Dynamically Plasma Diagnostics in MIG Welding of Aluminum *

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In this study, plasma diagnostics in MIG welding of aluminum is performed. In MIG welding, the metal vapor has the large influences on the welding process since the content of the metal vapor in the arc plasma is large. The distribution of metal vapor varies dynamically by a metal transfer. Therefore, the dynamical distributions of temperature and concentration of metal vapor are obtained by the spectral images pictured by high-speed video cameras. Consequently, the metal vapor is distributed near the center axis and the temperature of the arc plasma decreases. Finally, we discuss plasma physics in the welding arc through numerical simulations, using the basic conservation equations of mass, energy, momentum, current and electron density of plasma physics. There is close interaction between the electrode, the arc plasma, the weld pool, and also the metal vapor, which constitute the welding process, and must be considered as a unified system. The simulation results also show the temperature of the arc plasma decreases near the center axis. This is caused by the fact that the energy loss by the radiation increases with increases with the metal content.

Key Words: MIG welding, Aluminum, Plasma diagnostic, Numerical simulation

1. Introduction

In metal inert gas (MIG) welding, the arc discharge is utilized to melt and join a metal electrode and plates. Although the use of the GMA welding is spread over a variety of manufacturing industries because of its high efficiency and high quality of the obtained joint, further developments of MIG welding are demanded in controlability and weld quality. In order to meet these demands, better understanding of phenomena during MIG welding is necessary. Many researchers have studied from viewpoints of experimental measurement and numerical analysis for the understanding of MIG welding. The instrumentals and technical progress for the measurement of arc plasma allow us to observe the distributions of plasma temperature and content of metal vapor in the plasma during MIG welding. In recent years, researchers1, 2) have suggested the possibility that the temperature of the arc near the arc axis decreased comparing with that apart from the arc axis due to influence of the metal vapor during MIG welding of steel. They show that the metal vapor is distributed near the arc axis and the temperature of arc plasma decreases. In this study, distributions of temperature and metal vapor during MIG welding of aluminum are obtained. Since a droplet forms and detaches at a tip of wire, and pass through the arc plasma during MIG welding, dynamic plasma diagnostics are demanded. This study aims to develop method for measuring dynamical variation of two-dimensional distribution of temperature and metal vapor concentration in the arc through optical measurement and to analyze behavior of the metal vapor in MIG welding. Moreover, the influences of aluminum vapor on the arc plasma are clarified by the numerical analysis.

2. Experimental setup for plasma diagnostics

Figure 1 shows experimental setup for plasma diagnostic. This experimental setup consists of a MIG welding torch, an inverter power source, a wire feeder, two spectroscopes, two high speed video cameras and a PC. Two spectral images which are an Ar I spectrum (696 nm) and an Al I spectrum (669 nm) are obtained through this system3).

The spectroscopes are Czerny-Turner type and have diffraction grating with wavelength resolution of 0.4 nm. The recorded intensity distributions are converted to temperature distribution with Fowler-Milne method4-6) after Abel conversion7). The intensity of spectrum from the arc plasma is theoretically calculated from the equation (1).

Fig. 1 Schematic illustration of experimental setup for plasma diagnostic.
where, $A$ is transition probability, $\hbar$ is Plank constant, $\nu$ is frequency, $N$ is particle number density under the LTE assumption, $g_n$ is statistical weight, $E_n$ is level energy, $k$ is the Boltzmann constant, and $T$ is temperature. Figure 2 shows dependence of temperature on the normalized intensities of Ar I (696 nm) and Al I (669 nm). Normalized intensity is the intensity which is divided by the maximum intensity of the line spectrum. From Fig. 2, temperature of arc plasma is obtained.

After measurement of plasma temperature, aluminum vapor concentration distribution is obtained from temperature distribution and intensity distribution of Al I line spectrum by equation (1).

