Fluctuation Phenomena in Diode-Rectified Multiphase AC Arc for Improvement of Electrode Erosion

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Abstract: Fluctuation phenomena in an innovative multiphase AC arc with diode rectification was successfully visualized on the basis of the high-speed camera technique with appropriate band-pass filter optics. Electrode temperature fluctuation with and without diode-rectification was clarified. Effect of diode-rectification on the arc temperature fluctuation was also investigated. Obtained results suggested the diode-rectified multiphase AC arc is a promising thermal plasma source for material processing at high productivity.

Keywords: thermal plasmas, electrode erosion, electrode temperature, arc temperature

1. Introduction

A multiphase AC arc (MPA) is one of the most attractive thermal plasma sources due to its advantages such as higher energy efficiency compared with conventional thermal plasmas. Therefore, the MPA has been applied to an in-flight glass melting technology [1]. Furthermore, it is expected to be utilized in nanomaterial fabrication processes owing to its high processing rate. Fundamental studies for practical use of MPA in industry have been intensively reported in terms of the arc stability [2], the temporal and spatial characteristics of the arc discharge [3], arc temperature fluctuation [4, 5], and the electrode phenomena [6-8].

Electrode erosion in AC arc is one of the most important issues to be resolved because it determines the electrode lifetime and purity of the products. Required properties for cathode and anode in arc discharge are different. Low work function and high melting point are important cathode properties for stable electron emission. In contrast, high thermal conductivity is required for anode as electron recipient. However, there is a lack of appropriate electrode material which satisfies required properties at both cathodic and anodic periods. Tungsten based electrode are commonly used as AC electrode for stable thermionic emission, although the thermal conductivity is insufficient. This fact led to severe erosion in conventional single-phase AC arc [9, 10] and MPA [8].

Diode-rectified MPA (DRMPA) has been successfully developed to solve the above issue [11]. Diode rectification technique was utilized to separate an AC electrode into a pair of cathode and anode. This separation of the AC electrode led to drastic improvement of electrode erosion. **Figure 1** shows the comparison of the electrode erosion rate between the DRMPA and the conventional MPA, which was reported in our previous research [11]. Cathodic erosion was reduced by the absence of the anodic heat transfer in the DRMPA. Furthermore, erosion at anodic period was also drastically suppressed because of the high thermal conductivity of the copper anode in the DRMPA. Understanding of fundamental phenomena in the DRMPA has been poorly understood because of its novelty in spite of its importance.

Electrode phenomena in the DRMPA is one of the most important phenomena to be understood in order to improve the erosion characteristics and understand its erosion mechanism. Understanding of spatiotemporal characteristics of the arc temperature is also necessary to achieve practical use of the DRMPA in material processing at high productivity.

The purpose of the present work is to investigate fluctuation characteristics of the arc and electrode temperature. Visualization technique by a high-speed camera with appropriate band-pass filters was applied.

2. Experimental Setup

Schematic electric circuits and conceptual waveform of arc current are shown in **Figs. 2** and **3**. Twelve diodes are placed between the electrodes and transformers for DRMPA. The electrodes were divided into pairs of cathode and anode, namely bipolar electrodes. Each electrode consists of cathode and anode. The cathode was made of 2wt%-thoriated tungsten with 3.2 mm in diameter. The anode was made of copper rod with 25 mm in diameter and was directly cooled by city water.

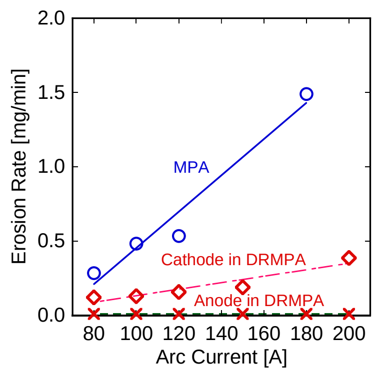

Fig. 1. Electrode erosion rates at different arc currents for MPA and DRMPA [11].

Figure 4 shows the schematics of the experimental setup with measurement system. Six pairs of the electrodes were symmetrically arranged at the angles of 60 deg. Odd numbered cathodes were placed above the corresponding anodes, while even numbered anodes were placed above the cathodes. DRMPA was generated among 6 bipolar electrodes in the chamber which was filled by argon under atmospheric pressure.

