Numerical Modeling of Nitrogen Absorption during Gas Tungsten Arc Welding*

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It is problem that nitrogen absorption in gas tungsten arc (GTA) weld metal. Recently, various arc welding simulation techniques have been developed. However, there are few models dealing with the absorption and a mixture of a shielding gas, an atmosphere and a metal vapor.. In this study, intruding behaviors of the atmospheric gas (N_2) into the molten pool and nitrogen transportation phenomenon in the molten pool during GTA welding was investigated using a unified numerical model. This model includes the tungsten cathode, arc plasma and base metal. We take atmosphere (N_2), shielding gas from the gas nozzle and metal vapor from the molten pool into consideration. As a result, we show nitrogen concentration distribution and nitrogen transportation in the molten pool. Additionally, we clarify that these behaviors are affected by the arc plasma characteristics.

Key Words: Numerical Model, Gas Tungsten Arc Welding, Nitrogen, Absorption

1. Introduction

Nitrogen absorption in weld metal causes deterioration of welding quality, such as blowhole generation or toughness degradation. According to previous studies, it is known that weld metals may generate blowholes when the nitrogen concentration exceeds around 200ppm, and the toughness begins to degrade sharply as it surpasses around 100ppm¹⁾. Meanwhile, various arc welding simulation techniques have been developed. However, in most of the conventional arc welding models, the atmosphere is treated the same as the shielding gas, and thus there are few models in which the mixture of atmospheric nitrogen is taken into consideration. Furthermore, the model which calculates the nitrogen absorption in the molten pool hardly exists. In this paper, the numerical-analysis model of GTA welding was developed for analysing the mixing behaviour of the atmospheric nitrogen in the shielding gas and dissolving phenomenon of the atomic nitrogen into molten pool. By using this model, the nitrogen transportation in the molten pool was calculated.

2. The numerical-analysis model of GTA welding

The atmospheric nitrogen is mixed in the shielding gas under the influence of the arc jet flow, and the nitrogen is

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disassociated in the plasma region of high temperature. Furthermore, the disassociated nitrogen dissolves in the molten metal surface, and it spreads through the molten metal by the convection flow and diffusion of molten pool. In order to calculate this intricate phenomenon, the mixture phenomenon of nitrogen and shielding gas, the nitrogen dissolution behaviour on molten pool surface, and the nitrogen transfer in molten pool were calculated simultaneously.

The simulation domain is shown in Fig.1. The two-dimensional cylindrical coordination model, which consists of a tungsten cathode having a diameter of 3.2 mm with a tip angle of 60°, a pure iron anode having a diameter of 25 mm and a shielding nozzle with an inner diameter of 12 mm, was adopted. Arc length is set as 5 mm. In addition, the current were set at 150A. Moreover, nitrogen was postulated as the atmosphere

Fig. 1. Schematic illustration of simulation domain.

In this model, mass conservation equation, momentum conservation equation, energy conservation equation and current conservation equation were used as the dominant equations. The mixture of the shielding gas (helium), the atmosphere (nitrogen) and the iron vapor from the molten pool was analyzed using such a conservation equation²⁾.

$$\frac{\partial}{\partial t}(\rho C_i) + \frac{1}{r} \frac{\partial}{\partial r}(r \rho v_r C_i) + \frac{\partial}{\partial z}(\rho v_z C_i) = \frac{1}{r} \frac{\partial}{\partial r} \left(r \rho D \frac{\partial C_i}{\partial r} \right) + \frac{\partial}{\partial z} \left(\rho D \frac{\partial C_i}{\partial z} \right) \quad (1)$$

where, C_i is the mass fraction of each elements, v_r and v_z are the respective gas flow velocity in the radial direction and the axial direction, and ρ is density. Furthermore, D is the two-dimensional diffusion coefficient which is expressed by the viscosity approximation equation

$$D = \frac{2\sqrt{2}(1/M_1 + 1/M_2)^{0.5}}{\left[(\rho_1^2 / \beta_1^2 \mu_1^2 M_1)^{0.25} + (\rho_2^2 / \beta_2^2 \mu_2^2 M_2)^{0.25} \right]^2} \quad (2)$$

where M_1 and M_2 are the molecular weights of iron and the shielding gas respectively. ρ_1 , ρ_2 , μ_1 and μ_2 are the density and viscosity of iron and the shielding gas respectively. β_1 and β_2 are the dimensionless constants. $\beta_1 = \beta_2 = 1.385$ is assumed based on the mean value of the experimental data³⁾.

The nitrogen concentration of the surface of a molten pool was defined by the following formula⁴⁾.

$$[N] = P_N \exp \left(- \frac{\Delta G_{N(g)}^0}{RT} \right) \quad (3)$$

Where, N is the nitrogen concentration, P_N is the monatomic nitrogen partial pressure, $\Delta G_{N(g)}^0$ is the free energy relationship

Fig. 2 Dependence of electrical conductivities of helium gas on temperature for each mixing ratio

for the nitrogen absorption reactions. It turns out to be that the amount of absorption of nitrogen increases by the increase in P_N , and decrease of T from this formula. The nitrogen concentration inside the molten pool was calculated by the convection flow and diffusion of nitrogen which defined by equation (1). The initial value of the nitrogen concentration of a base material was set at 30 ppm.

