Modeling of Temperature Distribution with Metal Vapor in Pulsed TIG Including Influence of Gas Flow Velocity Affected by Radiation Absorption*

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Pulsed tungsten inert gas (TIG) welding is used to improve the stability and speed of arc welding, and to provide greater control over the heat input to the weld. The temperature and the radiation power density of the pulsed arc vary as a function of time, as does the distribution of metal vapor. They also affect the arc. A self-consistent two-dimensional model of the arc and electrodes is used to calculate the arc properties as a function of time. Self-absorption of radiation is treated in three directions considering absorption throughout the plasma. The relation between the metal vapor and the radiation power density is analyzed by calculating the gas flow velocity affected by the radiation absorption with the iron vapor distribution. The temperature, iron vapor, and radiation power density distributions depend on the self-absorption model that is used. The temperature distribution becomes broader when self-absorption of radiation from all directions is considered. Results show that the temperature distribution is affected strongly by the fast gas flow velocity during the peak current period. During the base current period, it expands to the radial direction.

Key Words: Numerical calculation, Radiation, Self-absorption, TIG, Arc, Metal vapor, Welding

1. Introduction

Many reports in the literature have addressed the case of a constant arc current. However, pulsed arc currents are widely used in high-speed welding, and more generally to control the heat input and droplet transfer in arc welding. For tungsten inert gas (TIG) welding, in which the electrode rod does not melt and no droplet transfer occurs, pulsed currents are used to control the heat input to the arc and weld pool, and to facilitate high-speed welding. Rarely if ever is the time variation of the metal vapor distribution discussed for pulsed TIG welding. Nevertheless, understanding the time dependence of the metal vapor distribution is important because the mixing of metal vapor with the shielding gas affects fundamental properties such as the arc temperature and radiative emission. Furthermore, because self-absorption of the radiation strongly influences the arc temperature and the heat transfer to the weld pool^{1)~4)}, it is necessary to account for self-absorption of the arc radiation. When self-absorption is considered, the gas flow velocity in the arc changes because of the change in the temperature gradient. The temperature distribution changes concomitantly with changes in the gas flow velocity distribution. Therefore, self-absorption with metal vapor distribution should be considered when the modeling of TIG welding is computed.

As described in this paper, the time dependence of the distribution of temperature with vapor from the anode is analyzed

using an electromagnetohydrodynamic simulation that includes the influence of radiation self-absorption. Stainless steel's main component, iron, is often welded using TIG welding. The effects on the temperature distribution, including the influence of gas flow velocity by self-absorption, are assessed using plasma thermophysical data that incorporate the iron vapor concentration.

2. Calculation Method

Electromagnetohydrodynamic simulations of arcs are performed using a two-dimensional cylindrical coordinate system. However, treating radiative transfer in the cylindrical coordinate system is difficult because the circular grid does not conform to the linear propagation paths of light. A three-dimensional Cartesian coordinate system is used to solve this problem by calculating the radiation power distribution while incorporating self-absorption. A two-dimensional axisymmetric cylindrical coordinate system is used for all other aspects of the electromagnetohydrodynamic model. Because the arc's iron vapor concentration, arc temperature, and radiative properties all affect each other, a self-consistent modeling approach must be used.

Figure 1 shows the simulation model. Table 1 shows the boundary condition. A tungsten cathode and stainless steel anode are used. Iron vapor is generated by the molten region of the anode. The inter-electrode spacing is 5 mm, the shielding gas is argon, the gas flow rate is 10 slm, and the pressure is 0.1 MPa. The following assumptions are made: local thermodynamic

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equilibrium ¹⁾, laminar flow ²⁾, incompressible fluid ³⁾, only the anode is melted ⁴⁾, and the welding pool surface remains flat ⁵⁾. The model enables simultaneous calculation of the temperature, fluid flow, and distribution of electromagnetic properties in the electrodes and the arc.

Figure 2 shows the pulsed current waveform used in the calculation: the peak current is 150 A; the base current is 50 A; the duty ratio is 0.5; the transient time of the current is 0.2 ms; and the frequency is 100 Hz. Characters used in the figure signify the following: A, the time of transition to the base current; B, the time immediately before the transition from the base current to the peak current; C, the time of transition to peak current; and D, the time immediately before the transition from the peak current to the base current. The temperature distribution at each time is calculated self-consistently.

