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Numerical analysis of the heat transfer and material flow during keyhole plasma arc welding using a fully coupled tungsten–plasma–anode model

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A coupled tungsten–plasma–anode mathematical model is first proposed in this paper to analyze the heat transfer and fluid flow in stationary keyhole plasma arc welding (PAW). The calculated plasma arc pressure is validated by a water-cooled copper based arc pressure acquisition experiment. The plasma arc temperature calculated by spectrum experiment in radial direction is used to verify the arc temperature obtained by numerical simulation. The numerical results show that: the evolution of temperature and fluid flow behavior as well as the keyhole formation in the PAW process offers an invaluable insight into the understanding of the physical essence, revealing how the keyhole promotes the deep penetration welding. Besides, the driving forces are quantitatively analyzed to explain the material flow phenomenon in the molten pool. Moreover, the energy input, transformation, transfer, and dissipation due to different physical processes in the PAW process at 0.4 s after arc ignition are calculated and analyzed to understand the energy structure and flow in the system. The findings from the study provide guidance for engineers in designing plasma arc welding schedules to achieve quality welds.

1. Introduction

Arc welding is probably the most popular manufacturing process for joining metals used in structural applications [1]. As one of the most important arc welding method, plasma welding, which possesses the advantages of high energy density and small welding deformation, has been widely used in aviation, aerospace nuclear reactors, chemical machinery, boiler tubes and other fields.

In the keyhole plasma arc welding (PAW) process, a keyhole is formed by the comprehensive dynamic balance of the heat and force at the interface between the plasma arc and weld pool [2]. The keyhole behavior that significantly affecting heat transfer and material flow in the weld pool, is a key factor deternining the stability and weld joint quality [3]. In fact, the arc and molten pool interact with each other and mutually influence each other [4]. At present, although some models of plasma arc welding (PAW) process are available, many studies among them ignore the interaction between plasma arc and molten pool. Some mathematical models [5,6] are concerned only on the plasma arc, without considering the weld pool. Other mathematical models [7–11] are concerned only with the weld pool, without considering the welding arc. So far, no mathematical model has considered the tungsten–plasma arc–molten pool-keyhole coupling in the simulation of plasma welding process.

The fluid flow behavior in material, which is very important and considered in many welding simulation literatures [12–16], affects the heat transfer and microstructure in weld specimen. The fluid flow of material is driven by driving forces in the material. For arc welding, there are four driving forces in the molten anode, including the plasma drag force, the buoyancy force, the electromagnetic force, and the surface tension gradient force [17]. These driving forces are dependent not only on the physical properties of the anode materials but also the properties of the plasma state. Thus, clearly understanding the fluid flow behavior in molten pool coupled together with the plasma arc has very important theoretical significance.

There exist boundary layers on the tungsten-plasma arc interface, and the workpiece-plasma arc interface, which are not in the

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local thermodynamic equilibrium (LTE) state. Because of the existence of these boundary layers, current conduction between the cathode and the anode cannot be guaranteed. Calculations on the cathode/anode surface need special treatment at the boundary layers. Many written works [17–21] considered the boundary layers to improve the accuracy of the numerical model. Although some models [18,22] have calculated quantitative values of energy flow in the welding processes in plasma and electrode regions, there is still lack of numerical understanding of the quantitative values for the PAW process because of the existence of complicated interactive phenomena between the arc plasma and weld pool.

This article is focused on a keyhole plasma arc welding (PAW) process. The tungsten cathode, arc plasma, anode, keyhole and weld pool, are included in a unified numerical model, taking into account the close interaction between the arc plasma and weld pool. Boundary layers are considered in the coupled model for the PAW process. The local thermodynamic equilibrium diffusion approximation method is used to treat the interfaces on the tungsten-arc plasma and arc plasma-anode. The volume-of-fluid (VOF) method is employed to capture the interface between arc plasma and weld pool [4]. Based on the numerical model, this article attempts to systematically study the heat transfer and fluid flow characteristics of the plasma arc and molten pool. The arc voltage and welding arc pressure are captured by experiment. In addition, the electron temperature of the plasma arc is calculated by the spectrum experiment. The findings from the study provide guidance for engineers in designing plasma arc welding schedules to achieve quality welds.

2. Mathematical model

2.1. Basic assumptions

(1) The plasma arc is in local thermodynamic equilibrium (LTE) and optically thin [4].
(2) The fluids in the plasma arc and weld pool are incompressible [4].
(3) The flow of arc and weld pool is taken as turbulent, and the standard k-ε model is used in calculation [23,24].
(4) The tungsten, plasma arc and specimen are assumed to be stationary.
(5) Boussinesq's approximation is used to treat buoyancy force in molten pool [25].
(6) The specimen is treated as a porous medium, and the enthalpy-porosity technology is used to handle solid-liquid mixing zone [25].
(7) The gas plasma temperature is the same with the temperature of elctrons.