A frame rate is set to be 2000 fps. The distance between the wire tip and the base metal surface is 25 mm. An aluminum wire with diameter of 1.2mm and A1070 plate are employed as an anode and a cathode, respectively. A welding current and an arc voltage are set to be 220 A and 25 V. The shielding gas is pure argon and the gas flow rate is 25 ℓ/min.

3. Result and discussion

3.1 Plasma temperature distribution and concentration distribution of aluminum vapor

Figure 3 shows images of line spectrum of Ar I at 696 nm and Al I at 669 nm. The intensity of Al I is high near the arc axis. By these images, temperature distribution and concentration distribution of aluminum vapor are obtained. Figure 4 shows time variation of temperature distribution and concentration distribution of aluminum vapor.

The temperatures near the arc axis were about 7,000 K and those apart from the arc axis were about 11,000 K. From these results, decrease in temperature near the arc axis was confirmed and dynamic variation of the entire temperature distribution of the arc was presented. If the grown-up droplet existed at the tip of the wire, the low temperature region became large.

The concentrations of aluminum vapor near the arc axis were about 60 %. In these regions, temperature decrease. When droplet flies through the arc plasma, the concentration reached to 80 % at surrounding area of the droplet. If the grown-up droplet existed at the tip of the wire, the region of high concentration of aluminum vapor became large. This is because aluminum vapor source at the wire tip became large, since the droplet grew-up.

Consequently, the plasma temperature decreases with increase in the concentration of the aluminum vapor. Therefore, in MIG welding, the arc is double structure which consists of low...
3.2 Physics of decrease in plasma temperature

In order to discuss physics of decrease in plasma temperature, numerical model is also conducted. In this model, a weld wire, arc plasma and a base metal are described relative to cylindrical coordinates on the assumption that the system has rotational symmetry around the arc axis. The diameter of the wire is 1.2 mm, the wire extension 20.0 mm, and the arc length 5.0 mm. Therefore, the distance between the wire tip and the base metal is cathode (reverse polarity).

The governing equations used in the calculation are as follows:

The mass continuity equation is,
\[ \frac{1}{r} \frac{\partial}{\partial r} (r \rho v_r) + \frac{\partial}{\partial z} (\rho v_z) = S, \quad (2) \]

The radial momentum conservation equation is,
\[ \frac{1}{r} \frac{\partial}{\partial r} (r \rho v_r^2) + \frac{\partial}{\partial z} (\rho v_r v_z) = \frac{\partial p}{\partial r} - j_1 B_\theta + \frac{\partial}{\partial r} \left( \frac{\kappa}{\tau} \frac{\partial T}{\partial r} \right) + \frac{\partial}{\partial z} \left( \frac{\tau}{\rho} \frac{\partial T}{\partial z} \right) - 2 \eta \frac{v_r}{\tau}, \quad (3) \]

The axial momentum conservation equation is,
\[ \frac{1}{r} \frac{\partial}{\partial r} (r \rho v_r v_z) + \frac{\partial}{\partial z} (\rho v_z^2) = \frac{\partial p}{\partial z} - j_1 B_z + \frac{\partial}{\partial r} \left( \frac{\kappa}{\tau} \frac{\partial T}{\partial r} \right) + \frac{\partial}{\partial z} \left( \frac{\tau}{\rho} \frac{\partial T}{\partial z} \right) + \frac{\partial}{\partial r} \left( \frac{\kappa}{\tau} \frac{\partial T}{\partial r} \right) + \frac{\partial}{\partial z} \left( \frac{\tau}{\rho} \frac{\partial T}{\partial z} \right) + \rho g, \quad (4) \]

The energy conservation equation is,
\[ \frac{1}{r} \frac{\partial}{\partial r} \left( r (\rho c_p T) \right) + \frac{\partial}{\partial z} (\rho c_v T) = \frac{\partial}{\partial r} \left( \frac{\kappa}{\tau} \frac{\partial T}{\partial r} \right) + \frac{\partial}{\partial z} \left( \frac{\tau}{\rho} \frac{\partial T}{\partial z} \right) + j_1 E_r + j_2 E_z - U, \quad (5) \]

