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Numerical Simulation of a Combined Plasma Arc Based on Sequentially Coupled Physics Analysis

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Abstract. A three-dimensional axisymmetric mathematical model, including the influence of the swirl exiting in the plasma torch, was developed to describe the heat transfer and fluid flow within a combined plasma arc. In this model, a mapping method and a meshing method of variable step-size were adopted to mesh the calculation domain and to improve the computational precision. To overcome the problem issuing from a coexistence of non-transferred arc and transfer arc and a complicated interaction between electric, magnetic, heat flow and fluid flow phenomena in the combined plasma arc, a sequential coupling method and a physical environment approach were introduced into the finite element analysis on the behaviors of combined plasma arc. Furthermore, the characteristics of combined plasma arc such as temperature, velocity, current density and electromagnetic force were studied.

Introduction

Plasma arc has generally been applied to material processing such as welding, cutting, spraying, etc. Its characteristics have a crucial and direct influence on above processing quality. However, the generation of plasma arc involves complex physical phenomena, such as electromagnetic, heat flow and fluid flow, etc. Furthermore, the behavior of the coupling between these physical phenomena makes it quite difficult to grasp the distributions of temperature, velocity and current density of plasma arc with only experimental methods. Aimed at above problem, numerical simulation method was applied to plasma arc and it was proved feasible by some investigations. Westhoff and Szekely [1] made a numerical analysis of fluid, heat flow and electromagnetic phenomena in a non transferred arc plasma torch. Though provided an important finding that the electromagnetic forces could significantly modify the velocity profiles and affect the swirl of the plasma, they assumed the cathode tip as flat rather than pointed. Bauchire *et al*. [2] modeled a DC non-transferred plasma arc both in laminar and turbulent flow and found the result of the laminar flow model was more agreement with experimental measurements, while current density distribution was assumed when electromagnetic field being analyzed. Seungho Paik *et al*. [3] also presented an analysis of non transferred plasma arc with the Steenbeck theory, and investigated the effect of arc root position on the temperature and fluid flow of DC non-transferred plasma torch. Up to now, many studies on the characteristics of transferred plasma arc and non-transferred plasma arc have been published. However, little attentions are given to a numerical simulation of the combined plasma arc. As an ideal heat source, a combined plasma arc has been generally applied to precise welding and also involves complex physical phenomena. Therefore, it is necessary to make a numerical simulation of the combined plasma arc. Unfortunately, it is quite difficult to apply above methods to simulate the combined plasma arc, owing to the coexistence of non-transferred arc and transfer arc and the more complicated coupling between electric, magnetic, heat flow and fluid flow phenomena in the combined plasma arc. In this paper, a three-dimensional axisymmetric mathematical model on the combined plasma arc is developed according to the theories of magneto- hydrodynamics (MHD) and electromagnetics. It is solved with

the finite element methods including a sequential coupling method and a physical environment approach. In this model, a conservation of azimuthal momentum is introduced to avoid the assumption of plasma flow independent of the swirl existing in combined plasma arc. A mapping method and a variable step-size meshing method are also adopted to improve the calculation precision. Moreover, the distributions of the current density, electromagnetic force, temperature and velocity of combined plasma arc are described.

Modeling Approach

Calculation Domain. Fig. 1 presents a schematic sketch of a combined plasma arc. Firstly, the non-transferred arc between the tungsten cathode and the nozzle ignited, then the transferred arc between the tungsten cathode and anode workpiece also ignited. Consequentially, the combined plasma arc generated. Being a main working arc, the transferred arc plays a key role in the combined plasma arc, and non transferred arc can remarkably improve the stability of the transferred arc. It can be seen that the combined plasma arc consists of a non-transferred arc and a transferred arc. It results in a complicated coupling between physical phenomena such as electricity, magnetism, heat and force, etc. In order to objectively simulate the characteristics of combined plasma arc as much as possible, and to ensure boundary conditions easily determined, the calculation domain of combined plasma arc is shown in Fig. 2. The whole calculation domain can be divided into the domain of electromagnetic field and the domain of flow field. Each domain is consisted of a domain of non-transferred arc and a domain of non-transferred arc. The domain of ABCDEIJKLB is used for solving the electromagnetic field in non-transferred arc, and the domain of AEFGHIJKLBCDE is used for solving the electromagnetic field in transferred arc. To avoid an assumption of the current density distribution on the cathode surface, the tungsten cathode ABCDE is included into above both calculation domains. In addition, the domain of BCDEFGHIJKLB is used for solving the fluid field in the combined plasma arc. In order to easily establish a mathematical model of the combined plasma arc and to save the calculation time, the following assumptions have to be summarized as follows: The plasma arc is steady and optically thin and its flow is laminar; it is assumed to be pure argon in local thermodynamic equilibrium (LTE).

