Numerical Analysis of Fume Characteristics in Arc Welding

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1. Introduction

In arc welding, high temperature metal vapor is generated from the melting tip of a welding wire, a droplet and a weld pool [1]. This metal vapor is cooled rapidly during diffusion to surroundings of the arc. Then primary particles of metal with 1nm~100nm in those sizes are formed through the nucleation from the metal vapor. Furthermore, a part of those particles condense and produce secondary particles with over 1 μm maximum in sizes. The particles form smoke which ascends from the arc and this phenomenon is called fume in welding [2].

This study aims to clarify fume formation mechanism theoretically through visualization of fume shape. In this paper, a series of each process such as evaporation of metal vapor due to the arc and formation of fume from the metal vapor is totally discussed by numerical simulation which is calculated by coupling a MIG welding model with a fume formation model and then, general mechanism of fume formation for arc welding process is discussed.

2. Simulation model

The simulation model employed in this study consists of a MIG welding model taking account of metal transfer process developed based on the TIG welding model [3] and a fume formation model. A metal vapor pressure and a cooling rate at a nucleation site are calculated by giving a welding condition to the MIG welding model. Then, the formations of primary particles and secondary particles are calculated by assuming the metal vapor pressure and the cooling rate as the calculation condition and the mechanism of fume formation can be discussed. fume formation model uses the assumptions (1)~(6) listed below. The details of the calculation conditions are described in the literature [4]

(1) The formation of supersaturation of the iron vapor by cooling.
(2) The formation of the primary particle by the homogeneous nucleation.
(3) The growth of the primary particle by the heterogeneous condensation.
(4) The formation of the secondary particle by the coagulation.
(5) The growth of the secondary particle by the heterogeneous condensation and the coagulation.
(6) The particle velocity is determined from Brownian force and Coulomb force given as driving force of particles.

3. Results and discussion

Fig. 1 shows distributions of temperature and metal vapor pressure at 12ms after calculation start. The metal vapor pressure and the cooling rate as initial conditions of the fume formation model were determined from results at t=12ms when the metal vapor pressure reached the maximum. In the present study, the fume characteristics in three positions classified in the feature as shown in Fig. 1 were examined. In position 2, the metal vapor was swept away outward due to high speed plasma flow, and therefore metal vapor pressure was low. In position 3, the metal vapor pressure was higher than that in position 2 because of the sum of evaporation from the weld pool surface and compression due to the plasma flow from the electrode wire. Since this model assumes rotational symmetry around the arc axis, the droplet transfers along the central axis. However, in practice metal transfer tends to be unstable by various factors such as the arc pressure on the side under the droplet. Therefore, the possibility of the metal vapor near the droplet diffusing directly to the surroundings of the arc without getting on the plasma flow should be considered. Assuming such a situation, the metal vapor pressure near the droplet and the cooling rate in the edge of the arc column adjacent to the droplet were provided in position 1. The cooling rates in position 1, 2, and 3 were 1.1×10^5, 5.0×10^5 and 1.0×10^5K/s, respectively. The metal vapor pressures in each position were 26,000, 4.5 and 100Pa.

Fig. 2 shows dependences of particle diameter distribution on plasma temperature in case of position 1 for example of fume formation process. It was found that the nucleation occurred at approximately 2,400K. After that, particle diameter rapidly increased up to approximately 200nm due to the condensation and the coagulation. Finally, diameter of secondary particle reached 1 μm at the maximum due to coagulation among large particles.

Fig. 3 shows magnifications (5μm×5μm for position 1, 100nm×100nm for position 2, 100nm×100nm for position 3) of examples of secondary particles at 300K. Large spherical particles with sizes of 1μm were observed in position 1. It is suggested that the particle grows up due to the influence of fusion in the coagulation in addition to high metal vapor pressure near the droplet. On the other hand, in position 2 a number of primary particles with size of several nm constituted a secondary particle with size of 20 nm, because the coagulation occurred under the melting point and the metal vapor pressure was low in this position. In position 3, it can be seen that primary particles with size of several nm joined like a chain and constituted the secondary particle with size of 60nm. For a reason, it is considered that the metal vapor pressure increases near the weld pool surface because of the sum of metal vapor evaporated from the weld pool and that transported from the droplet by the plasma flow.

