International Journal of Heat and Mass Transfer 52 (2009) 1709–1724

Contents lists available at ScienceDirect

International Journal of Heat and Mass Transfer

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

Three-dimensional modeling of arc plasma and metal transfer in gas metal arc welding

G. Xu [a], J. Hu [b,*], H.L. Tsai [a]

[a] Department of Mechanical and Aerospace Engineering, Missouri University of Science and Technology (formerly University of Missouri-Rolla), 1870 Miner Circle, Rolla, MO 65409, USA

[b] Department of Mechanical Engineering, University of Bridgeport, Bridgeport, CT 06604, USA

ARTICLE INFO

Article history:
Received 12 May 2008
Received in revised form 25 September 2008
Available online 29 November 2008

ABSTRACT

An integrated comprehensive 3D model has been developed to study the transport phenomena in gas metal arc welding (GMAW). This includes the arc plasma, droplet generation, transfer and impingement onto the weld pool, and weld pool dynamics. The continuum formulation is used for the conservation equations of mass, momentum, and energy in the metal zone. The free surface is tracked using the volume-of-fluid (VOF) technique. The 3D plasma arc model is solved for the electric and magnetic fields in the entire domain. The interaction and coupling between the metal zone and the plasma zone is considered. The distributions of velocity, pressure, temperature, and free surface for the metal zone and the velocity, pressure, and temperature for the plasma zone are all calculated as a function of time. The numerical results show the time-dependant distributions of arc pressure, current density, and heat transfer at the workpiece surface are different from presumed Gaussian distributions in previous models. It is also observed that these distributions for a moving arc are non-axisymmetric and the peaks shift to the arc moving direction.

1. Introduction

Gas metal arc welding (GMAW), also referred to by metal inert gas (MIG) welding or metal active gas (MAG) welding, is a welding process in which an electric arc is struck between a consumable electrode and a workpiece. The arc carries electric current and generates intense heat. It ionizes the shielding gas, which consists of inert or active gas, or gas mixture, to its plasma phase. The high temperature plasma melts the filler-metal electrode and periodically generates droplets. A weld pool on the workpiece forms under the influence of both the plasma flow and the droplet impingement. Since the mass transfer and heat transfer in the GMAW process are considerably complicated, most researches and developments in industries are based on the trial and error approach. Even in the experimental studies it is difficult to measure some parameters and determine the detailed weld pool dynamics and droplet formation. Mathematical models have been developed to describe one or two separate components of the process [1–4] or the complete process [5–11]. These models provided a tool to understand the physics behind the complicated GMAW process.

The metal transfer mode in GMAW can be classified to two categories: free-flight transfer and bridging (short-circuiting) transfer [12]. The electric current in the short-circuiting GMAW is low and hence the heat input is low, which makes it suitable for welding thin sheets. A mathematical model for this short-circuiting metal transfer process was developed by Xu et al. [13] to study the effects of some welding parameters, such as welding current and Marangoni force.

The free-flight metal transfer in GMAW can be subdivided into two transfer modes: globular mode with big round droplets repelled from electrode tip and spray mode with small streaming droplets projected from a tapered and rotating electrode tip [12]. The most important parameters affecting the transfer mode and the consequent weld pool include welding current, arc length, shielding gas composition, alloying elements, wire feed speed, diameter of the wire, etc. In order to investigate the effects of some of these parameters, many mathematical models were developed. They were either for a separate component such as droplet (electrode) [4–6], plasma arc [1,5], or weld pool (workpiece) [2–4]; or for a completely integrated system [7–11]. According to a survey article [14], the former is classified as the first-generation arc welding models. Among these separate components the plasma arc is most important since it carries electric current and welding energy. A plasma arc model originally developed for GTAW was modified by Dunn and Eagar [1] to investigate arcs consisting of different shielding gas compositions in GMAW. Because Dunn and Eagar's GMAW arc model simply neglected the influence of metal droplets, it was still similar to GTAW arc models. The significance of the plasma arc model is that once the plasma flow is solved, the arc pressure, current density, and heat flux at the anode and cathode boundaries can be calculated. These boundary values

* Corresponding author. Fax: +1 203 576 4765.
E-mail address: jjhu@bridgeport.edu (J. Hu).

