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Influence of power source dynamics on metal and heat transfer behaviors in pulsed gas metal arc welding

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

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ABSTRACT

A numerical model has been constructed based on the solution of the magnetohydrodynamic equations within the framework of phase field algorithm to simulate the metal transfer process and to investigate the effect of power source dynamics on metal transfer and heat transfer behaviors in pulsed gas metal arc welding. Three typical kinds of power source dynamics (i.e. exponential, ideal square and trapezoidal waveform) using identical nominal pulsing parameters are considered and compared. The ideal square waveform with infinitely steep-sided pulse would lead to a higher detaching speed and an earlier detachment than other waveforms. Decrease in the response rate of the power source shows a retarding effect on the dynamic characteristics of the metal transfer, leading to a delay of detachment and a lower detaching speed. Moreover, this retarding effect is more and more significant as the response rate decreased and may even alter the transfer mode from one-drop-per-pulse to an undesired irregular pattern. Besides, a quantitative analysis of the heat fluxes into the electrode is further conducted, and the result shows that power source dynamics only has a quite slight influence on the heat transfer behavior.

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. GMAW using a pulsed current waveform, usually termed as pulsed gas metal arc welding (GMAW-P), was invented to generate a controlled metal transfer process over wide ranges of heat and mass input levels [1,2]. GMAW-P is characterized by using a low base current to maintain the arc and a high peak current to melt the electrode wire and detach the droplet at an average current lower than the threshold level for spray transfer [3–5]. The introduction of pulsing brings in additional welding parameters such as the peak and base currents and the peak and base duration, which increases the difficulty to select an optimum combination of welding parameters to detach one, and only one, droplet per pulse. Therefore, significant efforts have been made to understand the effect of pulsing parameters on the metal transfer behaviors and optimize the selection of pulsing parameters to achieve the desirable metal transfer mode of one-droplet-per-pulse [6–10].

However, differences in arc behavior and metal transfer dynamics have been observed for welds made with nominally identical pulsing parameters using different welding equipment [11–14]. In the absence of external factors, the differences are generated by arc-power source interactions and therefore would be related to the dynamic response of the power source, i.e. pulse profile and the rate of rise and fall of the current pulses [15]. Fig. 1 shows three typical types of pulse profile, including the ideal square, exponential and trapezoidal waveform. The ideal square waveform has an infinitely steep-sided pulse, while the exponential type uses an exponential ramp-up and down and trapezoidal type uses a linear ramp-up and down. Although observations suggested that different power source dynamics would result in differences in arc behavior and metal transfer dynamics, there are only quite limited results have been reported on explaining the influential mechanism of the power source dynamics on the metal transfer behavior. Richardson et al. [15] has presented an analytical method to investigate the effect of power source dynamics on the wire melting rate in GMAW-P. An understanding of the effect of power source dynamics on the dynamic characteristics of the metal transfer behavior and heat transfer behavior is essentially needed.

Experimental investigation of the effect of power source dynamics on metal transfer behavior could be extraordinarily costly and time-consuming, since a large number of power sources with different dynamic properties are needed. Therefore,

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

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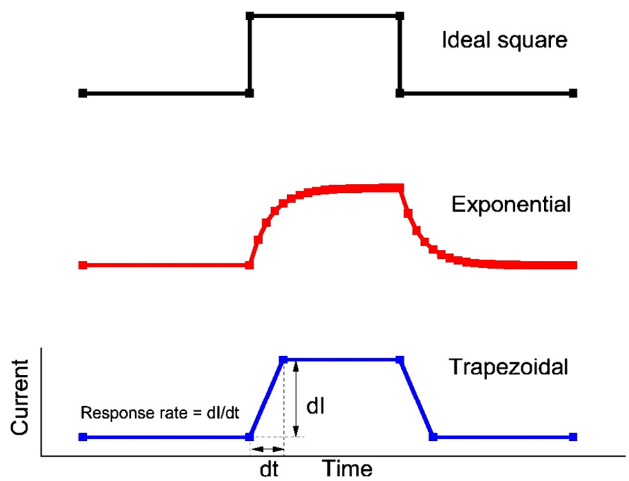

Fig. 1. Schematic representation of the three typical pulse profiles.

numerical approach could be more available. Recently, numerical simulation using CFD have been increasingly adopted to improve the visualization and characterization of the droplet transfer behavior in GMAW process [16–21]. For example, Hu and Tsai developed a unified electrode-arc-workpiece model to simulate the transport phenomena occurring during the GMAW process using a constant welding current [17,18]. Ogino et al. [19] investigated the effect of shielding gas composition on droplet transfer behavior using a constant current. For GMAW-P, Hertel et al. [20] presented a numerical simulation of arc plasma and droplet transfer in GMAW-P of mild steel in argon shielding gas. Ogino et al. [21] further investigated the effect of pulsing parameters (i.e. pulse duration), electrode wire material and surface tension on metal transfer behavior in GMAW-P. These advanced numerical models significantly improve our understanding of the metal transfer behavior in GMAW-P, unfortunately, the effect of power source dynamics was seldom considered.

Moreover, most of the published results are using the volume of fluid (VOF) method by assuming a sharp interface with zero thickness to track the moving interface between the droplet and the arc. Recently, phase field method [22] 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 and 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 [23,24] 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-P process is rarely reported.

Therefore, 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 to investigate the effect of power source dynamics on metal transfer and heat transfer behavior. Firstly, the typical metal transfer behavior in pulsed GMAW is investigated using an exponential type of current waveform, and the simulated results are validated by comparing with high-speed images at different times during the welding cycle. Then, the dynamic characteristics of metal transfer behavior using different types of current waveforms are analyzed and compared, and the effect of response rate is analyzed as well. Moreover, a quantitative analysis of the heat fluxes into the electrode is further conducted to understand the influence of power source dynamics on the heat transfer behavior.

2. Numerical modeling

2.1. Physical considerations

In this study, the presented model focuses on investigating the droplet transfer behavior in GMAW process. Therefore, the description of the workpiece and weld pool is omitted. Due to the symmetry of the GMAW system, it can be simplified to a 2D axisymmetric model.

The interactions between the liquid metal and the arc plasma are described by a multiphase formulation. Both the solid and molten regions of the electrode wire are treated as liquid phase, and the interface between the solid and molten regions is assumed to be constant [16]. Vaporizing of the liquid metal and the influence of the metal vapor is not considered. The arc plasma is considered as gaseous phase. These two phases are immiscible [17,18] and are separated by a moving interface which corresponds to the shape of the wire and the molten droplet. The algorithm of phase field method [22] is used to track the moving interface between the two phases. The multiphase model is combined with the magnetohydrodynamic equations in order to consider the electromagnetic effects in the metal and arc plasma.

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 to -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 [kg/m^3], the dynamic viscosity μ [Pa·s] and the electrical conductivity σ [S/m]. 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 [25]:

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

where ε is a capillary width that scales with the thickness of the diffusive interface [m] and is usually defined as half of the characteristic mesh size in the region passed by the interface and λ is the mixing energy density [N] which satisfies the following equation relates the mixing energy density λ [N] and the interface thickness ε [m] to the surface tension coefficient γ [N/m] [26]:

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

The chemical potential G [J/m^3] is the differential of the total free energy over the computational domain with respect to the phase field variable and is defined as:

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