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Dynamic behavior of hot cathode spot under high current DC arc plasma

大電流アーク放電陰極点における高熱流プラズマ−電極動的相互作用

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This paper describes the experimental results on the observation of the hot cathode spot in plasma arc cutting torch. We observed the cathode surface phenomena using color high-speed camera. Use of RGB signals of color camera enables us to estimate the cathode surface temperature. As a result, time evolution of the cathode arc spot temperature from arc ignition to steady state can be obtained. In addition to the cathode temperature measurement, the dynamic behavior of the molten cathode spot was seen as the hot spot rotation and, abrupt boiling and droplet ejection.

1. Introduction

The arc cathode is exposed directly by high heat flux arc plasmas. In the case of plasma arc cutting, the heat flux to the cathode spot is estimated to be several hundreds MW/m^2 in the steady state arc. The contact of such high heat flux plasmas with the cathode material can cause phase transitions from solid to liquid and from liquid to vapor instantaneously. As a result, multi-phase plasmas are generated near the cathode surface. The physical phenomena on the cathode spot are much complicated.

Today, arc plasma is applied to various equipment such as plasma arc cutting, circuit breaker and ignition plug. It is important to understand the physical and chemical phenomena of the cathode spot for improvement of the equipment above. We observed the cathode surface behavior during arc discharges using high-speed color camera. Arc plasmas of arc cutting torch is useful for cathode spot observation because reproducible arc plasmas discharges easily and the cathode spot is fixed on the electrode stably.

2. Experimental set up

The plasma arc cutting torch(Komatsu Industries) is shown in Fig.1. Arc plasmas generated between water-cooled hafnium(Hf) electrode as a cathode and a water-cooled copper target as an anode placed outside the torch. The arc plasma is erupted from the nozzle outlet with the plasma gas(O_2). The plasma gas is supplied as swirl gas so as to fix the cathode spot at the center of Hf electrode at the arc ignition phase. The nozzle works to shrink the arc column with the surrounding cold supply gas. The diameters of the Hf cathode and nozzle are 1.6 mm and 1.3 mm, respectively. In this study, a quartz window is installed in this nozzle in order to observe the cathode surface directly. Two types of high-speed color camera (Keyence:VW-6000, VW-9000) are used. The max frame rates of VW-6000 and VW-9000 are 24,000 fps and 230,000 fps, respectively.

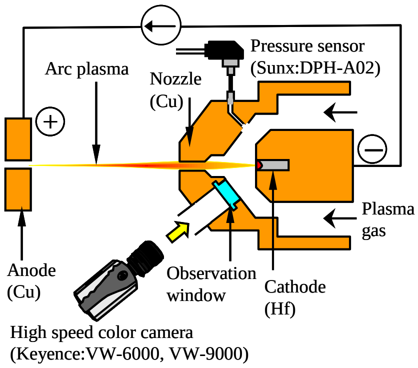

Fig.1. Schematic view of cathode spot observation

3. Estimation of cathode surface temperature by RGB signals of color camera

RGB signals of the color camera are obtained specific values to the black-body temperature. Theory of RGB intensity ratio to be observed is calculated by Planck's law. Calculated theory of RGB intensity ratios is compared with RGB signals of each pixel of high-speed color camera images. As a result, cathode surface temperature distribution can be estimated[1].

4. Experimental result

Time evolution of the cathode hot spot with arc current waveform is shown in Fig.2. Just after arc ignition, the cathode arc spot initially touches at the edge of the cathode, then rotates along the swirl gas and moves to the cathode center. This local hot spot rotation heats the Hf cathode surface gradually and

