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Plasma arc and weld pool coupled modeling of transport phenomena in keyhole welding

Yan Li[a], Yanhui Feng[b,c,*], Yafei Li[b], Xinxin Zhang[b,c], Chuansong Wu[d]

[a] *State Key Laboratory of Heavy Oil Processing, China University of Petroleum, Beijing 102249, China*
[b] *School of Mechanical Engineering, University of Science and Technology Beijing, Beijing 100083, China*
[c] *Beijing Key Laboratory of Energy Saving and Emission Reduction for Metallurgical Industry, University of Science and Technology Beijing, Beijing 100083, China*
[d] *MOE Key Lab for Liquid-Solid Structure Evolution and Materials Processing, Institute of Materials Joining, Shandong University, Jinan 250061, China*

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ABSTRACT

Plasma arc welding involves intricate thermal, electrical, magnetic and fluid dynamics phenomena. To date, tremendous research has been carried out on the weld pool or the thermal plasma arc separately. Yet few studies have integrated the both aspects, much less the keyhole effect in addition. Accordingly, as an endeavor to advance the understanding of the transport phenomena in keyhole welding with plasma arc, a unified model coupling plasma arc and weld pool has been developed to help gain access to the more complete knowledge of energy conversion in the thermal plasma process and heat transfer to the weld pool with the consideration of keyhole effect. By solving a series of governing equations that contain the mass, the momentum and the combined thermal, electric and magnetic energy, both temperature and velocity fields in the arc region and in the weld pool were exhibited. Results show that about 10% of plasma arc outflows from the keyhole exit. The heat conduction flux is more than two times of the electron condensation flux in the welding process. It is also found that the Marangoni shear takes obvious priority over the electromagnetic force, and two circular flows appear in the weld pool. Moreover, arc flows, electrical potential, current density and electromagnetic force were all predicted to further the understanding of thermal plasma process. Two velocity-transition points were found within the keyhole, from which the arc begins to flow outwards and upwards and finally outflows through the top metal surface. Finally, experiment was conducted on the stainless steel plate, and the measured weld pool is close to that calculated by our model.

1. Introduction

Welding is always a critical technique in the fabrication of most of the familiar objects, from buildings and bridges, to vehicles, computers, and medical devices. In recent years, although advanced welding technologies such as laser welding and electron beam welding have shown great promise in many sophisticated industries, still the arc welding is the world's most widely used welding method due to its versatility. The arc welding mainly includes the gas-tungsten arc welding (GTAW), gas-metal arc welding (GMAW), plasma arc welding (PAW), and so on. Much research has been conducted on GTAW and GMAW. For example, Tanaka et al. [1–3] investigated the interaction between the plasma and the weld pool in the GTAW by a unified model, and they predict detailed distributions of temperature and velocity both in the arc region and in the substrate, as well as the weld-penetration geometry. Traidia and Roger [4] proposed a numerical model coupling the welding arc and the weld pool dynamics to study the heat transfer, fluid flow and electromagnetic fields in pulsed gas tungsten arc welding. Fan and Kovacvic [5] studied the dynamic transport phenomena in gas metal arc welding including electrode, arc plasma and weld pool. Hu and Tsai [6,7] also developed a unified gas metal arc welding model to investigate the plasma arc characteristics, the droplet formation, detachment, transfer and impingement onto the workpiece, and the weld-pool formation and dynamics. They later extended the model from stationary 2D to 3D moving GMAW [8].

However, research on PAW is not sufficient due to much more complex technology. Different from the free burning arc in GTAW, arc in PAW is squeezed through a copper nozzle. As a consequence, the current path of the arc is limited around the restriction nozzle

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* Corresponding author at: School of Mechanical Engineering, University of Science and Technology Beijing, Beijing 100083, China.

E-mail address: yhfeng@me.ustb.edu.cn (Y. Feng).

