Molten metal shape affected by energy density of vacuum arc cathode spot

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Abstract: A remarkable characteristic of a vacuum arc cathode spot is that the cathode spot moves around on the metal surface. A cathode spot can remove an oxide layer and form a roughness. However, the factor of formation of molten metal shape remains unclear. This study elucidated the molten metal shape of cathode surface affected by the energy density of vacuum arc cathode spot in order to know the formation process of molten metal shape and removal process of oxide layer. The temperature distribution was calculated by the heat conduction simulation. The molten metal depth, molten width, and evaporated speed of bulk and oxide layer were calculated with changing the energy density of cathode spot. The energy density of cathode spot was changed by the moving speed and the area of cathode spot. The bulk is not melted easily in the case of high moving speed and low heat flux. The molten metal depth and molten volume increase with increasing the energy density. However, the molten metal width increases with decreasing the current density and moving speed. Therefore, the molten metal shape of cathode surface depends on the energy density.

Keywords: vacuum arc, cathode spot, surface treatment, heat conduction simulation

1. Introduction
Thermal spraying has been widely used because it can obtain the various functions using the coating materials on the surface. Adhesive strength of the coating and substrate is an important factor. Therefore, it is necessary to remove an oxide layer and form a roughness [1][2]. The main pretreatment of thermal spraying is blast. However, the blast has problems, such as crushing and wear of the particles. The residual grid becomes a starting point of rust and peeling. The particles become the secondary waste. In addition, the defects of coating and deficiency of adhesion strength depend on the coating material [2].

The pretreatment with vacuum arc cathode spot is focused on by this background [2]. It generates a few secondary waste or noise. Cathode spot with high energy density evaporates the oxide layer and melts the bulk for roughness [3][4]. However, the cathode spot has four moving modes, it has been reported that the area and moving speed of the cathode spot are changed while processing [5][6]. It is considered that surface roughness is changed by the power density and heating time because the roughness depends on the location [5]. It is necessary to elucidate the formation factor of roughness and removal process because of this problem. However, the formation factor of surface roughness is not clear [6]. Few reports has researched the movement of cathode spot with oxide layer and theoretically estimated energy density.

This paper elucidated the molten depth, molten width, molten volume, and $D/W$ (Depth/Width) ratio in order to know the heat conduction process of vacuum arc cathode spot. The objective is to analyze contribution of energy density and moving speed to elucidate the heat conduction process. As described herein, the temperature distribution was calculated by the heat conduction simulation.

2. Calculation method
Vacuum arc cathode spot generates on the bulk and contact with the oxide layer. Cathode spot moves with evaporation of the oxide layer. In this calculation, the cathode (iron and oxide layer) and the arc are combined into one system. A three-dimensional rectangular coordinate system is used. The half of bottom of the calculation area is cathode (Fe). The half of the cathode surface is covered with the oxide layer (FeO). The ambient gas is argon.

The heating source of cathode is Joule heating and ion heating. Joule heating only cathode spot was considered. The current density of cathode spot is calculated by Richardson-Dushman equation. Joule heating depends on this current density is source term of energy conservation equation. Ion current to compensate for it was calculated if the electron emission from the cathode cannot maintain the total current. The temperature distribution was calculated by unsteady heat conduction simulation in order to know the molten shape changing with the movement of cathode spot. In addition, the boundary conditions of the energy conservation equation are free boundary. The moving speed of cathode spot is $10^{-3}$ - $10^{1}$ m/s. The area of cathode spot is 0.5, 1, 2, 4 $\times$ $10^{-8}$ m$^2$ (S1, S2, S3, S4), respectively. The current density and ratio of ion current to electron current were changed by the area of cathode spot. The power density of cathode spot depends on the area of cathode spot.

3. Result and discussion
Fig. 1 shows the molten depth and molten width as a function of moving speed. Fig. 2 shows the $D/W$ ratio as a function of moving speed. The $D/W$ ratio is defined by the
ratio of depth to width. The temporal change of melting process with changing moving speed and area of cathode spot was calculated. The molten depth and molten volume increase with time. The cathode spot moves about 0.3 mm, and then the molten depth saturated. The reason of the molten depth saturation is that the heating time per unit area of cathode spot is constant. The molten volume linearly increases with increasing the time until the cathode spot moves about 0.5 mm. After that, the increments of molten volume decreases with increasing the time. These results under all calculation conditions were the same tendency.

The molten depth, width, volume, and $D/W$ ratio at 0.5 mm were calculated. The molten depth, molten width, molten volume, and $D/W$ ratio decrease with increasing the moving speed. Because the heating time at same location decreases with increasing the moving speed. The molten depth doesn't depend on the heat flux of surface in the case of long heating time. Then, the molten depth affected by the internal heat flux depends on the thermal conductivity and temperature gradient. The internal heat flux is lower than the surface heat flux. And, the internal heat flux doesn’t depend on the surface heat flux so much. Therefore, the molten depth depends on the heating time in the case of long heating time. The internal heat flux is high because of the high temperature gradient of surface in the case of the high moving speed. Then, the increments of molten depth is large. In addition, the molten depth increases with increasing the heat flux in the case of the high moving speed.

The molten width depends on the area of cathode spot in the case of the high moving speed. Because the cathode spot only melts the surface of bulk, and the molten area doesn't spread in the case of high moving speed. The moving speed of the cathode spot which melts the bulk is fast even if the heating time is short in the case of the high moving speed. Thus, the molten depth and molten width depend on the power density and moving speed in the case of high moving speed. However, they only depend on the moving speed in the case of low moving speed.

The molten depth is deep and molten width is narrow in the case of the high moving speed because of small area of cathode spot and high heat flux. Therefore, the $D/W$ ratio depends on the energy density, however it is saturated with increasing the heating time. The reason of this is the saturation of the molten depth and width in the case of long heating time.

4. Summary

This paper elucidated the molten depth, molten width, molten volume, and $D/W$ ratio in order to know the heat conduction process of vacuum arc cathode spot. The temperature distribution was calculated by the heat conduction simulation. The molten depth, molten width, molten volume, and $D/W$ ratio decrease with increasing the moving speed. They depend on energy density in the case of the high moving speed. However, they depend on input energy in the case of the low moving speed.

5. Acknowledgement

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6. References