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Three-dimensional numerical simulation of arc and metal transport in arc welding based additive manufacturing

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ABSTRACT

In arc welding based additive manufacturing, the surface topographies of deposited layer are more complex than conventional welding, therefore, the distribution of the electromagnetic force in molten pool, arc pressure, plasma shear stress and heat flux on molten pool surface are not the same as the conventional welding. A three-dimensional weak coupling modeling method of the arc and metal transport is developed to simulate the arc, molten pool dynamic and droplet impingement in arc welding based additive manufacturing. In the arc model, the molten pool is simplified to be solid state on the basis of experimentally observed results. The arc is simulated firstly, and then the electromagnetic force, arc pressure, plasma shear stress and heat flux are extracted and transmitted to metal transport model. The volume of fluid (VOF) method is employed to track free surface of molten pool and droplet, and the continuum surface force (CSF) method is applied to transform all the surface forces on free surface as localized body forces. This weak coupling model has better accuracy than empirical model and decreases computational consumption. The molten pool morphology and cross-sectional profile of simulated results accord well with experimental results in both single-bead deposition and overlapping deposition, which indicates that this weak coupling modeling method is capable of simulating the complex heat and mass transfer phenomena in arc welding based additive manufacturing.

1. Introduction

Additive manufacturing (AM) is a new technique of a great potential in reducing high cost of producing conventional components with complex structures or made from relatively expensive materials. Many AM techniques have been developed to fabricate metal components, such as selective laser melting (SLM) [1], selective laser sintering (SLS) [2], electron beam freeform fabrication (EBF^3) [3], and arc welding based additive manufacturing (AWAM) [4–7]. Compared with other AM techniques, the AWAM is an efficient AM technology which is a promising option to traditional subtractive manufacturing for fabricating large aeronautical and naval components that feature the higher deposition rate and lower cost.

In AWAM process, the gas metal arc welding (GMAW) or gas tungsten arc welding (GTAW) are usually employed as heat source, therefore the heat and mass transfer during the AWAM deposition are similar to the conventional arc welding process. A lot of works have focused on investigating the arc welding process by way of experiments [8,9] or simulations [10–32]. Although the information obtained through experimental observations is very useful, it is not sufficient for revealing underlying mechanisms due to the complexity of the welding process which involves high-temperature plasma and non-transparent metal. Mathematical modeling provides a convenient way to understand the physical phenomena observed in the welding process. There are two main types of mathematical models on arc welding simulation: unified model [10–20] and separated model [21–31]. Hu et al. [10,11] and Rao et al. [12,13] developed a two-dimensional unified comprehensive model to simulate the transport phenomena occurring during the gas metal arc welding process. And a harmonic mean of thermal conductivities was applied to process the heat conduction between the arc and the metal. Rao et al. [12,13] investigated the effect of the argon–helium mixtures on arc shape and metal transport phenomena. It found that the increase of helium content in the mixture shielding gas results in the change of arc shape and pressure distribution along the substrate surface as well as leads to the formation of larger droplets and the decrease of droplet detachment frequency. Based on previous studies, Xu et al. [14]

