International Journal of Heat and Mass Transfer 125 (2018) 471–484

Contents lists available at ScienceDirect

International Journal of Heat and Mass Transfer

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

Study of mass transport in cold wire deposition for Wire Arc Additive Manufacturing

Fatemeh Hejripour [*], Daniel T. Valentine, Daryush K. Aidun

Mechanical and Aeronautical Engineering Department, Clarkson University, 8 Clarkson Ave., Potsdam, NY 13699-5725, United States

ARTICLE INFO

Article history:
Received 22 February 2018
Received in revised form 16 April 2018
Accepted 18 April 2018

ABSTRACT

Wire Arc Additive Manufacturing (WAAM) is a combination of an electric arc and wire feeding system used extensively in building components and repair operations. The heat transfer, fluid flow and mass transport were investigated in a numerical simulation of WAAM process with dissimilar substrate. Experiments were performed to verify the numerical results. The predicted clad layer (1st layer) profile (width and height) is in good agreement with experiment. The cold wire transfer (CWT) impact on the velocity field and mass transport were predicted around the cold wire immersion inlet in the weld pool (WP). The effect of arc travel speed and wire feed rate on the homogenization process were studied. Both the numerical and experimental results show that the increase of wire feed rate leads to homogenous composition in fusion zone (FZ). The predicted composition distribution in the clad layer and measured concentrations in experiments show a well-mixed region in middle of the clad layer.

1. Introduction

Wire Arc Additive Manufacturing (WAAM) is a technology used for prototyping by additive layers. In this method, the arc is used as power source and the wire is the feeding system. WAAM has high deposition rate, which is used for making large components without material waste. Defect occurrence is unlikely because the wire is completely melted at the time of deposition [1]. Since the deposition procedure is similar to cladding process, cladding terminology can be used for WAAM. There are functioning parameters in the deposition process which affects mechanical properties. An efficient process can be achieved by developing a numerical model. Simulations could be used to optimize the process parameters and predict the dimensions of deposited layer profile and chemical composition distribution in the clad layer.

Gas Tungsten Arc (GTA) and Gas Metal Arc (GMA) processes are employed in WAAM. The advantage of GTA welding (GTAW) is the production of a smooth and spatter free clad layer. There are two feeding systems containing hot wire and cold wire. In the hot wire feeding system, the wire gets heat by electrical resistance heating before entering the welding arc region. In the Cold Wire Transfer (CWT) method, the welding arc heats the wire to reach the wire melting point from the ambient temperature. There are some experimental and numerical investigations on droplet transfer to the Weld Zone (WZ). Chen et al. investigated two types of droplet transfer modes include touching and free transfer modes in arcing-wire GTAW [2]. The experiments showed the transfer period and the droplets size are dependent to the distance from the initial position of the wire to the Weld Pool (WP), the current on the wire and the distance from the tungsten electrode to the WP in the touching transfer. The bridging and globular transfers in GTAW based additive manufacturing are studied by Geng et al. [3]. They developed a mathematical model to optimize the wire feed flying distance in the arc zone. They predicted the droplet landing position in bridging transfer under a certain vertical distance of melting wire tip to tungsten electrode.

Numerous researchers modeled WP behavior by adding wire to the molten pool using laser as the heat source [4,5,6]. However, limited studies investigated numerically the fluid flow in the CWT weld zone in presence of the arc as the heat source. In arc welding, electromagnetic field produced by the arc, affects the fluid flow in the WP. Traidia et al. developed a 2D model to compute Lorentz forces and Joule heating effects [7]. Then, the fluid dynamic and heat transfer equations were solved under steady state conditions for a 3D model that used the results of the 2D model. They studied the effect of adding cold filler wire on the velocity field and molten pool geometry. Pan et al. developed a 3D model of WP and bead surface in high speed variable polarity GTAW [8]. A mass source as a Gaussian distribution was added to the substrate. The molten pool characterizations and transport phenomena investigation showed the velocity of the molten flow becomes stable after the initial stage of the WP formation. Bishal Silwal and Santangelo used volume of fluid method to model bead on

---

[*] Corresponding author.
E-mail address: hejripf@clarkson.edu (F. Hejripour).