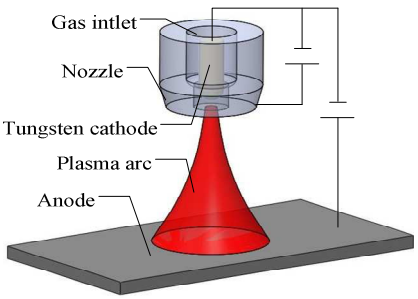

Fig.1. Schematic of the combined plasma arc

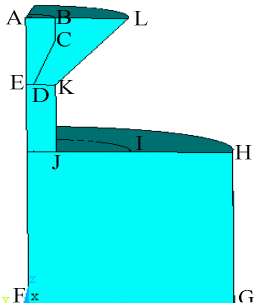

Fig.2. Computational domain of combined plasma arc

MHD Equations. With above-mentioned assumptions, a group of magnetohydrodynamics equations are expressed in terms of cylindrical coordinates as follows:

$$\frac{1}{r}\frac{\partial(r\rho v)}{\partial r}+\frac{\partial(\rho u)}{\partial z}=0 \tag{1}$$

$$\frac{1}{r}\frac{\partial}{\partial r}(\rho ruv)+\frac{\partial}{\partial z}\left(\rho u^2\right)=-\frac{\partial P}{\partial z}+j_r B_\theta+\frac{\partial}{\partial z}\left(2\mu\frac{\partial u}{\partial z}\right)+\frac{1}{r}\frac{\partial}{\partial r}\left(r\mu\left(\frac{\partial v}{\partial z}+\frac{\partial u}{\partial r}\right)\right)+\rho g \tag{2}$$

$$\frac{1}{r}\frac{\partial}{\partial r}\left(r\rho v^2\right)+\frac{\partial}{\partial z}(\rho uv)=-\frac{\partial P}{\partial r}-j_z B_\theta+\rho\frac{w^2}{r}-2\mu\frac{v}{r^2}+\frac{\partial}{\partial r}\left(2\mu r\frac{\partial v}{\partial r}\right)+\frac{\partial}{\partial z}\left(\mu\left(\frac{\partial v}{\partial z}+\frac{\partial u}{\partial r}\right)\right) \tag{3}$$

$$\frac{1}{r}\frac{\partial}{\partial r}(r\rho vw)+\frac{\partial}{\partial z}(\rho uv)+\rho\frac{vw}{r}=\frac{1}{r}\frac{\partial}{\partial r}\left(\mu r^2\frac{\partial}{\partial r}\left(\frac{w}{r}\right)\right)+\mu\frac{\partial}{\partial r}\left(\frac{w}{r}\right)+\frac{\partial}{\partial z}\left(\mu\frac{\partial w}{\partial z}\right) \tag{4}$$

$$\frac{1}{r}\frac{\partial}{\partial r}(r\rho vT)+\frac{\partial}{\partial z}(\rho uT)=\frac{1}{r}\frac{\partial}{\partial r}\left(\frac{rk}{c_p}\frac{\partial T}{\partial r}\right)-S+\frac{\partial}{\partial z}\left(\frac{k}{c_p}\frac{\partial T}{\partial z}\right)+\frac{5k_b}{2e}\left(j_r\frac{\partial T}{\partial r}+j_z\frac{\partial T}{\partial z}\right)+\frac{j_r^2+j_z^2}{\sigma} \tag{5}$$

where ρ is the mass density of the gas, P is pressure, j_r is radial component of the current density, j_z is the axial component of the current density vector, B_θ is self-induced magnetic field intensity, μ is the gas viscosity, g is the acceleration of gravity, T is temperature, c_p is specific heat, σ is electric conductivity, k is thermal conductivity, k_b is Boltzman constant, e is electronic charge, and S is the volumetric radiative loss term; u, v and w are axial, radial and azimuthal velocity, respectively. Otherwise, The terms of j_rB_θ and j_zB_θ are the electromagnetic forces, where **J** is the current density vector and **B** is the magnetic flux density vector.

Maxwell Equations. There exit Lorentz force terms in above momentum equations. Moreover, the energy equation contains the joule heating term and an additional term which represents the transport of electron enthalpy due to the drift of electrons. Therefore, it is necessary to introduce Maxwell equations to solve above terms of electromagnetic field.

$$\frac{1}{r}\frac{\partial}{\partial r}\left(r\sigma\frac{\partial\phi}{\partial r}\right)+\frac{\partial}{\partial z}\left(\sigma\frac{\partial\phi}{\partial z}\right)=0 \tag{6}$$

$$j_r=-\sigma\frac{\partial\phi}{\partial r};\ j_z=-\sigma\frac{\partial\phi}{\partial z} \tag{7}$$

$$\frac{1}{r}\frac{\partial}{\partial r}(rB_\theta)=\mu_0 j_z \tag{8}$$

where Φ is the electrical potential, μ_0 is the vacuum permeability ($4\pi\times10^{-7}$H/m).