The current continuity equation is,
\[ \frac{1}{r} \frac{\partial}{\partial r} (r j_r) + \frac{\partial}{\partial z} (j_z) = 0, \quad (6) \]

The conservation equation for the behavior of aluminum vapor is,
\[ \frac{1}{r} \frac{\partial}{\partial r} (r \rho v_r C) + \frac{\partial}{\partial z} (\rho v_z C) = \frac{\partial}{\partial r} \left( \frac{\kappa}{\tau} \frac{\partial T}{\partial r} \right) + \frac{\partial}{\partial z} \left( \frac{\tau}{\rho} \frac{\partial T}{\partial z} \right) + \rho D \frac{\partial C}{\partial z} + S, \quad (7) \]

where, \( h \) 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, \( S \) is vaporization rate of metal vapor at the electrodes surface, \( g \) is acceleration due to gravity, \( c_p \) is specific heat, \( \kappa \) is thermal conductivity, \( \rho \) is density, \( \eta \) is viscosity, \( U \) is radiative emission coefficient, \( \sigma \) is electrical conductivity, \( E_r \) and \( E_z \) are the radial and axial components of the electric field, and \( C \) is the concentration of aluminum vapor in mass fraction. The vaporization rate of aluminum vapor \( S \) is expressed by the following equation\(^8\),
\[ S = \rho_v \int \frac{M_{Al}}{2 \pi R T}, \quad (8) \]

where, \( \rho_v \) is the vapor pressure of aluminum, \( M_{Al} \) is the molecular weight of aluminum, \( R \) is the gas constant, and \( T \) is the temperature. The vaporization rate of aluminum becomes markedly elevated with increase of temperature.

Details of the approximations, governing equations and boundary conditions are given in our previous paper\(^9\). In this simulation, a radiant power is paid attention, since the radiation depends on the content of aluminum vapor\(^{10, 11}\). The numerical simulation was carried out assuming two radiant powers: the radiation depending on the content of aluminum vapor and the radiation that is independent of the content. The results from this simulation are shown in Fig. 5.

Fig. 5 Simulation results.
aluminum vapor corresponding to the practical situation, the simulation results also showed that the arc was double structure which consists of low temperature region near the arc axis occupied mainly with the aluminum vapor and high temperature region apart from the arc axis occupied with the shielding gas. It was seen that mainly the metal vapor from the wire tip was transported into the arc through the plasma jet.

In case of the radiant power that was independent of the content of aluminum vapor, the temperature near the arc axis didn’t decrease although large number of aluminum vapor exists near the arc axis. Thus, it was suggested that difference in temperature distribution of the arc plasma is caused by difference of the radiant power density of the arc plasma.

Figure 6 shows the influence of aluminum vapor on radiant power density of the arc plasma[2]. As shown in this figure, the radiant power density increases with content of aluminum vapor. The temperature of arc plasma at the region of high concentration of aluminum vapor became low because of intensive radiation loss[6-8]. The simulation results showed that the temperature near the arc axis decreased through the intensive radiation loss for aluminum vapor. It was found that if the aluminum vapor was evaporated from the wire tip, the arc had double structure consisting of high temperature region apart from the arc axis and low temperature region near the arc axis as confirmed in the experiment. It was because the arc was cooled especially near the arc axis through the intensive radiation loss caused by high concentration of the metal vapor.

4. Conclusions

Conclusions are summarized as follows:
1) In MIG welding of aluminum, the arc plasma had double structure consisting of high temperature region apart from the arc axis and low temperature region near the arc axis due to influence of the aluminum vapor.
2) The low temperature region near the arc axis occurred because the arc plasma was cooled especially through the intensive radiation loss caused by high concentration of the metal vapor.

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Reference

3) NIST: http://physics.nist.gov/PhysRefData/ASD/lines_form.html