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Influences of deposited metal material parameters on weld pool geometry during shield metal arc welding

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ABSTRACT

Weld pool geometry performs an important function in improving weld quality during welding. In the present work, the influences of deposited metal material parameters, including surface tension gradient, magnetic permittivity, and thermal expansion coefficient, on weld pool geometry were investigated. Fusion length (FL) and fusion ratio (FR) were proposed to analyze weld pool evolution quantitatively. Results reveal that surface tension gradient exerts the most significant effects on weld pool geometry. The effects of magnetic permittivity are less extensive than those of surface tension gradient, and thermal expansion coefficient exerts only slight influences on weld pool geometry. Considering the effects of surface tension gradient, magnetic permittivity, and thermal expansion coefficient, a classification method for deposited metals was proposed. Based on the characteristics of the weld pool geometry, heat and mass transfer processes in the weld pool, and application conditions, various types of deposited metals were analyzed. Comparison of the simulated and experimental results showed that the error ranges of FR and FL are 3.66–4.53% and 1.03–2.83%, respectively.

1. Introduction

Shield metal arc welding (SMAW) has been widely applied in the field of welding [1]. Quantitative analysis of the factors affecting weld quality has profound and far-reaching significance. Weld pool geometry is closely related to weld quality [2–4]. Welding is a complex process combining electromagnetic effects, heat transfer, fluid flow, and solidification. As experimental research on SMAW processing is difficult to perform, establishing a model of heat and mass transfer is necessary to investigate the effects of different factors on weld pool geometry.

Heat and mass transfer perform important functions on weld pool geometry and determine weld quality [5–8]. Kim and Na [9] investigated weld pool convection and claimed that heat transfer and fluid flow in the weld pool significantly affect weld pool geometry and influence the temperature gradients of the weld pool, its local cooling rates, and its solidification structure. Traidia and Roger [10] proposed an axisymmetric finite element model to simulate the behavior of fluid flow and heat transfer in weld pools and calculated the electromagnetic field and shape of the deformable free surface. Wu and Zheng [11] investigated the effects of electromagnetic, Marangoni, and buoyancy forces on heat and mass transfer based on the static balance of all forces exerted on the weld pool and confirmed that the velocity distribution of the weld pool has a significant effect on its geometry.

Surface tension and electromagnetic and buoyancy forces significantly affect heat and mass transfer in weld pools [12]. Mathematical models have been proposed to calculate the effects of surface tension and electromagnetic and buoyancy forces on heat and mass transfer during welding [10,13,14]. Jones [15] found that temperature distributions lead to variations in surface tension in several regions of the weld pool surface; this effect is also called the Marangoni effect. The Marangoni effect has an important influence on heat and mass transfer in weld pools. Mendez and Eagar [16] reported that electromagnetic forces increase with increasing current and can dominate flows when the current exceeds a certain value. The numerical results of Traidia and Roger [17] showed that the Marangoni effect and electromagnetic forces present important functions on heat and mass transfer in welds. While the Marangoni effect, which dominates flow at the weld pool surface, exerts minimal influences, the influence of electromagnetic forces dominates at regions close to the bottom of the weld pool. Achebo [12] determined the relations among electromagnetic force, Marangoni effect, and buoyancy; of these, the effect of electromagnetic force

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Nomenclature

$\vec{A}$	vector of boundary section (m^2)
a_1, a_2, b, c	shape coefficient of double-ellipsoid heat source model (m)
B	self-induced azimuthal magnetic field (T)
C_p	specific heat ($J\ kg^{-1}\ K^{-1}$)
c_1	mushy zone constant (m^{-2})
F	force ($N\ m^{-3}$)
f_l	liquid fraction ($m^3\ m^{-3}$)
h	enthalpy ($J\ kg^{-1}$)
h_{con}	comprehensive convective heat transfer coefficient ($W\ m^{-2}\ K^{-1}$)
h_f	convective heat transfer coefficient ($W\ m^{-2}\ K^{-1}$)
K	permeability of a porous medium (m^{-2})
k	thermal conductivity ($W\ m^{-1}\ K^{-1}$)
L_a	latent heat of material ($J\ kg^{-1}$)
$\vec{l}$	vector of fusion line's movement (m)
$l(x_1, y_1, z_1, t)$	moving distance of fusion line (m)
$\vec{m}$	mass flux in boundary ($kg\ s^{-1}$)
$\dot{m}_{pq}, \dot{m}_{qp}$	mass transfer from phase p to phase q and mass transfer from phase q to phase p ($kg\ m^{-2}\ s^{-1}$)
p	pressure (Pa)
Q	heat input power (W)
$q(x, y, z)$	heat flux ($W\ m^{-3}$)
r	distance of point to center of heat source (m)
$S_{\alpha q}$	mass source of q phase ($kg\ m^{-2}\ s^{-1}$)
S	area (m^2)
T	temperature (K)
t	time (s)
$\vec{u}$	velocity vector ($m\ s^{-1}$)
$\vec{V}_{wire}$	wire feed speed ($m\ s^{-1}$)
$\vec{v}_q$	velocity vector of phase q ($m\ s^{-1}$)
v_{weld}	weld velocity ($m\ s^{-1}$)
u, v, w	velocities in the X, Y, and Z axis ($m\ s^{-1}$)
x, y, z	coordinates of X, Y, and Z axis (m)

