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Numerical analysis of heat transfer and fluid flow in multilayer deposition of PAW-based wire and arc additive manufacturing

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ABSTRACT

A three-dimensional numerical model has been developed to investigate the fluid flow and heat transfer behaviors in multilayer deposition of plasma arc welding (PAW) based wire and arc additive manufacture (WAAM). The volume of fluid (VOF) and porosity enthalpy methods are employed to track the molten pool free surface and solidification front, respectively. A modified double ellipsoidal heat source model is utilized to ensure constant arc heat input in calculation in the case that molten pool surface dynamically changes. Transient simulations were conducted for the 1st, 2nd and 21st layer depositions. The shape and size of deposited bead and weld pool were predicted and compared with experimental results. The results show that for each layer of deposition the Marangoni force plays the most important role in affecting fluid flow, conduction is the dominant method of heat dissipation compared to convection and radiation to the air. As the layer number increases, the length and width of molten pool and the width of deposited bead increase, whilst the layer height decreases. However these dimensions remain constant when the deposited part is sufficiently high. In high layer deposition, where side support is absent, the depth of the molten pool at the rear part is almost flat in the Y direction. The profile of the deposited bead is mainly determined by static pressure caused by gravity and surface tension pressure, therefore the bead profile is nearly circular. The simulated profiles and size dimensions of deposited bead and molten pool were validated with experimental weld appearance, cross-sectional images and process camera images. The simulated results are in good agreement with experimental results.

1. Introduction

Additive manufacturing (AM) is attracting increasing interest from academic and industrial communities due to the advantages of low production costs, short lead time and materials saving. AM technologies, especially those for metallic materials, have experienced striking advances over the last decade [1]. There are three main categories of AM processes which are based respectively on laser, electron beam and arc welding, and they have occupied different competitive positions for the direct manufacture of metallic parts [2–4]. Laser-based AM processes are capable of fabricating small parts with fine shape detail and lattice structures with high complexity; Electron-beam-based AM processes fabricate parts with high chemical purity; while arc-based AM process, i.e. wire and arc additive manufacture (WAAM), is characterized by a high deposition rate and low equipment costs [4]. WAAM utilizes metal wire as the feedstock, gas metal arc welding (GMAW), gas tungsten arc welding (GTAW) or plasma arc welding (PAW) as the heat source, and manipulation is done with either a robot or numerical control system. It is suitable for fabricating medium to large scale metal parts, including titanium structures for aerospace application. As the GMAW process of titanium is easily affected by arc wandering which results in increased surface roughness, GTAW or PAW are currently used for titanium deposition [5,6]. The higher energy density of PAW leads to a higher deposition rate and lower surface roughness [7].

One of the main requirements for automatic deposition is to know the shape and size of the deposited bead [8]. Bead modelling work using empirical models or artificial neural networks can establish the relationship between deposition parameters and bead shape [8–10]. The dependence of bead shape on thermal

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Nomenclature

A_{mush}	mushy zone constant, kg m^{-3} s^{-1}
A_W	cross-sectional area of wire, m^2
a_{g1}~a_{g7}	coefficients used in arc shear stress mode
a_1	front ellipsoid radius of heat source model, m
a_2	rear ellipsoid radius of heat source model, m
b	half width of heat source model, m
c	depth of heat source model, m
c_p	specific heat, J kg^{-1} K^{-1}
$\mathbf{F}_g$	body force, N m^{-3}
$\mathbf{F}_{ap}$	momentum source of arc pressure, N m^{-3}
$\mathbf{F}_{as}$	momentum source of arc shear stress, N m^{-3}
$\mathbf{F}_{jb}$	momentum source of electromagnetic force, N m^{-3}
$\mathbf{F}_{ms}$	momentum source of enthalpy-porosity model, N m^{-3}
$\mathbf{F}_{ma}$	momentum source of Marangoni force, N m^{-3}
$\mathbf{F}_{st}$	momentum source of surface tension, N m^{-3}
F	volume fraction function of fluid
F_{arc}	total arc force, N
F_{jbx}	x component of electromagnetic force, N m^{-3}
F_{jby}	y component of electromagnetic force, N m^{-3}
F_{jbz}	z component of electromagnetic force, N m^{-3}
f_l	liquid fraction
$\mathbf{g}$	acceleration of gravity, m s^{-2}
g_a	distribution function of arc shear stress
h	enthalpy, J kg^{-1}
h_{conv}	heat convection coefficient, W m^{-2} K^{-1}
h_{ref}	reference enthalpy, J kg^{-1}
h_{sum}	combined heat transfer coefficient, W m^{-2} K^{-1}
ΔH	latent heat of melting, J kg^{-1}
I	deposition current, A
k	thermal conductivity, W m^{-1} K^{-1}
k_b	Stefan-Boltzmann constant, W m^{-2} K^{-4}
L_0	thickness of base plate, m
$\mathbf{n}$	vector normal to the local free surface, m
p	pressure, Pa
p_{st}	surface tension pressure, Pa
p_{arc}	arc pressure, Pa
P_{max}	maximum of arc pressure, Pa
Q_{arc}	heat of the arc heat source model, W
q_{arc}	arc heat source, W m^{-3}
q_{metal}	heat of the feeding metal, W m^{-3}
q_{loss}	heat loss due to radiation and convection, W m^{-3}
r	radius value of XY plane, m
r_d	parameter used in arc shear stress model, m
$\mathbf{r}$	radius vector of XY plane, m
R_M	radius of mass input spherical region, m
$\mathbf{s}$	vector tangent to the local free surface, m
S_C	mass source terms, kg m^{-3} s^{-1}
T	temperature, K
T_L	liquidus temperature of metal, K
T_S	solidus temperature of metal, K
T_{ref}	reference temperature, K
T_{amb}	ambient temperature, K
t	time, s
U	arc voltage, V
x	x-coordinate value, m
x_0	x-coordinate value of starting location, m
y	y-coordinate value, m
y_0	y-coordinate value of starting location, m
z	z-coordinate value, m
z_s	z distance to free surface, m
z_0	z-coordinate value of starting location, m
$\mathbf{V}$	velocity vector, m s^{-1}
V_T	welding travelling speed, m s^{-1}
V_W	wire feeding speed, m s^{-1}
V_y	y component of velocity vector, m s^{-1}