https://doi.org/10.1016/j.ijheatmasstransfer.2018.04.092
0017-9310/

Nomenclature

a	material property
a_l	material property in liquid state
a_s	material property in solid state
A_m	large number
A_w	wire cross sectional area [m^2]
$\bar{B}$	magnetic flux density [$V\ s\ m^{-2}$]
C_i	concentration of the i th alloying element [wt%]
$C_{Fe_{clad}}$	concentration of iron in the clad layer [wt%]
$C_{Fe_{substrate}}$	concentration of iron in the substrate [wt%]
c_p	equivalent specific heat capacity [$J\ kg^{-1}\ K^{-1}$]
c_{pl}	liquid specific heat capacity [$J\ kg^{-1}\ K^{-1}$]
c_{ps}	solid specific heat capacity [$J\ kg^{-1}\ K^{-1}$]
c_{pw}	wire specific heat capacity [$J\ kg^{-1}\ K^{-1}$]
D_i	diffusion coefficient [$m^2\ s^{-1}$]
$\bar{E}$	electrical field [$V\ m^{-1}$]
$\overline{F_{eq}}$	fluid volume force [$N\ m^{-3}$]
$\bar{g}$	gravitational acceleration [$m\ s^{-2}$]
h	convective heat transfer coefficient [$W\ m^{-2}\ K^{-1}$]
$\bar{\imath}$	unit vector in x-direction
I_a	arc current [A]
$\bar{J}$	electrical current density [$A\ m^{-2}$]
$\bar{k}$	unit vector in z-direction
k	thermal conductivity [$W\ m^{-1}\ K^{-1}$]
k_l	liquid thermal conductivity [$W\ m^{-1}\ K^{-1}$]
k_s	solid thermal conductivity [$W\ m^{-1}\ K^{-1}$]
L	latent heat [$J\ kg^{-1}$]
L_w	wire latent heat [$J\ kg^{-1}$]
MF	mass fraction of alloying element
$\bar{n}$	normal vector
$\bar{p}$	pressure field [Pa]
P_a	arc pressure [Pa]
P_{max}	maximum arc pressure [Pa]
$\bar{q}$	heat flux in considered domain [$W\ m^{-2}$]
$q_\forall$	rate of volumetric energy loss [$W\ m^{-3}$]
r_i	arc radius [m]
r_a	effective radius of heat source [m]
r_p	effective radius of arc pressure [m]
r_w	wire radius [m]
T	temperature field [K]
T_l	liquidous temperature [K]
T_s	solidus temperature [K]
T_0	ambient temperature [K]
$\bar{u}$	relative velocity field [$m\ s^{-1}$]
U_t	arc travel speed [$m\ s^{-1}$]
U_w	wire feed rate [$m\ s^{-1}$]
$\bar{v}$	inlet velocity field [$m\ s^{-1}$]
$\bar{V}$	electrical potential [V]
V_a	arc voltage [V]
α	averaged mass fraction
β_T	thermal expansion coefficient [K^{-1}]
γ	surface tension [$N\ m^{-1}$]
Γ_w	wire inlet boundary
$\boldsymbol{\varepsilon}$	small number
ϵ	emissivity coefficient [$W\ m^{-3}\ sr^{-1}$]
η	arc efficiency
θ	liquid fraction
Θ	angle between the x-axis and the wire feeding direction [rad]
λ	Lagrange multiplayer
μ	dynamic viscosity [$kg\ m^{-1}\ s^{-1}$]
μ_r	magnetic permeability of the material [$N\ A^{-2}$]
μ_0	magnetic permeability of the free space [$N\ A^{-2}$]
ρ	material density [$kg\ m^{-3}$]
ρ_l	liquid density [$kg\ m^{-3}$]
ρ_s	solid density [$kg\ m^{-3}$]
ρ_w	wire density [$kg\ m^{-3}$]
σ	Stefan-Boltzmann constant [$W\ m^{-2}\ K^{-4}$]
σ_e	electrical conductivity [$S\ m^{-1}$]
φ	weld free surface profile [m]
φ_x	first partial derivative of φ in x-direction
φ_y	first partial derivative of φ in y-direction
Ω_l	liquid domain
Ω_s	solid domain
∇	gradient operator
∇_s	tangential gradient operator

plate and predict fluid flow in the WP and subsequent WP profile [9]. They found that vibration of wire feeder reduced the droplet release time in the cold wire GTAW. Their model showed that the hot wire droplet resulted to a smaller width but with larger penetration compared to the cold wire GTAW.

Mass transport study in dissimilar metal weld is important to predict element distributions in the WZ achieve improved weld properties. Bahrami et al. investigated mass transport phenomena in linear dissimilar metals welding [10]. The alloying concentrations in the numerical WZ had a reasonable agreement with the experimental measurements. Regarding WAAM process, CWT produces a low dilution cladding and it is appropriate for dissimilar metal joining. There is no study done on the investigation of fluid flow and mass transport in CWT-GTAW with CWT on a dissimilar substrate.

In the current study, a numerical simulation of the CWT using GTAW process is developed for WAAM purposes. A 3D multiphysics model is solved that includes electromagnetic, heat transfer, fluid flow and mass transfer physics. The proposed model is used to predict the clad geometry (width, thickness and penetration (or dilution)) as a function of process parameters such as travel speed, wire feed rate and material thermal properties. The current model also predicts compositional mixing phenomena in the clad layer in the case of building a multi-material part using WAAM process.

2. Experimental details

The substrate used in this experiment was made of stainless steel 410 and received in coupons with dimension of 180 × 30 × 7 mm. The wire with 1 mm diameter was made of Inconel 718; it was used as deposited layer. The chemical composition provided by vendor, is given in Table 1. The feeder is set at angle of 30° with respect to the welding torch. The shielding gas used is pure Argon with flow rate of 27 cfm. The welding mode is direct current electrode negative (DCEN). The arc length is 5 mm and the electrode tip angle is 30-degree. The temperature is measured during welding using two thermocouples attached in the center of the top and bottom surfaces of the coupons. The weld coupons are sectioned using a diamond saw and then, mounted and polished to prepare the samples surfaces for performing metallography. The microstructure was revealed using Glyceregia with instruction of “9 ml glycerol + 6 ml HCl + 3 ml HNO_3”.