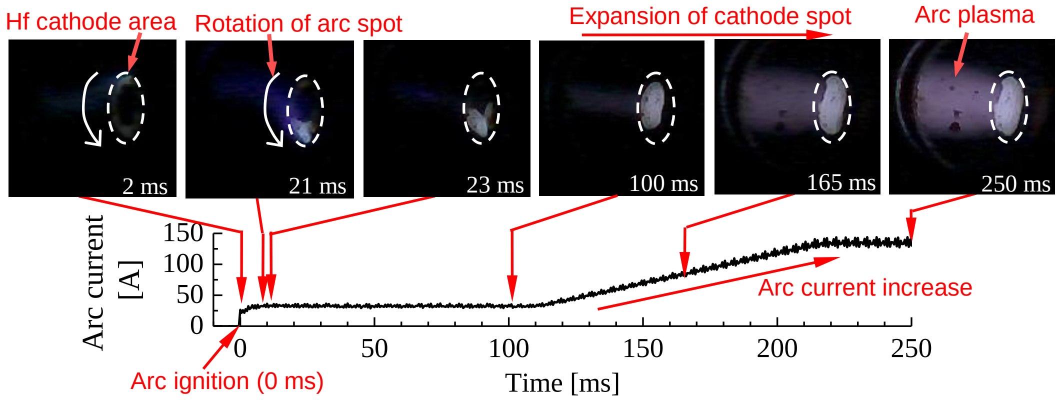

Fig.2. Time evolution of cathode hot spot was observed by VW-6000

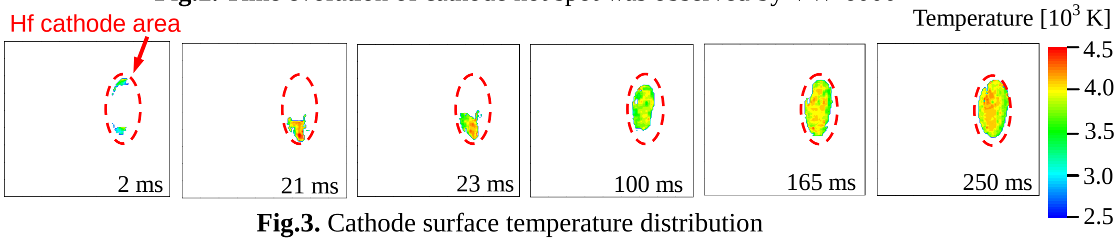

Fig.3. Cathode surface temperature distribution

forms the round cathode spot on the Hf electrode at t ~100 ms after ignition. The cathode spot area spreads gradually from the fixed local cathode spot to the whole Hf cathode. Moreover, the cathode emission area becomes larger with increase of the arc current. Figure.3 shows time evolution of cathode surface temperature distribution estimated from RGB signals of the pictures shown in Fig.2. The temperature distribution shows that cathode surface temperature is between 3700 K and 4300 K. This temperature is higher than Hf melting temperature (2503 K) and lower than Hf boiling temperature (4547 K)[2]. Therefore, it is clear that the cathode surface is melted during arc discharges.

Thermionic electron emission current density J is calculated from the estimated cathode temperature. Hafnium oxide(HfO_2) is formed on the Hf cathode surface by oxygen plasma discharges. However rates of Hf and HfO_2 on the cathode surface are not known. The J is calculated under the assumption that whole cathode surface is solid Hf or solid HfO_2. J_{Hf} and J_{HfO_2} is calculated with work function of solid Hf and HfO_2, and Richardson constant of Hf and HfO_2, respectively. As a result, thermionic electron emission current $I_{Hf(thermo)}$ and $I_{HfO_2(thermo)}$ are estimated about 160 A / mm^2 and 40 A / mm^2 respectively when arc current of power supply $I_{(arc)}$ is 135 A. Compared to the $I_{(arc)}$, $I_{Hf(thermo)}/I_{(arc)}$=1.19 and $I_{HfO_2(thermo)}/I_{(arc)}$=0.30 can be calculated. Although the physical properties of the hot cathode spot have large ambiguity, such as cathode surface irregularity and formation of oxidation layer, it may say that reasonable value of $I_{(thermo)}$ is calculated. To evaluate J in detail, physical properties of Hf and HfO_2 as hot liquid are needed.

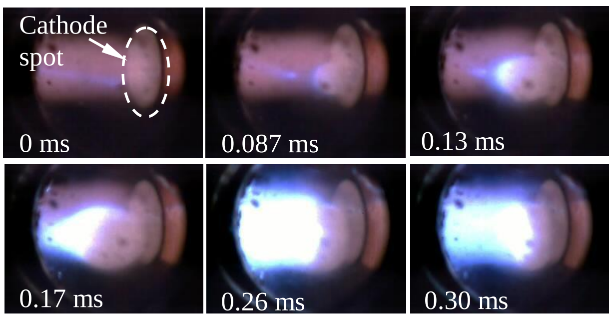

Fig.4. Observation of the cathode material ejection was observed by VW-9000 (The arc current is 150 A)

However such physical properties cannot be obtained at the moment.

Unstable phenomena of the molten cathode spot, such as the wavy motion, and ejection of the molten materials from the cathode surface, are often observed. One is the ejection of droplet. Small particles of molten material are dispersed abruptly from cathode surface. The other is bubble formation. The images of a large bubble formation in the molten cathode spot are shown in Fig.4. The bubble appears from the spot and grows within ~0.1 ms, then evaporates intensively, leading the bubble explosion. After the bubble explosion, cathode spot goes back to the quiet phase. These intensive and dynamic cathode phenomena can not be seen in the arc voltage and current measurement.

References

[1] Y. Yamaguchi: Journal of the Japan Welding Society Vol.29 No.1 p. 010-017(2011).
[2] S. Izumi: Data book of metal, Maruzen Company (1984).