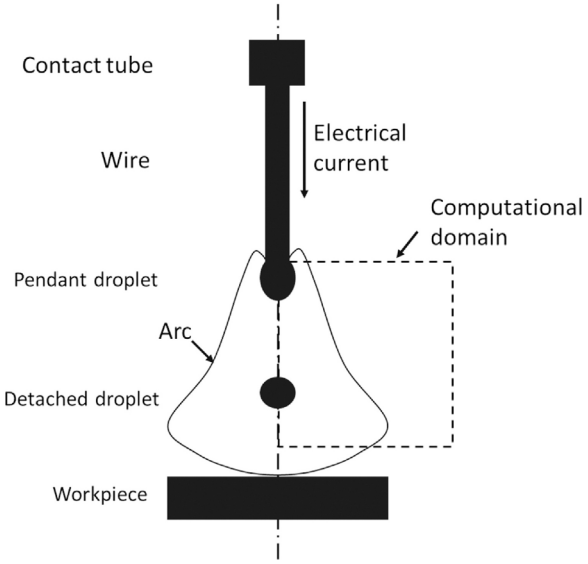

Fig. 1. Schematic of the GMAW system and computational domain.

(d) Physical properties of the two fluid phases are assumed to be constant (Kadota and Hirata, 2011).

2.2. Phase field method

Phase field variable φ is used to represent the fluid configuration. The 0 contour of the phase field variable φ indicates the interface, where φ equals −1 in gaseous phase and 1 in liquid phase. In a transition layer at the interface, φ goes smoothly from −1 to 1. The physical properties of the multiphase mixture are also represented by a function of φ, including the density ρ, the dynamic viscosity μ and the electrical conductivity σ. The subscript m and g indicates the metal phase and gaseous phase, respectively.

$$\rho = \rho_g + (\rho_m - \rho_g)\frac{1+\varphi}{2} \tag{1}$$

$$\mu = \mu_g + (\mu_m - \mu_g)\frac{1+\varphi}{2} \tag{2}$$

$$\sigma = \sigma_g + (\sigma_m - \sigma_g)\frac{1+\varphi}{2} \tag{3}$$

For the free energy density, the familiar Ginzburg-Landau form of free energy density is adopted (Yue et al., 2006):

$$f_{free}(\varphi) = \frac{1}{2}\lambda|\nabla\varphi|^2 + \frac{1}{4}\frac{\lambda}{\varepsilon^2}(\varphi^2-1)^2 \tag{4}$$

Where ε is a capillary width that scales with the thickness of the diffusive interface, and λ is the mixing energy density. The following equation relates the mixing energy density and the interface thickness to the surface tension coefficient γ (Jacqmin, 1999):

$$\gamma = \frac{2\sqrt{2}}{3}\frac{\lambda}{\varepsilon} \tag{5}$$

The chemical potential G which is the differential of the total free energy of the computational domain with respect to the phase field variable and is defined as:

$$G = \frac{\delta f_{free}\, d\Omega}{\delta\varphi} = \lambda\left[-\nabla\cdot\nabla\varphi + \frac{(\varphi^2-1)\varphi}{\varepsilon^2}\right] \tag{6}$$

In the above equation, Ω is the computational domain.

The evolution of phase field variable is governed by a Cahn-Hilliard equation.