Numerical Analysis of Heat Source Properties of Pulsed Tungsten Inert Gas Arc

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The heat source properties of TIG arc strongly depend on composition of shielding gas. For example, since the arc column is constricted due to high specific heat, heat flux onto a base metal in case of CO₂ TIG arc is higher than that of argon TIG arc. The heat source properties can be controlled also by current waveform. Pulsed TIG welding is suitable for back-bead welding and thin plate welding, because the heat flux onto the base metal can be controlled by adjusting peak / base current ratio and frequency. In this paper, numerical simulation result of the heat source properties of pulsed TIG arc for various shielding gas composition will be reported. As a result, it was found that the heat flux increased immediately after transition from base current to peak current because of the thermal pinch effect. Furthermore, in CO₂, although the heat transport toward the anode by convective flow was seen, that in radial direction due to thermal conduction was smaller than that of argon because of influence of large specific heat.

Key words: Numerical simulation, Pulsed TIG arc, Heat source property, Argon, CO₂

1. INTRODUCTION

The heat source properties of TIG arcs strongly depend on physical properties of the shielding gas. For example, argon, helium, oxygen and carbon dioxide and so on are generally employed as the shielding gas. Recently, a novel heat source for oxygen and carbon dioxide was developed [1]. It has a double gas shielded system which employs carbon dioxide or oxygen and inert gas to avoid the consumption of the tungsten electrode by oxidation. Since helium with low electrical conductivity [2] or carbon dioxide with high specific heat [3] causes the constriction of the current channel in the arc plasma, these gases enable to produce the arc plasma with high energy density and are suitable especially for processes to require concentrating the heat input at a point. Furthermore, the target material can be heated without any chemical reaction by using an inert gas such as argon or helium as the shielding gas. On the other hand, oxygen or carbon dioxide is chosen if the oxidation of the target material is required, for example, for cutting. Thus, suitable shielding gas composition for each process is selected.

The heat source properties can be controlled also by current waveform. Pulsed TIG welding is suitable for back-bead welding and thin plate welding, because the heat flux onto the base metal can be controlled by adjusting peak / base current ratio and frequency. A number of results on experimental and theoretical investigations of the heat source properties of DC TIG arc have been reported. However, those of pulsed TIG arc are still not fully understood because of the complexity of the phenomenon. In this study, the heat source properties of pulsed TIG arc for various shielding gas composition was numerically analyzed.

2. SIMULATION MODEL

Fig. 1 shows the calculation region for TIG arc consisting of a tungsten cathode with diameter of 3.2mm and tip angle of 60 degrees, arc plasma and a water-cooled copper anode. It is described in a frame of cylindrical coordinate with axial symmetry around the arc axis. The electrode gap is set to be 5mm. Argon (Ar) or carbon dioxide (CO₂) is introduced as shielding gas from the upper boundary at the flow rate of 10 l min⁻¹. For example of physical properties of each gas, specific heat, thermal conductivity and electrical conductivity are shown in Fig. 2. An arc current has wave form with the peak current of 150A and the base current of 50A. The frequency is 100Hz and the pulse width is 5ms. The laminar flow is assumed, and the arc plasma is considered to be in the local thermodynamic equilibrium (LTE). The governing equations (1)-(6) are solved iteratively by the SIMPLER numerical procedure [4]. The other numerical modeling methods are given in detail in our previous paper [5].

Mass continuity equation is

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

Radial momentum conservation equation is

$$\frac{\partial \rho v_r}{\partial t} + \frac{1}{r} \frac{\partial}{\partial r} (r \rho v_r v_r) + \frac{\partial}{\partial z} (\rho v_z v_r) = -\frac{\partial p}{\partial r} - \sigma_B$$

Axial momentum conservation equation is

$$\frac{\partial \rho v_z}{\partial t} + \frac{1}{r} \frac{\partial}{\partial r} (r \rho v_z v_r) + \frac{\partial}{\partial z} (\rho v_z v_z) = -\frac{\partial p}{\partial z} + \sigma_B$$

Energy conservation equation is

$$\frac{\partial \rho E}{\partial t} + \frac{1}{r} \frac{\partial}{\partial r} (r \rho E v_r) + \frac{\partial}{\partial z} (\rho E v_z) = -\frac{\partial}{\partial r} (\rho \mathbf{v} \cdot \mathbf{v}_r) - \frac{\partial}{\partial z} (\rho \mathbf{v} \cdot \mathbf{v}_z) + \sigma_B$$
\[
\frac{\partial \rho h}{\partial t} + \frac{1}{r} \frac{\partial}{\partial r} (r \rho v_r h) + \frac{\partial}{\partial z} (\rho v_z h) = \frac{1}{c_p} \left( \frac{\partial}{\partial r} (r c_p \frac{\partial h}{\partial r}) + \frac{\partial}{\partial z} (c_p \frac{\partial h}{\partial z}) + j_r E_r + j_z E_z - U \right)
\]

Current continuity equation is
\[
\frac{1}{r} \frac{\partial}{\partial r} (r j_r) + \frac{\partial}{\partial z} (j_z) = 0
\]

