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An improved simulation of heat transfer and fluid flow in plasma arc welding with modified heat source model

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ABSTRACT

A three dimensional numerical model is developed to investigate the plasma arc welding (PAW) process, featured by the compound volumetric heat source movement and heat transfer with phase change in the weld pool, where fluid flow is driven by a combination of surface tension, electromagnetic and buoyancy forces. Based on the actual configuration of PAW welds, a modified heat source model is proposed to involve the key-holing effect of PAW. It is composed of a double-ellipsoidal volumetric heat source at the upper and a conical volumetric heat source at the lower. It is proven that the modified heat source model as well as fluid flow consideration can improve the PAW simulation. The predicted weld bead is in good agreement with the experimental results, along with the hump in the fusion line. The effect of fluid flow in molten pool is indicated to be non-negligible. In addition, the evolution of the weld pool is presented along with the temperature field and velocity field. A discussion is made on the process parameters such as plasma arc power and welding speed. It turns out that high plasma arc power or/and low welding speed is beneficial to complete joint penetration, but optimum process parameters are good choice to ensure both the high weld quality and complete joint penetration.

1. Introduction

Plasma arc welding (PAW) is one of the most highly efficient welding technologies with the best perspective in the 21st century [1]. Characterized by high concentration of energy and fierce arc force, plasma arc can provoke local melting instantly, and result in a molten pool in a very short time. Meanwhile, owing to the extremely high temperature (1.0×10^4–2.0×10^4 K) and velocity (300–2000 m/s) [2], it can easily penetrate the pool and yield complete penetration weld. So the plasma arc welding can weld thicker pieces with a single pass, and doesn't require preparation of joints, which enormously improves the welding efficiency that normal welding can hardly achieve. Besides, it yields so large a depth-to-width ratio of weld bead that solidified workpieces are more available in good joining. Compared with other highly efficient welding technologies, such as laser beam welding (LBW) and electron beam welding (EBW), the PAW is more applicable to large-scale industrial production for the reasons of low-cost equipment, low operating costs and low requirements for joint fit-up because of large diameter of plasma arc beam. Recently, as PAW has being extensively applied in various industrial areas, numerical simulations associated with those processes become a hot spot. Researchers model PAW processes with modern computer in order to help understand complex physical mechanisms of heat transfer, fluid flow with material melting, solidification and so on. In addition, dominant factors that determine weld quality and weld shape are also discussed.

The keyhole formation and its dynamic variation play an important role in improving the PAW process and weld quality [3]. However, in early PAW simulations, it was quite difficult to model key-holing process due to the extremely cumbersome features of plasma jet and lack of free-surface tracking technologies. Usually, a fixed keyhole was presupposed, and then study was carried out to analyze heat transfer and fluid flow happened in the PAW process with phase change. For example, Hsu and Rubinsky [4] presented the solid–liquid interface moving by a two-dimensional finite element model with the assumption of a constant radius keyhole. Nehad [5] simulated the development of the weld pool and the temperature history of the workpiece by enthalpy technology, also with an assumption of circular keyhole.

To further characterize the key-holing effect, Keanini and Rubinsky [6] applied the Young–Laplace equation to compute the keyhole interface in three dimensional PAW simulation. Fan and Kovacevic [7] employed the Volume of Fluid (VOF) method to track the keyhole formation, growth and collapse in a two dimensional simulation of stationary PAW. Li et al. [8] used the Level Set (LS) method to track the dynamic-variation keyhole in analyzing the fluid flow and heat transfer in the weld pool. In fact, thanks to the great development of

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Nomenclature

a_1, a_2, b, c	Shape coefficient of heat source in Eq. (3)
C_p	Specific heat
D_0	Mushy zone constant in Eq. (10)
f^α	Sulfur concentration in Eq. (15)
f_b	Buoyancy force
f_l, f_s	Liquid fraction and solid fraction
F_x, F_y, F_z	Electromagnetic force in the X,Y and Z direction
g	Acceleration of gravity
h	Convective heat transfer coefficient
h_T	Sensible enthalpy of material in Eq. (5)
H_T	Enthalpy of material
I	Current
k	Thermal conductivity
K	Permeability in Eq. (11)
L	Thickness of the workpiece
L_a	Latent heat of material
L_{en}	Length of the workpiece
p	Pressure in molten pool
q_{conv}, q_{rad}	Convective heat flux and radiative heat flux
$q(x, y, z)$	Heat source
R	Ideal gas constant
r_e, r_i	Radius of cone ends in Eq. (4)
S	Source term
t	Time
T_l, T_s	Liquidus temperature and solidus temperature
T_m	Melting temperature of material in Eq. (2)
T_∞	Ambient temperature
u	Velocity vector
u, v, w	Velocity in the X, Y and Z direction
U	Voltage
$\vec{v}$	Darcy velocity vector in Eq. (9)
V_0	Moving speed of welding torch
W	Half-width of the material
x, y, z	Coordinate of X, Y and Z axis
x_0, y_0, z_0	Initial position of heat source
z_e, z_i	Z-coordinate of cone ends in Eq. (4)

