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Numerical Simulation for TIG Welding of Stainless Steel with Metal Vapor

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Summary

Authors have used a numerical model of stationary helium TIG arc welding taking into account the iron, chromium and manganese vapors produced from the weld pool surface and have simulated the distribution of the metal vapors, plasma temperature, fluid flow velocity and the formation of the weld pool. The concentration of manganese vapor in arc plasma was much higher compared with the composition of manganese for stainless steel.

Introduction

Due to the remarkable progress in computer simulation and observation techniques recently, it has become possible to understand the phenomena in arc welding processes quantitatively [1]. However, it has not been possible to accurately predict the welding parameters, such as the arc voltage and the weld geometry. It is known empirically that the arc voltage in TIG arc on water-cooled copper differs from that in TIG arc welding. This phenomenon is caused by the metal vapor from the weld pool surface. For a full understanding and accurate prediction of these parameters, it is necessary to understand the behavior of metal vapor in the arc plasma.

Tashiro et al. [2] conducted a virtual experiment by numerical simulating a pure helium arc and an arc in helium uniformly mixed with 30 mol% iron atoms, and showed that an obvious arc constriction occurred for the latter case. Furthermore, they reported that the energy efficiency greatly decreased from about 80% to about 35%. These results suggested that existence of metal vapor changed the heat source property in the arc welding process, and consequently changed the size and the shape of the molten pool. Calculations of the behavior of metal vapor in an atmospheric pressure plasma have also been reported [3]. However, the conditions were far from those of welding because a solid electrode with constant temperature was assumed. It is important for accurate understanding of the arc welding process to consider the mixing of the metal vapor in a model that takes into account the tungsten cathode, the arc plasma and the weld pool.

So that, authors developed a numerical model for TIG arc welding taking into account the metal vapor produced from the weld pool surface [4]. The anode was assumed to be a stainless steel. In practice, metal vapor species in an arc plasma

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with a stainless steel anode include Fe, Cr, Ni, Mn and so on. However, only iron vapor was considered in the model.

In the present paper, a numerical model for stationary TIG arc welding taking into account the iron, chromium and manganese vapors is used, and we simulate the distribution of the metal vapors, plasma temperature, fluid flow velocity and the formation of the weld pool.

Simulation Model

The tungsten cathode, arc plasma and anode are described relative to cylindrical coordinates, assuming rotational symmetry around the arc axis. The diameter of the tungsten cathode is 3.2 mm with a 60 degrees conical tip. Radial distance of calculation domain is 25 mm and axial distance is 45 mm (cathode: 30 mm, arc gap: 5 mm, anode: 10 mm). The anode is of a stainless steel and composition for a stainless steel in the present model is given in Table 1. Helium shielding gas is introduced from the outside of the cathode on the upper boundary at the flow rate of 30 L/min.

Table 1: Composition for a stainless steel used in the model

Fe	Cr	Mn
81.85 wt%	18 wt%	0.15 wt%

A species conservation equation expressed by Equation (1) is applied to take into account the metal vapors behavior [3]. Iron, chromium and manganese vapors are considered in this model. However, to simplify the model and facilitate calculation, those vapors are not calculated simultaneously but are calculated separately, as He-Fe, He-Cr and He-Mn system.

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

where t is time, v_r and v_z are the radial and axial velocities, ρ is the density, C_i is mass fraction concentration of metal vapor and D_i is the binary diffusion coefficient, which is expressed by the viscosity approximation equation:

$$D_i=\frac{2\sqrt{2}\,(1/M_i+1/M_g)^{0.5}}{\left[\left(\rho_i^2/\beta_i^2\eta_i^2 M_i\right)^{0.25}+\left(\rho_g^2/\beta_g^2\eta_g^2 M_g\right)^{0.25}\right]^2} \quad (2)$$

where M_i and M_g are the molecular weights of metals and the helium gas respectively. Similarly, ρ_i, ρ_g, η_i, η_g are respectively the density and viscosity of metals and the helium gas. It is assumed that $\beta_i=\beta_g$=1.385, which is based on the mean value of experimental data [5]. The viscosity approximation is not strictly justified since it does not take into account ionized species and is at best reasonably accurate

[6]; however it is considered to be a useful first approximation for the arc welding model.