Ohm’s law is
\[
j_r = -\sigma E_r, j_z = -\sigma E_z
\]

where \( t \) is time, \( h \) is enthalpy, \( p \) is pressure, \( v_r \) and \( v_z \) are radial and axial velocities, \( j_r \) and \( j_z \) are the radial and axial components of the current density, \( g \) is acceleration due to gravity, \( c_p \) is specific heat, \( k \) is thermal conductivity, \( \rho \) is density, \( \eta \) is viscosity, \( U \) is radiative emission coefficient and \( \sigma \) is electrical conductivity. \( E_r \) and \( E_z \) are the radial and axial components of the electric field defined by
\[
E_r = -\frac{\partial V}{\partial r}, E_z = -\frac{\partial V}{\partial z}
\]

where \( V \) is electric potential. The azimuthal magnetic field \( B_\theta \) induced by arc current is evaluated by Maxwell’s equation
\[
\frac{1}{r} \frac{\partial}{\partial r} (r B_\theta) = \mu_0 j_z
\]

where \( \mu_0 \) is the permeability of free space. It is necessary to consider the effects of energy transfer at the electrode surfaces. The additional energy fluxes at the cathode and anode are described as.

Cathode : \( F_K = -\alpha \phi_K T^4 - |j_i| \phi_K + |j_i| V_i \)

Anode : \( F_A = -\alpha \phi_A T^4 - |j_i| \phi_A \)

where \( \varepsilon \) is surface emissivity, \( \alpha \) is the Stefan–Boltzmann constant, \( \phi_K \) is the work function of the tungsten cathode, \( V_i \) is the ionisation potential of the plasma gas, \( j_i \) is the ion current density, \( j_e \) is the electron current density, \( \phi_A \) is the work function of the anode and \( T \) is the temperature. For the cathode surface, \( \Phi_k \) needs to be included in equation (4) to take into account the thermionic cooling by emission of electrons, radiative cooling and ion heating. Similarly, for the anode surface, \( \Phi_\lambda \) is required in equation (4) to take into account radiative cooling and thermionic heating. Furthermore, for the cathode surface, the electron current and the ion current are considered separately and defined based on the Richardson–Dushman equation of thermionic emission as follows
\[
j_e = A T^2 \exp \left( \frac{-e \phi_e}{k_B T} \right)
\]

where \( k_B \) is the Boltzmann’s constant and \( A \) is the Richardson’s constant, which depend on the cathode material. The ion-current density \( j_i \) is then assumed to be \( |j_i| \) if \( |j_i| \) is greater than \( |j_e| \); where \( |j| \) is the total current density at the cathode surface.

3. RESULTS AND DISCUSSION

Fig. 3 shows two-dimensional temperature distributions at \( t=30 \text{ms} \) (the end of base current), 32.5ms (peak current), 35ms (the end of peak current) and 37.5ms (base current) in case of Ar. Fig. 4 shows dependence of axial temperature distribution along the central axis on time. During the peak current, the heat caused by Joule heating near the cathode tip was transported toward the anode by convective flow and was also transported in radial direction by thermal conduction. Fig.5 shows dependence of the max. arc pressure to anode and the max. plasma temperature on time. It was seen that change in plasma temperature immediately after change in the current was large and approached to temperature in steady state. The arc pressure increased gradually after the change to the peak current because of time lag for the plasma flow.
accelerated near the cathode to reach the region near the anode. Fig. 6 shows dependence of the max. heat flux to anode on time. In addition to the total heat flux, heat flux due to thermal conduction and electron condensation were also presented. It was found that heat flux due to electron condensation and that due to thermal conduction are dominant in the peak current and the base current, respectively. It was considered that the heat flux due to electron condensation peaked after the transition from the base current to the peak current because of thermal pinch effect caused by low plasma temperature.

Fig. 7 shows two-dimensional temperature distributions in case of CO$_2$. Fig. 8 shows dependence of axial temperature distribution along the central axis on time. In this case, although the heat transport toward the anode by convective flow was seen, that in radial direction due to thermal conduction was smaller than that of Ar because of influence of large specific heat. As a result, the radius of the arc column hardly changed during the calculation. Fig. 9 shows dependence of the max. arc pressure to anode and the max. plasma temperature on time. It was found that time variation in the max plasma temperature was larger than that in case of Ar. For a reason, it was considered that the plasma temperature easily increased following increase in the current because energy loss to the surrounding due to thermal conduction decreased due to influence of large specific heat. Fig. 10 shows dependence of the max. heat flux to anode on time. It was found that proportion of heat flux due to thermal conduction in total heat flux was larger than that in case of Ar because the plasma temperature near the anode tended to increases comparing to that in Ar.
4. CONCLUSIONS

(1) In case of Ar, the heat caused by Joule heating near the cathode tip was transported toward the anode by convective flow and was also transported in radial direction by thermal conduction.

(2) In case of CO₂, although the heat transport toward the anode by convective flow was seen, that in radial direction due to thermal conduction was smaller than that of Ar because of influence of large specific heat.

(3) The heat flux due to electron condensation increased immediately after transition from base current to peak current because of the thermal pinch effect.

REFERENCES


(Received January 17, 2012; Accepted April 12, 2012)