According to the fact of non-transferred arc coexisting with transferred arc in the combined plasma arc, it is necessary to apply a sequential coupling method. That is to say, the whole solving process of above MHD equations and Maxwell equations can be divided into two stages. During the first stage non-transferred arc is calculated. In addition, the distributions of current density, temperature and velocity are obtained. During the second stage, above distributions from the former stage are introduced into the transferred arc to be iteratively calculated until the solution of above mathematical model of combined plasma arc is convergent. Consequentially, the distributions of electromagnetic field and fluid field in the combined plasma arc can be acquired.

Boundary Conditions and Technique of Solution. In view of the influence of the cathode geometric shape and the accuracy of the finite element simulation, a mapping method is introduced into the finite element model of combined plasma arc to obtain the finer hexahedral meshes. Existed the steep gradients between the cathode and the anodes, a variable step-size meshing method has to be also introduced into the finite element model of the combined plasma arc. So the region near to the model center line will be hold finer meshes. For the finite element model of combined plasma arc being axisymmetric, a quarter of this model is regarded as the substitution of whole calculation model to save computation time. For solving the potential equation, the working current passing through tungsten cathode is considered as uniform, so the current density of AB can be taken from the investigation of Lu [4]. At the anode surfaces FG and JL, the electrical potential is assumed to be zero. Meanwhile, $\partial\Phi/\partial n=0$ has been set on other places to represent the condition that no current flow crosses this boundary. For solving the momentum and energy equations, at BE and FG, a temperature of 3000K is assumed. An adiabatic condition is applied to the symmetrical surface EF. On other surfaces, the temperature is assumed to be 1000K. Furthermore, at the interior wall of the nozzle IL, wall of the cathode BE and anode surface FG, a no-slip condition is used. At the gas outlet GH,

relative pressure P is assumed to 0. $\partial u/\partial r=0$, $v=0$, $w=0$ are specified to the symmetrical surface AF and shielding gas inlet HI. Along the working gas inlet BL, the radial and azimuthal velocity components are neglected, and the axial velocity component is determined from Yin [5]. In addition, in the process of analysis of electro-magnetic coupling field, magnetic lines of force are assumed to perpendicularly pass the symmetry plane and the boundary condition of the magnetic vector potential being zero is imposed on other surfaces in the calculation domain of the combined plasma arc.

Physical environment approach is applied into the iterative analysis on coupled phenomena. In this paper, three physical environment files are created by finite element software ANSYS including electric field, magnetic field and flow field. In the finite element analysis process, the operation command LDREAD is introduced to help these physical environment files successively correlated. That is, the results from one file can be loaded into another file using LDREAD. To ensure above iterative analysis convergent a minor convergence of temperature is set, which results from the normalization value of the temperature change between two adjacent iterative steps. In addition, to make argon gas fully ionize a temperature of 100000K is imposed to the region of arc column in the initial calculation of electric field.

Calculation and Discussion

The process parameters adopted in the simulation are that the diameter of tungsten cathode is 1mm, its cone angle and length in the calculation domain is 60° and 3mm respectively, the interior radius of nozzle inlet and outlet is 3.5mm, its length is 6mm, and the radius of workpiece anode is 7mm.

The calculated current density distribution is shown in Fig. 3(a). As shown, the current departs from the anode surface and enters the electrode tip through the tungsten cathode spot. The current density reaches highest value at the cathode tip for its smaller area and higher temperature. Furthermore, the current density becomes larger with axial distance nearing to the cathode, and decreases with radial distance increasing owing to the effect of temperature distribution of combined plasma arc on argon gas electric conductivity. The higher the temperature, the larger conductivity is. Consequently, it results in the larger current density distribution of combined plasma arc. Fig. 3(b) shows the calculated distribution of the electromagnetic force both in the arc column and tungsten cathode. Based on the left-hand rule, the direction of electromagnetic force can be determined with the current density and magnetic flux density. As shown, in the region of combined plasma arc column the direction of electromagnetic force is inward and downward, which compels the combined plasma arc to flow towards the workpiece anode and to be compressed at the same time. Furthermore, it can be seen that the electromagnetic force at the cathode tip is larger than the one at the lower portion of the arc, which also makes the combined plasma arc flow downward and inward.