2.2. Computation domain

The computational domain and its mesh are presented on the right and left of Fig. 1. The plasma gas flows into the inner nozzle through gas inlet BC, then it is ionized under the effect of electric field between the anode and the cathode. Due to the squeezing effect of the constraining nozzle, the velocity and energy intensity of plasma arc are high. When the plasma arc impinges on the workpiece, it releases heat and produces a large arc pressure at the workpiece surface. The anode (workpiece) is melted and a keyhole is established in the molten pool under the combined heat and pressure effects of plasma arc [3]. When the weld pool forms, the molten pool surface depressed, then a keyhole is established. The interface between the arc plasma and the weld pool, i.e., the keyhole boundary, is constantly changing with time.

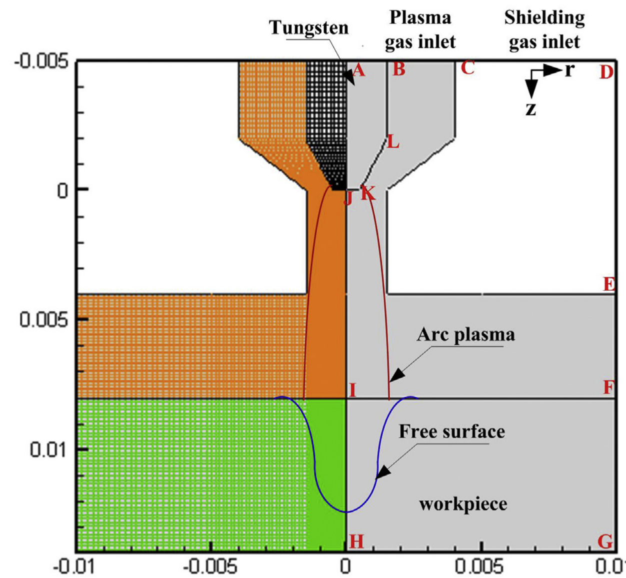

Fig. 1. Schematic illustration of the calculation domain and its mesh.

The inner surface of BLKJ is treated as coupled wall boundary. FI is the top surface of workpiece, i.e., the initial flat interface between the arc plasma and the workpiece. There exist boundary layers around BLKJ and FI, which are not satisfy the assumption of local thermodynamic equilibrium.

2.3. Governing equations

A cylindrical coordinate system (r, z) is set up at the tungsten electrode tip. One set of conservation equations is used for the whole domain, but different thermodynamic and transport parameters are taken in different zones. The governing equations are shown as follows [26]:

(a) Mass continuity equation:

$$\frac{\partial \rho}{\partial t}+\frac{1}{r}\frac{\partial}{\partial r}(r\rho v_r)+\frac{\partial}{\partial r}(\rho v_z)=0 \tag{1}$$

(b) Radial momentum equation:

$$\begin{aligned}\frac{1}{r}\frac{\partial \rho v_r}{\partial t}+\frac{1}{r}\frac{\partial}{\partial r}\left(r\rho v_r^2\right)+\frac{\partial}{\partial z}(\rho v_z v_r)&=-\frac{\partial P}{\partial r}+\frac{1}{r}\frac{\partial}{\partial r}\left(2\eta\frac{\partial v_r}{\partial r}\right)\\&+\frac{\partial}{\partial z}\left(\eta\frac{\partial v_r}{\partial z}+\eta\frac{\partial v_z}{\partial r}\right)-2\eta\frac{\partial v_r}{r^2}-Mv_r-J_zB_\theta\end{aligned} \tag{2}$$

(c) Axial momentum equation:

$$\begin{aligned}\frac{1}{r}\frac{\partial \rho v_z}{\partial t}+\frac{1}{r}\frac{\partial}{\partial r}(r\rho v_r v_z)+\frac{\partial}{\partial z}\left(\rho v_z^2\right)&=-\frac{\partial P}{\partial z}+\frac{\partial}{\partial z}\left(2\eta\frac{\partial v_z}{\partial r}\right)\\&+\frac{1}{r}\frac{\partial}{\partial r}\left(r\eta\frac{\partial v_r}{\partial z}+r\eta\frac{\partial v_z}{\partial r}\right)-Mv_z+S_m\end{aligned} \tag{3}$$

$$S_m^{arc}=J_rB_\theta \tag{4}$$

$$S_m^{pool}=J_rB_\theta+\rho g\beta(T-T_r) \tag{5}$$