0017-9310/$ - see front matter © 2008 Elsevier Ltd. All rights reserved.
doi:10.1016/j.ijheatmasstransfer.2008.09.018

Nomenclature

A_v	constant, defined in Eq. (35)
$\vec{B}$	magnetic field vector
B_x, B_y, B_z	magnetic field in x, y, and z direction
B_θ	azimuthal magnetic field
C	specific heat, or color function
c_1, c_2	color functions in fluid 1 and 2
C	coefficient, defined in Eq. (15)
C_{ds}	drag coefficient
C_1	permeability coefficient, defined in Eq. (14)
d	dendrite arm spacing
D_d	droplet diameter
e	elementary charge
F	volume-of-fluid function
F_{drag}	plasma drag force
$\vec{F}_{sv}$	surface tension volume force
$\vec{F}_{pa}$	plasma arc pressure volume force
f	mass fraction
g	volume fraction or gravitational acceleration
h	enthalpy
H	latent heat of fusion
H_{ev}	latent hat of vaporization
I	welding current
$\vec{j}$	current density vector
j_a	current density at anode
j_x, j_y, j_z	current density at x, y, and z direction
k	thermal conductivity
K	permeability, defined in Eq. (13)
kb	Boltzmann constant
k_{eff}	effective thermal conductivity
$\vec{n}$	normal vector to the free surface
p	pressure
p_s	surface tension pressure
P_{atm}	atmosphere pressure
q_{ev}	evaporation mass rate of metal vapor
r	radial distance from the electrode axis
R_a	radius of the electrode
R_e	Reynolds number
$\vec{s}$	tangential vector to the free surface
S_a	anode energy source term for the metal
S_{ap}	anode energy source term for the plasma arc
S_c	cathode energy source term for the metal
S_{cp}	cathode energy source term for the plasma arc
$\vec{S}_m$	momentum source term for the metal
S_R	radiation heat loss
t	time
T	temperature
$T_{p,a}$,$T_{p,c}$	arc plasma temperature adjacent to the anode and cathode
T_a,T_c	temperature of anode and cathode
T_l	liquidus temperature
T_s	solidus temperature
u, v, w	velocity in x, y, and z direction
$\vec{V}$	velocity vector
$\vec{V}_r$	relative velocity vector
V_c	cathode fall voltage
w_g	axial plasma velocity
x, y, z	Cartesian coordinate system

Greek symbols

γ	surface tension coefficient
ε	radiation emissivity
κ	free surface curvature
μ_l	dynamic viscosity
μ_g	dynamic viscosity of plasma
ϕ	electric potential
ϕ_w	work function of the anode material
σ_e	electrical conductivity
ρ	density
ρ_g	density of plasma
τ_{ij}	stress tensor
$\vec{\tau}_{Ms}$	Marangoni shear stress
$\vec{\tau}_{ps}$	plasma shear stress
δ	effective heat transfer length

Subscripts

a	anode
c	cathode
l	liquid phase
s	solid phase

Superscripts

n	time step n
$n+1$	time step $n+1$

are necessary for weld pool and droplet models. However, most researchers used the presumed distributions of these boundary values in their models in order to significantly cut the computational efforts and achieve relatively reasonable numerical results at the same time. The Gaussian distributions with carefully selected mean and variance values were normally assumed. For example, Hu et al. [3] utilized such assumptions in their droplet-impinged weld pool model. Other non-Gaussian distribution formulas were also utilized based on experimental results. Particularly, Wang et al. [4] used the integral formulas for the distributions of current density and heat flux in their droplet generations model.

Though the separated models for each component were generally able to obtain good numerical results, their presumed boundary conditions are arbitrary and can be inaccurate. A more rigorous model needs to integrate all the components. This kind of model is classified as the second-generation arc welding model [14] and its development is one of the research objectives of many researchers. Fan and Kovacevic [11] have developed such a unified 2D model for the globular metal transfer in GMAW. Hu and Tsai [7–10] developed a completely integrated 2D model and studied metal transfer and arc plasma characteristics. Haidar's earlier unified model [6] focused on the metal droplet formation and the predicted droplet diameter, droplet detachment frequency, and transition from globular to spray transfer mode and the results agreed with experimental measurements.

All the aforementioned complete models are two-dimensional, thus applicable only to the stationary axisymmetric arc welding. In a real world welding, the arc is moving, the weld pool is non-axisymmetric, and the heat flux and current density at the workpiece are greatly affected by the weld pool shape [15]. In addition, the geometries of many weld joints such as T joint, lap joint, corner joint, and groove weld butt joint are naturally three-dimensional. Finally, perturbations such as external magnetic field may deflect axisymmetric plasma arc from its axisymmetry [16]. A 3D model is necessary to investigate all these applications. Most previous 3D attempts focused on the weld pool, but almost all of them still used the axisymmetric assumptions for boundary conditions [2,3].