In this calculation model, the electrode and the arc are combined into one system and analyzed simultaneously. The transfer of energy between the arc and the electrode is calculated ⁵⁾ and added as a localized source term to the equation for conservation of energy.

The iron vapor concentration on the anode surface is determined using the saturation vapor pressure and the ambient pressure. The saturation vapor pressure is determined by the temperature at the welding pool surface. The concentration distribution is obtained by solving the conservation equation of the iron vapor, using the iron vapor concentration on the anode surface as a boundary condition. Changes in the fundamental characteristics of the arc caused by mixing of the iron vapor are studied considering the influence of the iron vapor concentration on thermophysical properties.

The transfer of radiation to and from a control volume is calculated using two methods ⁵⁾. In the simple self-absorption model, the calculation domain is the same cylindrical coordinate system used for the electromagnetohydrodynamic model. Absorption is calculated only within the control volume in which emission occurs. It depends only on the temperature and the radial dimension of the control volume (absorption length). In the full self-absorption model case, the calculation domain is divided into a three-dimensional Cartesian grid. Incident radiation entering a control volume from all three adjacent control volumes is considered. The flux of incident radiation from each direction is normalized to the area of the interface relative to the control volume's total surface area. With each passage through the control volume, the incident radiation intensity decreases because of self-absorption and increases according to the influence of the radiative emission from within the control volume.

Fig. 3 shows the net emission coefficient of Ar: 99.9% - Fe 0.1% and Ar: 100% with consideration of self-absorption

Fig. 1 Simulation model.

Table 1 Boundary conditions

	T	ϕ	v	C
A-B (Cathode)	300 K	-	$v_z = v_r = 0$	$C = 0$
B-C (Inflow)	300 K	$\frac{\partial \phi}{\partial z} = 0$	Inflow = 10 slm, $v_r = 0$	$C = 0$
C-D (Nozzle)	300 K	$\frac{\partial \phi}{\partial z} = 0$	$v_z = v_r = 0$	$C = 0$
D-E (Outflow)	300 K	$\frac{\partial \phi}{\partial z} = 0$	$v_z = 0$, $v_r = \text{Outflow}$	$C = 0$
E-F (Anode)	300 K	$\frac{\partial \phi}{\partial r} = 0$	$v_z = v_r = 0$	$C = 0$
F-G (Anode)	300 K	$\phi = 0$	$v_z = v_r = 0$	$C = 0$
G-A (Axis)	$\frac{\partial T}{\partial r} = 0$	$\frac{\partial \phi}{\partial r} = 0$	$\frac{\partial v_z}{\partial r} = 0$, $v_r = 0$	$\frac{\partial C}{\partial r} = 0$

Fig. 2 Current waveform.

(absorption length = 1 m). Absorption occurs at a low temperature gas around 7000 K because of absorption from atomic species and high-temperature gas at around 13000 K because of absorption from ionization species. The absorption calculation method was described in an earlier report ⁵⁾.

3. Results and discussion

Figures 4 and 5 show distributions of the arc temperature and radiation for a simple model that incorporates control volumes and directions, with a full self-absorption model that incorporates

data of all three adjacent control volumes and directions.

The arc temperature distribution was calculated self-consistently. The relation between metal vapor and the radiation power density is analyzed by calculating the gas flow velocity as affected by radiation absorption with the iron vapor distribution⁵⁾. The temperature, iron vapor, and radiation power density distributions depend on the self-absorption model that is used. The temperature distribution widens when self-absorption of radiation from all directions is considered.

When self-absorption is considered, its effects are expected to be more pronounced at high temperature at the arc center and in the low-temperature region at the arc periphery. Therefore, the absorption is greatest at the arc center and where a large amount of metal vapor is present at low temperatures. These locations with metal vapor correspond to regions in the arc periphery near the anode⁵⁾. It is therefore these regions where the temperature is increased. The temperature gradient is important: a high gradient favors localized absorption because low-temperature absorbing regions are closer to high-temperature emitting regions⁵⁾.