C_i is set to be zero in the cathode area and in the solid area of the anode. However, at the anode surface where the temperature is above the melting point, C_i is set to:

$$C_i = \frac{n_i p_{v,i} M_i}{n_i p_{v,i} M_i + (p_{atm} - n_i p_{v,i}) M_g} \tag{3}$$

where p_{atm} is atmospheric pressure and $p_{v,i}$ is the partial pressure of metal vapor [7], which is a function of the weld pool temperature, and n_i is mol fraction of a metal in stainless steel. According to Equation (3), C_i has values between zero and 1.0. $(\partial C_i/\partial r) = 0$ at the arc axis and for other boundary conditions, C_i=0 .

In the present model, plasma properties are dependent on not only the temperature but also the mole fraction of iron, chromium and manganese vapors. However, iron, chromium and manganese vapors are all considered as iron vapor in calculating plasma properties for the simplification. Plasma properties at intermediate concentrations of iron vapor are calculated using a linear approximation based on the properties at 0 mol%, 1 mol%, 10 mol%, 20 mol% and 30 mol% [8]. The properties were calculated assuming the arc plasma to be in the local thermodynamic equilibrium (LTE), and using the Chapman-Enskog approximation [8]. For example, the electrical conductivities, which are significantly affected, are shown in Figure 1. The electrical conductivities are greatly increased by the addition of iron vapor at temperatures below 15 000 K, and the values for mixing ratios 1%, 10%, 20% and 30% are almost the same.

The other approximations, governing equations and boundary conditions are given in detail in our previous papers [2]. The governing and auxiliary equations are solved iteratively by the SIMPLEC numerical procedure.

Calculation Results

The present model is applied to the case of stationary helium TIG arc welding of stainless steel. Figure 2 shows the two-dimensional distribution of temperature and fluid flow velocity at a time 20 s after arc ignition. Figure 3 shows the distributions of iron, chromium and manganese vapor in arc plasma. The distributions of metal vapors depend on the diffusion term and the convection term, as described in Equation (1). Due to the cathode jet, which leads to flow velocities of over 300 m/s in the welding arc, the convection term has a strong effect. Therefore, it is found that distribution of iron vapor expands in the radial direction and is concentrated around the weld pool surface. The maximum concentrations of iron and chromium vapors are about 4 mol%. Otherwise, the maximum concentration of manganese vapor is 0.5 mol%, a factor of 8 smaller than those of iron and chromium vapors.

Figure 4 shows the concentration of metal vapors around the anode surface.

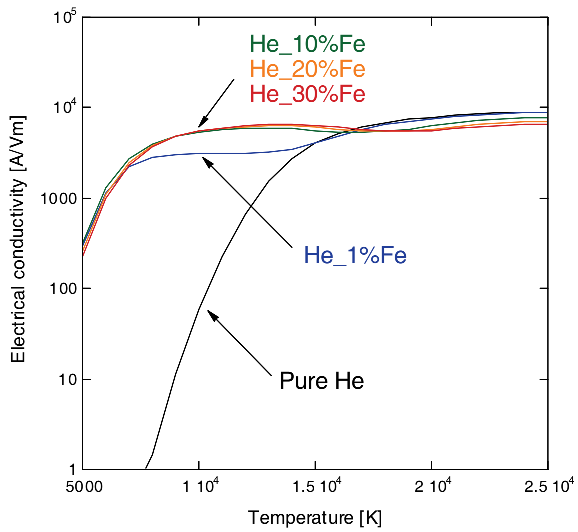

Figure 1: Dependence of electrical conductivities of helium gas on temperature for each mixing ratio.