Greek symbols

β	Thermal expansion coefficient
ε	Radiation emissivity
η	Thermal efficiency of plasma arc welding
μ	Dynamic viscosity
μ_m	Magnetic permeability of material
ρ	Density
σ	Stefan–Boltzmann constant
σ_j	Current distribution parameter in Eq. (3)
χ_1, χ_2	Energy distribution coefficient
γ	Surface tension
$\partial\gamma/\partial T$	Temperature gradient of surface tension

interface tracking methods, such as the VOF method and Level Set (LS) method, the keyhole dynamics is not only studied in PAW process [9–11], but also widely investigated in Laser Welding [12–14], Gas Metal Arc Welding [15] and GMA-Laser Hybrid Welding [16] and so on.

Different from the above key-holing dynamics method, another available and simplified method to take the key-holing effect into account is to develop effective heat source models for energy equation. That is, the effective heat source model accounts for not only the heating effect, but also the key-holing effect of the plasma arc. Effective heat source model method is relatively easier to implement, because it removes the requirement of keyhole interface tracking which is numerically cumbersome and time-consuming. Different effective heat source models were proposed. Gaussian surface heat flux distribution was once generally adopted to describe plasma arc thermal energy [7,17,18], but it couldn't give an adaptive result since it didn't consider key-holing effect. Liu et al. [19] applied a three-dimensional conical heat source to investigate the evolution of temperature field and molten pool as well as fluid flow. Their experiments proved the superiority of the conical heat source over Gaussian surface heat flux distribution. Wu et al. [20] proposed a modified conical heat source, i.e. Transient Thermal Model for Plasma Arc Welding (TPAW), to describe and reflect the "reversed bugle" configuration of PAW weld cross-section. Later, Wu et al. [21] constructed another 3-D effective heat source model, which was a combination of a double-ellipsoidal heat source and a cylindrical heat source. This model could reflect the large aspect ratio of welds and the volumetric distribution characteristics of plasma heat intensity along the direction of the workpiece.

In this paper, we improved the previous combined heat source model [21] into a new kind of effective heat source model for PAW. The modified heat source model is shaped as a double-ellipsoidal volumetric heat source and a conical volumetric heat source, which is more approximate to the actual configuration of welds. Meanwhile, surface tension was also incorporated into our model as a main driving force in the weld pool. By using the improved mathematical model, heat transfer and fluid flow were numerically studied with phase change in the weld pool. The simulated results were further compared with the experimental data and other models. Finally, the process parameters were discussed, such as the plasma arc power and welding speed.

2. Mathematical model

2.1. Physical model

In PAW process, the high-temperature and high-velocity plasma arc impinges on the area where two workpieces are to be joined. As a result of its exceedingly high energy density, the plasma arc can instantly melt material, create a molten liquid pool and lead to other complex physical phenomena. This process is schematically presented in Fig. 1.

2.2. Governing differential equations

A three dimensional mathematical model was developed to describe the PAW process by introducing the following assumptions.

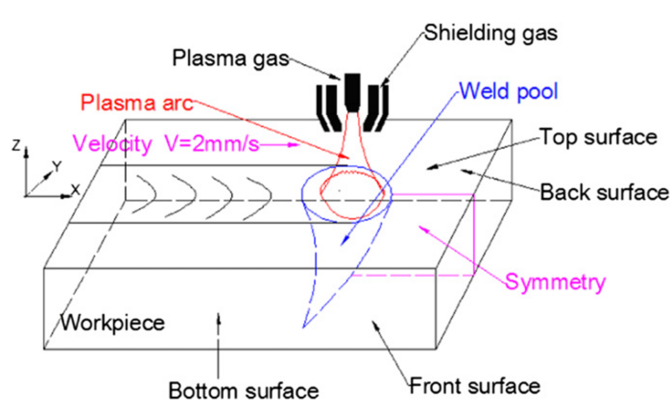

Fig. 1. Physical model of PAW process.