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Nomenclature

$\mathbf{A}$	magnetic vector potential
A_{mush}	mushy zone constant
a_f	front ellipsoid radius of initial temperature field
a_r	rear ellipsoid radius of initial temperature field
$\mathbf{B}$	magnetic flux density
b	the ellipsoid radius of width direction of initial temperature field
c	the ellipsoid radius of depth direction of initial temperature field
c_p	specific heat
D_w	wire diameter
e	elementary electric charge
F	volume of fraction
F_b	buoyance
F_{ms}	momentum source of enthalpy-porosity model
F_{mag}	electromagnetic force
F_{vol}	localized body forces
f_d	droplet transfer frequency
g	acceleration of gravity
H_{ev}	latent heat for liquid-vapor phase-change
h	enthalpy
h_{conv}	heat convection coefficient
I_w	deposition current
$\mathbf{J}$	current density
K_{eff}	effective thermal conductivity
k	thermal conductivity
k_b	Boltzmann constant
$\mathbf{n}$	vector tangential to the local free surface
p	pressure
Q	flow rate of shielding gas
q_{ev}	melt mass evaporation rate
q_{net}	net heat flux
R_n	nozzle inner radius
R_w	wire radius
r	radius value of XY plane
S_{mass}	mass source terms
S_M	momentum source terms
S_E	energy source terms
S_R	radiation heat loss
S_{arc}	arc heat
S_{drop}	droplet heat
S_L	latent heat
T	temperature
T_{ref}	reference temperature
$T_{p,c}$	plasma temperature adjacent to cathode
T_{amb}	ambient temperature
T_c	cathode temperature
T_{center}	center temperature of initial temperature field
$T_0(x, y, z)$	initial temperature field of molten pool
t	time
x	x-coordinate value
y	y-coordinate value
z	z-coordinate value
$\mathbf{V}$	velocity vector
$\mathbf{V}_{ps}$	velocity of plasma adjacent to metal surface
v_0	initial velocity of droplet
v_f	wire feeding rate

Greek symbols

β	thermal expansion coefficient
β_l	volume fraction of liquid metal
γ	surface tension coefficient
$\partial\gamma/\partial T$	surface tension temperature gradient
ε	radiation emissivity
κ	curvature of free surface
μ	viscosity
μ_{ps}	viscosity of plasma
μ_0	permeability
Φ	electric potential
φ	shape function of free surface
σ_e	electric conductivity
ρ	density
ρ_1	density of first phases
ρ_2	density of second phases
ρ_w	density of wire
ρ_d	density of droplet
τ_{ps}	plasma shear stress
τ_{Ma}	Marangoni shear stress
τ_{st}	surface tension
τ_{SF}	surface force on free surface
δ	length of the cathode sheath
π	circumference ratio
ω	a small number to prevent division by zero
η_d	proportion of droplet energy to deposition
Δt	droplet generation time

developed an integrated comprehensive three-dimensional model to study the transport phenomena in gas metal arc welding considering the moving arc. Murphy [15,16] presented a self-consistent three-dimensional model to investigate the heat and mass transport phenomena in gas metal arc welding by taking a special treatment of energy transfer between the workpiece and arc, namely the heating effect of the excited atoms that cause electrons to be emitted from the workpiece and accelerated by the sheath voltage was added to the energy conservation equation. In addition, an equilibrium surface (ES) method was used to track the free surface. Compared with the widely used volume of fluid (VOF) method, the ES method had higher computational efficiency. Wang et al. [17,18] developed a unified model of coupled arc and weld pool for double electrodes GTAW. The weld pool dynamic was described by taking into account buoyance, electromagnetic force, surface tension and plasma drag force. And the influence of electrode separation on the flow and temperature fields of arc and weld pool were studied [18]. Yin et al. [19] established a full coupled model of arc and weld pool for single electrodes GTAW with applied axial magnetic fields. It found that the axial magnetic fields resulted in a reverse flow appearing over the anode in arc, and the fluid flow cycle brought about a wide and shallow weld pool. The models of Wang and Yin took the sheath area as a special internal boundary condition, and the free surface of weld pool was not considered. Recently, Jian and Wu [20] developed a unified fluid flow and heat transfer model for stationary plasma arc welding. The VOF method was employed to track the keyhole boundary. And the whole evolution processes of keyhole formation were numerically simulated.

The separated model also has been widely applied in arc welding simulation, in which the model of arc and metal transport are not simulated simultaneously. Consequently, the complex energy and momentum boundary conditions between the arc and the metal do not need to calculate directly. Wu et al. [21] presented a numerical simulation method for predicting the profile of the free surface deformation of fully-penetrated GTAW weld pool. The physical terms and the sign of Lagrange multiplier were used to derive the both front- and back-side deformation of weld pool surfaces equations. Chen et al. [22] developed a three-dimensional weld pool dynamics model for groove gas metal arc welding processes to study the influence of groove angle on welding of