In the present model, plasma properties are dependent on not only the temperature but also the mole fraction of iron vapor and nitrogen. The plasma properties at the intermediate concentrations of iron vapor are calculated using a linear approximation based on the properties at 0, 1, 10, 20 and 30 mol.-% of iron vapor mixture rate⁵⁾. The properties were calculated using the Chapman-Enskog approximation⁶⁾ under the assumption that the arc plasma is in a local thermodynamic equilibrium (LTE) condition. All of electron temperature, ion temperature and heavy particle temperature are the same in the LTE condition. For example, the electrical conductivities and the radiative emission coefficients, which are significantly affected by the mixture of iron vapor, are shown in Figs. 2 and 3 respectively. As shown in Fig. 2 concerning the change in electrical conductivity of helium plasma, electrical conductivity greatly increases by the addition of iron vapor at the temperatures below 15 000 K and the effect of the iron vapor addition does not differ between 1, 10, 20 and 30% of the mixing ratio. Figure 3 shows the change in the radiative emission coefficient. The radiative emission coefficient increases with increased mixing ratio of iron vapor while it remains in a very low level for pure helium plasma.

The governing and auxiliary equations were solved iteratively by the SIMPLEX numerical procedure.

Fig. 3 Dependence of radiant power density of helium gas on temperature for each mixing ratio

3. Result and discussion

Fig.4 shows temperature distribution in the arc plasma and in the base metal. Fig.5 shows concentration distribution of helium in the arc plasma. Fig.6 shows the mole fraction of iron vapor. The distribution of iron vapor is determined by the diffusion term and the convection term as described in equation (1). It is seen that distribution of iron vapor expands in the radial direction, concentrating just above the weld pool surface. The concentration of iron vapor mixed in arc plasma attains to 20 mol.-%.

Fig.7 shows the fluid flow path in the arc plasma and the molten pool. In an arc atmosphere where high speed plasma flow of 300 m/s exists, the convection term dominates. In the molten pool, the nitrogen concentration in the molten pool is dominated

by two whirlpools. It is thought that drag and Marangoni force were mainly dominating the radial flow and electromagnetic force was mainly dominating the flow of the depth direction. The calculated maximum velocities for radial and vertical directions were 43cm/sec at the surface of the pool and 14.6cm/sec at the center of the pool.

Fig.8 shows the concentration distribution of nitrogen in the arc plasma and in the base metal for each flow rate. The nitrogen concentration of the domain except a molten pool was 30 ppm. In the condition of arc ignition, the position of the maximum nitrogen concentration is located at the place away from the center of molten pool surface. In the central part of the molten pool surface, the nitrogen concentration decreases because the partial pressure of atomic nitrogen reduces caused by the metal

Fig.4 Temperature distribution in the arc plasma and in the base metal

Fig. 6 Concentration distribution of Fe metal vapor in the arc plasma

Fig. 5 Concentration distribution of helium in the arc plasma

Fig. 7 Fluid flow path in the arc plasma and in the molten pool.

Fig. 8 Concentration distribution of nitrogen in the arc plasma and inside the molten pool

Shielding gas flow is (a) 5L/min (b) 10L/min (c) 20L/min.

vapor generation, and the nitrogen absorption in molten pool is inhibited with the increase of the molten pool surface temperature. There were two whirlpools in the molten pool. The one is near the surface and another is near the center of the pool. Most nitrogen seemed to be transported to the depth direction by the whirlpool near the center. The other was seemed to be transported to the circumferential direction by the whirlpool near the surface, and emitted from a peripheral zone. The concentration of nitrogen in the arc plasma became larger when the shielding gas flow decreases. In the same way, the nitrogen concentration inside the molten pool increases dramatically with the decrease of shielding gas flow rate.

4. Conclusions

The numerical model of the GTA welding was developed, and the nitrogen concentration distribution and the transportation phenomenon in the molten pool were analyzed. The main conclusions are summarized as follows.

- 1) The position of the maximum nitrogen concentration existed in the place away from the molten pool surface center.
- 2) In the molten pool, the nitrogen concentration in the molten pool is dominated by two whirlpools. Most nitrogen seemed to be transported to the depth direction by the whirlpool near the center.

The other was seemed to be transported to the circumferential direction by the whirlpool near the surface, and emitted from a peripheral zone. The calculated maximum velocities for radial and vertical directions were 43cm/sec at the surface of the pool and 14.6cm/sec at the center of the pool.

- 3) The concentration of nitrogen inside the molten pool increased dramatically as a shielding gas flow rate decreases.

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