Electrode temperature during discharge was measured by the high-speed camera. Conventionally, electrode temperature measurement during the arc discharge was difficult due to the strong emissions from the arc. Recently developed technique with high-speed camera (FASTCAM SA5, Photron Ltd., Japan) was utilized in the present work. Only thermal radiation from the electrode surface was visualized without strong emissions from the arc by appropriate band-pass filters which transmission wavelengths were 785 ± 2.5 and 880 ± 5 nm. Then, surface temperature was measured on the basis of the two-colour pyrometry. Typical framerate was 1x10^{4}fps with shutter speed of 20-50 μs.

Arc temperature in the DRMPA was also measured by the same high-speed camera mentioned above. The difference from the electrode temperature measurements was the observed wavelengths. The band-pass filters of 675 ± 5 nm and 794 ± 5 nm, which include line emissions from atomic argon at 675.2834 nm and 794.8176 nm respectively were used. Excitation temperature of atomic argon was then calculated based on the Boltzmann plot method.

3. Results and Discussions

3.1 Arc temperature fluctuation in DRMPA

Temperature distributions of tungsten electrode for MPA and DRMPA during arc discharge at 80 A of arc current are presented in **Fig. 5**. In the case of MPA, the electrode tip was melted at both anodic and cathodic periods. In contrast, the cathode tip in DRMPA was not

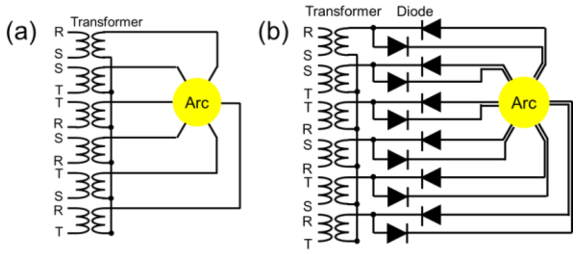

Fig. 2. Schematic electric circuits for conventional MPA (a) and innovative DRMPA (b).

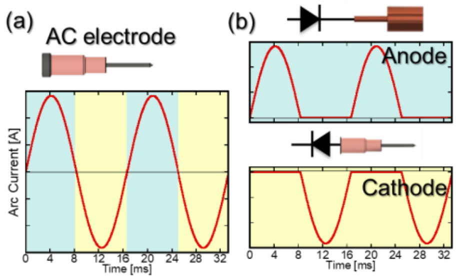

Fig. 3. Conceptual waveforms of arc current for MPA (a) and DRMPA electrode (b).

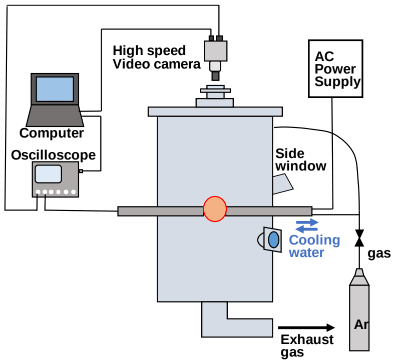

Fig. 4. Schematic image of experimental setup and measurement system of high-speed camera.

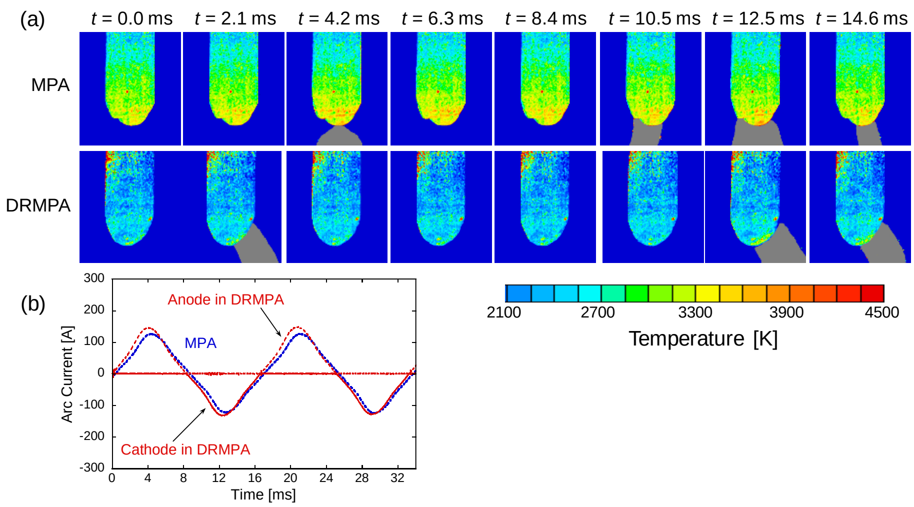

Fig. 5. Electrode temperature distributions during an AC cycle for the conventional MPA and DRMPA at 80 A of arc current (a) and the corresponding waveforms of arc current (b).

melted. This is due to the absence of the anodic heat transfer from the arc to the tungsten electrode in DRMPA.