Fig. 4 shows typical experimental examples of the fume shape in GMA welding with different two types of shielding gas compositions, namely, MIG(Ar+2%O_2), and CO_2. It is found that particles with size of several nm ~ several tens nm join like a chain and constituted a secondary particle with size of several μm in MIG. In CO_2, these particles grow up like a spider's web. Furthermore, small number of large particles with size of several hundreds nm exist as marked in Fig. 4. These kinds of particles are found especially in CO_2. In case of MIG in which the metal transfer is smooth and stable, particle shape is similar to that in positions 2 and 3 of simulation results as shown in Fig. 3 (b) and (c). It is expected that large part of the fume was produced by the metal vapor evaporated from the electrode wire, the droplet and the weld pool through the downstream region of the arc. On the contrary, since the arc was constricted by high specific heat of CO_2, namely, *the thermal pinch effect*, the arc pressure lifting the droplet increases in CO_2 welding. Consequently, the droplet tends to grow largely and the whole surface of the droplet can be hardly covered by the arc. It is suggested that the disturbance of the metal transfer leads to direct diffusion and quenching of the metal vapor without a path through the downstream region of the arc. Therefore, the fume with size of 1μm can be produced specially in CO_2 as shown in simulation results in position 1 in Fig. 3 (a).

As explained above, it was shown that most part of the fume was produced in downstream region of the arc originating from the metal vapor evaporated mainly from the droplet by employing the MIG welding model. This kind of the fume was constituted of particles with size of several nm. On the other hand, if the metal transfer becomes unstable and the metal vapor near the droplet diffuses directly toward the surroundings of the arc not getting on the plasma flow, the size of particles reaches 1μm. This tendency agrees with morphological shape of fume in CO_2 obtained from experimental observations.

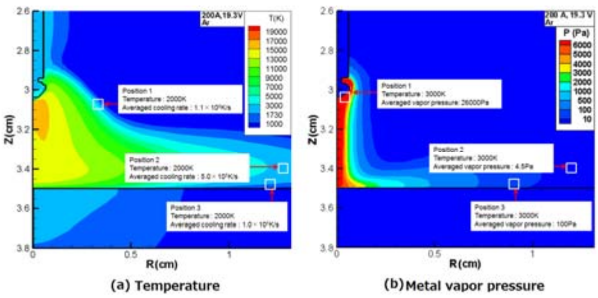

Fig. 1 Distribution of temperature and metal vapor pressure at t=12ms.

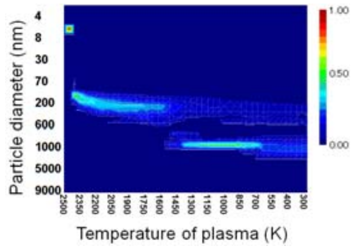

Fig. 2 Dependences of particle diameter distribution on plasma temperature in case of position 1.

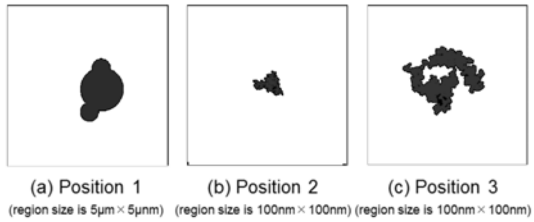

Fig. 3 Shapes of secondary particles at 300K.

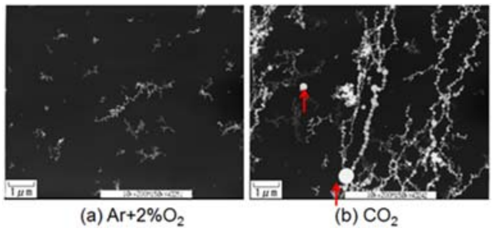

Fig. 4 Fume shapes obtained by TEM observation in MIG and CO2 welding

Conclusions

Main conclusions are summarized as follows:

1) Most part of the fume was produced in downstream region of the arc originating from the metal vapor evaporated mainly from the droplet.

2) The size of this kind of the secondary particles consisting of small particles with size of several nm reached 60nm at maximum and the form of the secondary particle became a chain shape.

3) If the metal vapor near the droplet was assumed to diffuse directly toward the surroundings of the arc not getting on the plasma flow, the size of the particle reaches 1μm in MIG welding. This tendency agreed with the fume shape in CO2 obtained from experimental observations.

References

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