Greek symbols

α_q	volume fraction of phase q ($m^3\ m^{-3}$)
β	expansion coefficient (K^{-1})
ε	emissivity ($J\ J^{-1}$)
μ	dynamic viscosity ($N\ s\ m^{-2}$)
μ_m	magnetic permittivity ($H\ m^{-1}$)
ρ	density ($kg\ m^{-3}$)
ρ_q	density of phase q ($kg\ m^{-3}$)
σ	Stefan–Boltzmann constant ($W\ m^{-2}\ K^{-4}$)
σ_ε	electrical conductivity ($S\ m^{-1}$)
τ	Marangoni force ($N\ m^{-3}$)
γ	surface tension (Pa)
φ	electric potential (V)

Superscript

b	buoyancy
d	additional source of mushy zone
r	r direction
x	x direction
y	y direction
z	z direction
g	groove
m	molten base metal
l	liquid
s	solid
m	reference
w	wall
f	fluid

on heat and mass transfer in weld pools is the most significant. Marangoni effects are less extensive than electromagnetic force effects in weld pools. Buoyancy forces only slightly influence heat and mass transfer in weld pools. Given their effects on heat and mass transfer, the Marangoni effect and electromagnetic and buoyancy forces also affect weld pool geometry and weld quality. Deposited metal material parameters present a direct relationship with the Marangoni effect and electromagnetic and buoyancy forces; thus, these parameters exert a significant influence on weld quality.

Weld depth and width are often adopted to analyze weld pool geometry. However, the weld depth and width cannot properly characterize weld pool geometry when grooves are present during welding. In practical applications, a groove is usually present in the base metal. Therefore, proposing new parameters that take the effects of grooves, the welding process, and so on into consideration to analyze the geometry of weld pools completely is necessary.

In this study, new parameters were proposed to analyze the effects of deposited metal material parameters, including surface tension gradient ($d\gamma/dT$), magnetic permittivity (μ_m), and thermal expansion coefficient (β), on weld pool geometry. The evolution and geometry of a weld pool with V-type grooves during butt SMAW were investigated. The results provide a theoretical basis for improving the welding process and welding quality while avoiding welding defects.

2. Mathematical formulation

2.1. Physical model

A model of the butt SMAW process with V-type grooves is proposed. The direction of welding is X, and the direction of gravity is $-Z$. Assumed the polarity of electrode is not changed and the welding torch is anode and the base metal is cathode. The welding velocity is 6.0 mm s^{-1}, and the wire feed speed is 40.0 mm s^{-1}. The size of the simulation model is presented in Fig. 1. The wire diameter is 1 mm, and the base metal material is X80 steel. The chemical composition of base material X80 steel is shown in Table 1. The thermophysical parameters of the deposited metal are summarized in Table 2. Here, thermal conductivity k and dynamic viscosity μ are functions of temperature, as described in the literature [18]. The ranges of μ_m, $d\gamma/dT$, and β of common E6010 and E5015 welding wires are summarized in Table 3 [19].

Physical fluid dynamics and the thermal behavior model were obtained using Gambit. The assumptions are as follows:

(1) The pool followed a laminar flow, and the fluid was incompressible.
(2) The density of the deposited metal was obtained from the Boussinesq assumption.
(3) The model was mirror-symmetrical at the x–z plane, as presented in Fig. 1.