Figure 6 shows the gas flow velocity and absorption ratio distribution. In the case of A, the gas flow velocity becomes high at the arc center near the cathode. At this point, the absorption ratio becomes high. Therefore, the temperature rises because of self-absorption. When the temperature rises, the gas flow velocity increases because of the increase in the temperature gradient between the cathode and anode. Furthermore, the metal vapor is evaporated from the anode. The radiation increases and the temperature decreases when the metal vapor contaminates the arc. At this point, the absorption ratio decreases. Moreover, absorption occurs at the arc periphery. Figure 3 shows that the absorption occurs with low-temperature gas at around 7000 K and with high-temperature gas at around 13000 K.

In the case of B, with base current of 50 A, the gas flow velocity decreases and temperature decreases. In this case, absorption occurs mainly at the arc center and at the arc periphery.

In the case of C, the current is 150 A base-to-peak. The gas flow velocity increases and temperature decreases. In this case, absorption occurs at the center and periphery of the arc. Self-absorption occurs in the area between the arc and periphery because the temperature at this area becomes low. In addition, the gas flow velocity direction has a complex at the boundary of the absorption ratio. Therefore, the gas becomes a circular flow at the middle of the arc between the inter-electrodes, and the temperature distribution expands in the radial direction.

For D, the peak current is 150 A; the gas flow velocity increases and temperature increases. In this case, the absorption occurs mainly at the center and periphery of the arc. At this point,

Fig. 3 Net emission coefficient of Ar: 99.9% - Fe 0.1% and Ar: 100% under consideration of self-absorption as function of temperature.

Fig. 4 Distribution of arc temperature for the simple model and the full self-absorption model.

the gas flow does not become a circular flow because the gas flow velocity becomes high. Therefore, the temperature distribution does not expand to the radial direction.

4. Conclusions

A time-dependent electromagnetohydrodynamic simulation of pulsed TIG arc welding was performed with the electrodes and

Fig. 5 Distribution of radiation distribution for the simple model and full self-absorption model.

Fig. 6 Gas flow velocity and absorption ratio distribution for full self-absorption model.

are included in the computational domain. The distribution of temperature with vapor generated from the anode was calculated using thermophysical properties that incorporate the iron vapor concentration. The main results are presented below.

- (1) The influence of self-absorption of radiation was calculated using a Cartesian grid, allowing consideration of radiation from all three adjacent control volumes and directions. The arc temperature distribution was calculated self-consistently.
- (2) The mutual relation between the metal vapor and radiation power density was analyzed by calculating the gas flow velocity affected by radiation absorption with the iron vapor distribution.
- (3) The temperature, iron vapor, and radiation power density distributions depend on the self-absorption model used. The temperature distribution widens when self-absorption of radiation from all directions is considered.
- (4) The temperature distribution is strongly affected by the fast gas flow velocity during the peak current period. Moreover, absorption occurs at the arc periphery. Absorption occurs in low-temperature gas at around 7000 K and high-temperature gas at around 13000 K.
- (5) The gas flow becomes a circular flow in the middle of the arc between the inter-electrodes when the current is base-to-peak. Therefore, the temperature distribution expands in the radial direction.

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References

- 1) A. Essoltani, P. Proulx, M. L. Boulos and A. Gleizes: Volumetric emission of argon plasmas in the presence of vapors of Fe, Si, and Al, 14 (1994), pp.437–450.
- 2) J.J. Gonzalez, A. Gleizes, P. Proulx and M. Boulos: Mathematical modeling of a free-burning arc in the presence of metal vapor, J. Appl. Phys. 74 (1993), pp.3065–3070.
- 3) J. Haidar: The dynamic effects of metal vapor in gas metal arc welding, J. Phys. D: Appl. Phys. 43 (2010), pp.165204.
- 4) M. Schnick, U. Füssel, M. Hertel, A. Spille-Kohoff and A.B. Murphy, Metal vapor causes a central minimum in arc temperature in gas–metal arc welding through increased radiative emission. J. Phys. D: Appl. Phys. 43 (1994), pp. 022001.
- 5) T. Iwao, M. Yusuke, O. Masato, S. Tadashi, T. Shinichi, T. Manabu, Y. Motoshige, Modelling of metal vapour in pulsed TIG including influence of self-absorption, J. Phys. D: Appl. Phys. 43 (2010), pp.434010.