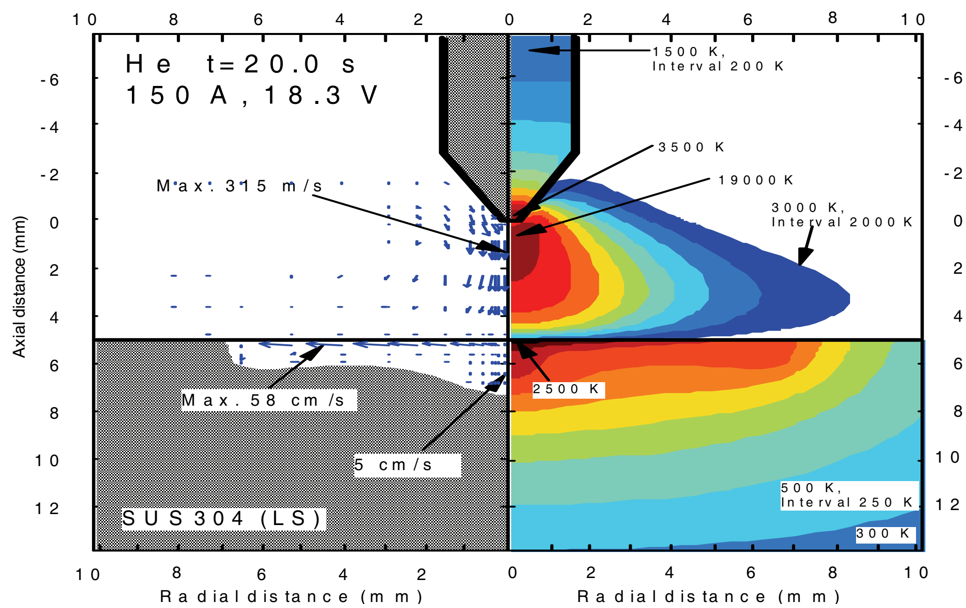

Figure 2: Calculated results for helium TIG arc welding for 150 A at 20 s after arc ignition.

The concentrations of iron and chromium vapors are almost same. Due to the higher partial pressure of manganese at low temperature, concentration of manganese vapor is close to those of iron and chromium vapors at the area where

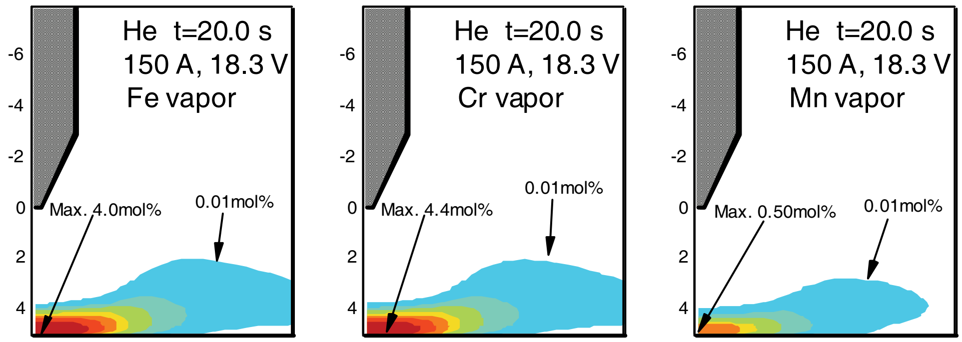

Figure 3: Distributions of iron, chromium and manganese vapor in arc plasma.

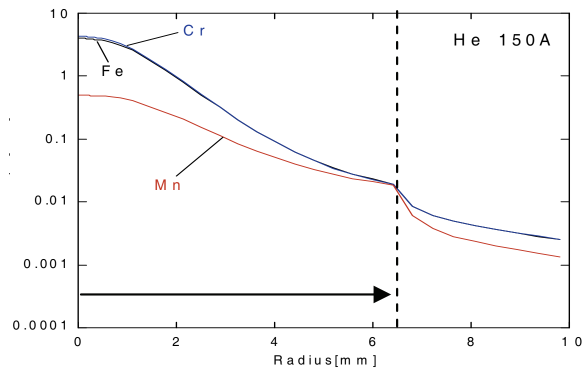

Figure 4: Concentrations of metal vapors around the anode surface.

weld pool temperature is lower although composition of manganese is significantly smaller.

Conclusions

(1) A numerical model for stationary helium TIG arc welding taking into account the iron, chromium and manganese vapors produced from the weld pool surface have used to simulate the distribution of the metal vapors, plasma temperature, fluid flow velocity and the formation of the weld pool.

(2) Due to the cathode jet velocity of over 300 m/s in the welding arc, the convection term strongly affects the distributions of metal vapors. It was found that metal vapors expanded mainly in the radial direction and remained concentrated around the weld pool surface.

(3) The concentration of manganese vapor in arc plasma is much higher compared with the composition of manganese for stainless steel, especially at the area where weld pool temperature is lower because of the higher partial pressure of manganese at low temperature.

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