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Numerical simulation of droplet transfer behavior in variable polarity gas metal arc welding

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ABSTRACT

Gas metal arc welding (GMAW) using an alternating current waveform is usually termed as variable polarity GMAW (VP-GMAW), during which the electrode polarity switches between positive and negative periodically. The arc properties and the droplet transfer in VP-GMAW would be different from traditional direct current GMAW. In order to clarify the droplet transfer phenomena during a VP-GMAW process, a unified numerical model including the interaction between the arc plasma and the moving droplet is developed. The simulation results indicate that the arc plasma generated at electrode negative polarity shows a less constricted shape, a lower plasma temperature and velocity, compared to positive polarity. The resultant droplet is found to have a bigger size and a lower temperature than that of direct current gas metal arc welding with the same average welding current. Moreover, a quantitative analysis of the heat fluxes into the electrode is further conducted to explain the thermal mechanism for the differences in droplet properties between variable polarity and direct current gas metal arc welding. Finally, the simulated results are compared with the high-speed images, and the simulated and experiment results show good agreements.

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 and workpiece in the atmosphere of shielding gas. Due to the heating effect of the arc, the electrode gradually melts, leading to formation of droplet at the electrode tip. The droplet is then detached and transferred through the arc to the workpiece. Conventionally, the GMAW process is conducted with direct current and the electrode is used at anodic polarity. More recently, GMAW using an alternating current waveform, usually termed as alternative current GMAW (AC-GMAW) or variable polarity GMAW (VP-GMAW), is available due to the development of microcomputer-controlled inverter-type GMAW power source [1]. In VP-GMAW, the electrode alternates between direct current electrode positive (DCEP) and direct current electrode negative (DCEN) polarities within one cycle of current waveform, and thus the VP-GMAW combines the advantages of good arc stability in DCEP phase with the increase of wire melting efficiency and the reduction of thermal input into the workpieces in DCEN phase [1,2]. Testing results show that stronger fusion-bridging ability [3–5], reduced welding fume generation [6], higher melting coefficient [7–10] and shorter droplet stagnation time on the wire tip [11] can be achieved in VP-GMAW. Therefore, VP-GMAW is considered as an effective and productive welding process and is attracting increasing attention from both academia and industry.

The capability and quality of the GMAW process is strongly affected by the characteristics of the metal transfer, such as droplet size/temperature and frequency of transfer. Understanding of the droplet transfer phenomenon in GMAW process is of great significance for further process enhancement and control. Nevertheless, the formation and transfer of the molten droplet are governed by the balances of forces and the heat transfer inside the droplet and between the droplet and the arc plasma. The forces mainly include electromagnetic force, surface tension force and gravity, while the heat transfer contains joule heating, heat conduction between the arc plasma and electrode and the heating effect at the surface of anode and cathode. Unfortunately, many process determining factors such as the heat flux into the electrode surface and the driving forces (i.e. electromagnetic force) acting on the

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Nomenclature

A	constant, defined in Eq. (24)
$\vec{A}$	magnetic vector potential
B	magnetic field
c	specific heat
C	constant
$\vec{F}_{ST}$	surface tension force
$\vec{F}_{SLD}$	additional holding force
$\vec{g}$	gravitational acceleration
h	enthalpy
$\vec{j}$	electrical current density
k	thermal conductivity
L	latent heat of fusion.
p	pressure
Q	inflow rate of the shielding gas
Q_{rad}	radiation heat loss
q	constant
R_w	radius of the wire
R_n	radius of the gas nozzle.
S	energy source term at plasma-wire interface
t	time
T	temperature
T_m	melting temperature
$\vec{u}$	velocity vector
$\vec{u}_{wire}$	wire feeding speed
V_{sheath}	voltage drop of non-thermionic cathode sheath

Greek symbols

γ	surface tension
ε	half of the temperature range between liquidus and solidus
ε_m	emissivity of the wire surface
λ	volume fraction of the liquid phase
λ_{mass}	mass fraction of the liquid phase
μ	dynamic viscosity
μ_0	magnetic permeability.
ϕ	Level set function
φ	electric potential
φ_{Wire}	work function the electrode wire
σ	electrical conductivity
σ_{SB}	Stefan-Boltzmann constant.
ρ	density
τ	stress tensor

Subscripts

g	gaseous phase
l	liquid phase
m	metal phase
s	solid phase

droplet are very difficult to determine using experimental approaches [12–14]. Therefore, numerical simulations based on computational fluid dynamics have been increasingly adopted to improve the visualization and characterization of the droplet transfer behavior in direct current GMAW (DC-GMAW) process [12–18]. 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 [12,13]. Hertel et al. [14] presented a numerical simulation of arc and droplet transfer in pulsed GMAW of mild steel in argon shielding gas. Rao at al. [15,16] and Ogino et al. [17] have investigated the effect of shielding gas composition on droplet transfer behavior using a constant current.

Unlike the conventional DC-GMAW process, the thermal-force behavior of VP-GMAW changes periodically as the electrode polarity switches. The arc plasma properties and the heat transfer between the arc plasma and electrode could be highly different between DCEP and DCEN phase, which would eventually lead to a different droplet transfer behavior in VP-GMAW. However, almost all the published numerical studies investigating the arc plasma and heat transfer behavior are based on DC-GMAW using constant current or pulsed current. A clear understanding of the arc plasma properties, heat transfer mechanism and droplet transfer behavior in VP-GMAW process is essentially needed.

In this regard, a numerical model coupled with electromagnetic-thermal-fluid dynamic analysis is constructed to investigate the metal transfer and heat transfer behavior in VP-GMAW process. Firstly, the effect of electrode polarity on arc properties is investigated. Then, the droplet transfer behavior in terms of droplet size, shape and temperature is systematically analyzed and compared between DC- and VP-GMAW. Furthermore, a quantitative analysis of the heat fluxes to the electrode is also conducted to explain the thermal mechanism for the differences of droplet transfer between DC- and VP-GMAW. To validate the numerical model, the simulated results are then compared with high-speed images at different times during the welding cycle.

2. Numerical modeling

2.1. Basic assumptions

In this study, the presented model focuses on investigating the arc property and droplet transfer behavior in VP-GMAW process. Due to the symmetry of the VP-GMAW system, a 2D axisymmetric model has been used to describe the system based on the simulation software COMSOL Multiphysics (version 5.2), and the following assumptions are made in order to simplify the calculation:

(a) Both the molten and solid regions of the electrode wire are treated as liquid phase, while the arc plasma is considered as gaseous phase. These two phases are immiscible and incompressible, and the fluid flow of both the liquid and gaseous phase are assumed to be laminar flow [12,13].
(b) Additional holding force is used to avoid unphysical flow of the solid part of the electrode, and the definition of the holding force will be described in Section 2.5. And the enthalpy-porous method is adopted to model the solid-liquid mushy zone of the electrode [19,20].
(c) The arc plasma is assumed to be optically thin and in local thermo-dynamic equilibrium (LTE) state and the gravity of arc plasma is also ignored [21]. Besides, the effects of metal vapors are not considered.
(d) The interactions between the arc and workpiece are not considered. The surface of the workpiece is considered flat and we assume a constant temperature of 300 K at the surface of the workpiece.

2.2. Governing equations

The following magneto-hydrodynamic equation system is used, including mass continuity, momentum conservation, energy conservation, potential continuity equations and the likes.