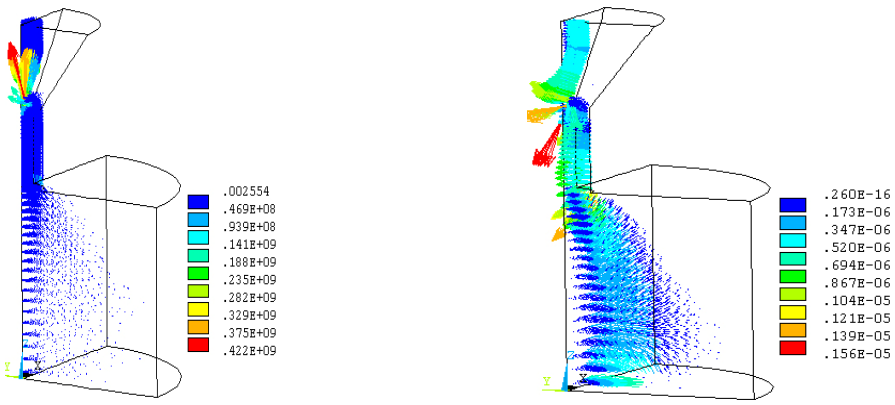

Fig.3. Current density distribution and electromagnetic force distribution in the combined plasma arc

The calculated temperature distribution of combined plasma arc is shown in Fig. 4(a). As shown, there exists a maximum temperature in the region near to the tungsten cathode where the current density is higher. Larger temperature gradients appear to the cathode region and workpiece anode regions, respectively. It can be also seen that the temperature of combined plasma arc becomes lower with axial distance away from the cathode, and increases with radial distance decreasing. Fig. 4(b) shows the velocity distribution of the combined plasma arc. It can be seen that after passing the nozzle inlet, argon gas flows downward and inward. Once it reaches the cathode tip, the combined plasma arc is accelerated from the cathode towards the workpiece anode. When approaching this working anode it is forced to turn around radial direction, which causes a bell shape of combined plasma arc and transforms the momentum of high speed flow into the impact force of the combined plasma arc.

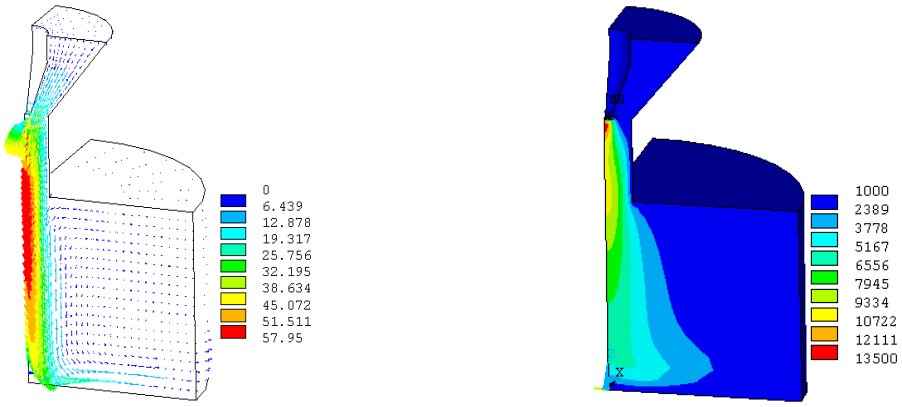

Fig.4. Temperature distribution and Velocity distribution in the combined plasma arc

Conclusions

It's well known that the transferred arc and non-transferred arc have poor stability when working current is lower. However, as an ideal heating source for precise welding, the arc current of micro plasma is usually less than 15A and more stable due to the use of combined plasma arc. In this paper, a three-dimensional mathematical model on the combined plasma arc was established, including the influence of the swirl exiting in the plasma torch, without the assumption of plasma flow independent of the swirl existing in the combined plasma arc. Using the sequential coupling method and physical environment approach, the coexistence of non-transferred arc and transfer arc in the combined plasma arc was successively simulated. Consequentially, it proved that the non-transferred arc can provide a good conducting channel for the transferred arc in combined plasma arc and improve the stability of the transferred arc.

An important finding of this work is that the distributions of current density, electromagnetic force, temperature and velocity in the plasma arc are interesting. The peak values of the current density and electromagnetic force emerge at the cathode tip. Far from the cathode tip, the current density descends and the electromagnetic force becomes smaller. And the direction of electromagnetic force is inward and downward. Furthermore, there exists a maximum temperature in the region near to the cathode tip. Far from the cathode tip or the center line of the arc column, the temperature becomes lower. The electromagnetic force plays a very important role in determining both the distributions of the temperature and velocity. Consequently, the combined plasma arc is accelerated from the cathode towards the workpiece anode and be forced to constrict inward.

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