Greek symbols

β	thermal expansion coefficient, 1 K^{-1}
γ	surface tension coefficient, N m^{-1}
$\partial\gamma/\partial T$	surface tension temperature gradient, N m^{-1} K^{-1}
ε	radiation emissivity
ε_0	a small number to prevent division by zero
η	arc heat efficiency
κ	curvature of free surface, 1 m^{-1}
μ	viscosity, Pa s
μ_m	permeability, H m^{-1}
π	circumference ratio
ρ	density, kg m^{-3}
ρ_0	metal density at ambient temperature, kg m^{-3}
ρ_{gas}	density of gas phase, kg m^{-3}
ρ_{metal}	density of metal phase, kg m^{-3}
σ_p	distribution of plasma arc pressure, m
σ_j	distribution of arc density, m
$\boldsymbol{\tau}_{arc}$	arc shear stress, Pa
$\boldsymbol{\tau}_{ma}$	Marangoni shear stress, Pa
$\hat{\boldsymbol{\tau}}$	unit vector of arc shear stress
τ_{max}	maximum of arc shear stress, Pa

history and base surface condition are often ignored to save time in these studies. The deposited bead shape and size are a consequence of heat transfer and fluid flow in the molten pool. So an accurate bead prediction should combine experimental observation and fluid models. Numerical modelling of the molten pool can provide predictions, not only for molten pool shape and deposited bead shape, but also for the mass and heat transfer process, which is critical for understanding and control of the microstructure evolution of the deposited parts [11]. For most metal materials, coarse primary columnar grains are formed in the WAAM process [12,13], there is a big demand for a microstructure control method. Recently, the authors [14] developed a three-dimensional numerical model of an electric arc based on magnetic fluid dynamics for arc based additive forming process with pure argon shielding gas. The influence of base surface topographies on the deposited bead shape and the heat and mass transfer of electric arc were investigated in detail. However, to the best knowledge of the authors, computational fluid flow (CFD) modeling of the WAAM process is still in its infancy.

Despite much more complex deposition conditions and paths, the WAAM process has similar molten pool dynamics to conventional arc welding. There are a large number of studies devoted to CFD modeling of arc welding. Tanaka [15], Murphy [16] and Traidia [17] presented unified two-dimensional models for GTAW. Wang [18] developed a 3D unified model for double electrodes GTAW. Hu and Tsai [19,20] also developed a 3D unified model to study the transport phenomena including arc plasma, droplet generation, transfer and impingement, and the molten pool dynamics in GMAW. These unified models treat electrodes, plasma arc and molten pool in a whole model, providing more accurate results at higher computational cost. In contrast, a separated model simulates only the arc or the molten pool, treating the arc-electrode interface by using empirical equations [21–28]. The separated model is a more economical choice in many cases due to the less computational cost. In separated models that simulate molten pool, the free surface of the molten pool needs to be calculated through profile equilibrium method [21], volume of fluid (VOF) method [22–27], or Level-set method [28]. Empirical Gaussian dis-