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Nomenclature

A_0	mushy zone constant in Eq. (9)
B_θ	self-induced azimuthal magnetic field
c_p	specific heat
c_{pm}	specific heat of metal
e	electronic charge
f^α	sulfur concentration in Eq. (15)
f_l	liquid fraction
g	acceleration of gravity
h	sensible enthalpy of material
h_{conv}	convective heat transfer coefficient
H	enthalpy of material
$\triangle H$	latent enthalpy
I	welding current
k	thermal conductivity
k_a	thermal conductivity of arc
k_b	Boltzmann constant
k_m	thermal conductivity of metal
K	permeability in Eq. (8)
L	latent heat of fusion in Eq. (10)
$\lvert j_a \rvert$	current density at the anode surface
j_r, j_z	current density in r and z direction
p	pressure
q	heat flux
q_a	heat flux in arc
q_m	heat flux in metal
R	ideal gas constant
R_d	radius of electrode tip in Eq. (16)
$\vec{s}$	tangential direction to the free surface
S	source term in Eq. (13)
S_{rad}	radiation heat loss in Eq. (4)
t	time
T	temperature
T_a	temperature in arc
T_l, T_s	liquidus and solidus temperature
T_m	temperature in metal
T_{melt}	melting temperature
T_{ref}	reference temperature
T_w	temperature at the wall
T_∞	ambient temperature
u, v	velocity in the r and z direction
V	velocity vector
V_{pl}	inlet velocity of plasma arc
V_{shield}	inlet velocity of shielding gas
r, z	coordinate of r and z axis

Greek symbols

α	electrode angle
γ	surface tension
$\partial\gamma/\partial T$	temperature gradient of surface tension
ε	radiation emissivity
μ	dynamic viscosity
μ_0	magnetic permeability
μ_m	dynamic viscosity of molten metal
ρ	density
ρ_m	density of metal
σ	Stefan–Boltzmann constant
σ_e	electrical conductivity
τ	Marangoni shear stress
ϕ	electric potential
ϕ_w	work function of the anode

Subscripts

a	arc
l	liquidus phase
m	metal
s	solidus phase
w	wall

so that the current density enriches and the arc temperature rises in this area. Besides, the hottest area of the plasma is extended farther down toward the work surface. The overall result is a longer, thinner and more focused arc with higher temperatures that greatly increases heat transfer efficiency. Meanwhile, the plasma jet velocity increases due to the electromagnetic pinch force, and thus makes it available to achieve the "keyhole mode" that has the ability to form a deep and relatively narrow weld bead like in laser welding. Up to now, quite few literatures concern the arc characteristics in PAW. Aithal et al. [9] simulated a transferred plasma arc flow within the torch and then impinging on a surface, and the result shows good agreement with their experiment. Yin et al. [10] presented a 2D model about the constricted transferred-type plasma arc. Taking into account the influence of cathode and the restricted nozzle, they calculated the arc temperature and flow fields as well as the distributions of heat flux and arc pressure at the anode.

On the other hand, most of the PAW research, either experimental or theoretical, has focused only on the workpiece. YM Zhang and SB Zhang [11] observed the keyhole image and the weld pool in PAW experiments. Jia et al. [12] developed a sensing and control system to realize the stable keyhole welding. Liu et al. [13,14] analyzed the influence of keyhole geometry on a steady and high-quality PAW process. Some researchers developed various numerical models to calculate weld pool shape, flow pattern in the pool and temperature history of workpiece by presupposing keyhole shape [15–17]. Fan and Kovacevic [18] employed the Volume of Fluid (VOF) technique to track the keyhole formation, growth and collapse in a two dimensional PAW simulation. Zhang et al. [19,20] and Li et al. [21,22] also established 3D models by VOF technique to investigate the transient evolution of keyhole geometry and weld pool in PAW process, respectively. Besides, many researchers computed the dynamic developments of PAW keyhole geometry by the Level Set (LS) method [23,24] and force balance analysis [25,26]. In addition, Wu et al. [27,28] constructed a series of heat source models to reveal the volumetric distribution characteristics of plasma heat intensity along the direction of thickness. Li et al. [29] developed an improved heat source model taking into account the influence of fluid flow in the weld pool, thus predicting a more precise weld geometry as well as an obvious hump in the fusion line.

In reality, however, the stable keyhole plasma arc welding is strongly associated with the thermo-mechanical effect of the thermal plasma. In order to more accurately understand the complete welding mechanism, it becomes quite important to investigate the interaction between the plasma arc and the weld pool. Especially, heat transfer in the keyhole is even less discussed in an integrated physical process. Hence, a unified model coupling plasma arc and weld pool has been developed to help gain access to the knowledge of energy conversion in the thermal plasma process and heat transfer to the weld pool with the consideration of keyhole effect. The keyhole was pre-established according to previous experimental research [22], and detailed thermo-physical process was presented in this paper.