Time variations of the electrode tip temperature for the MPA and the DRMPA during AC cycles with corresponding waveforms of the arc current are shown in **Fig. 6**. Temperature peaks originated in the maximum instantaneous values of the arc current during AC cycles. Around the peak time of the arc current, electrode tip temperature in MPA became higher than the melting point of tungsten (3,695 K), resulting in the severer erosion due to tungsten evaporation and the droplet ejection. On the other hand, electrode tip temperature in DRMPA was lower than the melting point of tungsten at all times during AC cycle. Therefore, the erosion due to tungsten evaporation and droplet ejection was drastically reduced.

3.2 Electrode temperature in DRMPA

Arc behaviour in DRMPA was observed by high-speed camera system without band-pass filters. **Figure 7** shows the high-speed snapshots of the MPA and the DRMPA during an AC cycle. Electrode No. 1 was in the anodic period from 0.00 ms to 8.33 ms, while electrode No. 4 was in the cathodic period at the same time. In the case of MPA, strong cathode jet was observed at near the electrode No. 1 when the time was 4.2 ms. The strong anode jet near the electrode No. 4 was also observed at the same time. These arcs are connected around the centre region among the electrodes.

In the case of DRMPA, anode jet was not clearly observed at around the anode No. 4, while cathode jet can be observed at near the cathode No. 1. The reason for the absence of the anode jet in DRMPA can be explained by lower current density in front of the DRMPA anode than that of the MPA electrode at anodic period. As shown in Fig. 7, arc near the DRMPA anode was not constricted, while the constriction of the arc near the DRMPA cathode was observed. These different constriction behaviours are possibly affected by the metal vapour from the electrode. Evaporation of tungsten electrode leads to the arc constriction due to high electrical conductivity of metal vapour. On the other hand, the evaporation of copper anode was negligible due to its high thermal conductivity. Therefore, absence of the metal vapour in front of the anode leads to the weak anode jet in DRMPA.

Figure 8 shows the visualized temperature fields of the MPA and the DRMPA. These temperature distributions correspond to the high-speed snapshots in Fig. 7. the results indicated that the temperature of the both MPA and DRMPA were fluctuated in the range of 7,000 K to 13,000 K. The arc temperature near the electrode was higher than 10,000 K, while the temperature in the centre

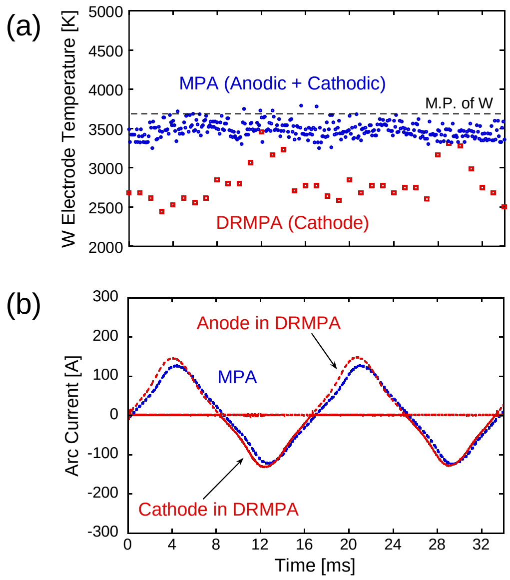

Fig. 6. Time variation of the highest electrode temperature during two AC cycles at 80 A of arc current (a) and the corresponding waveforms of arc current (b).

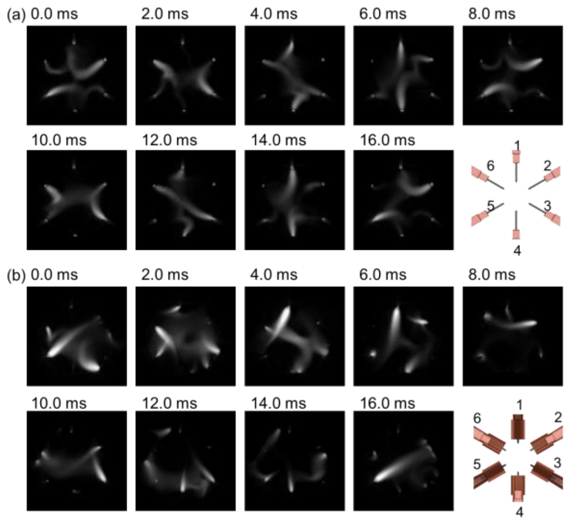

Fig. 7. High-speed snapshots of the MPA (a) and the DRMPA during one AC period (b).

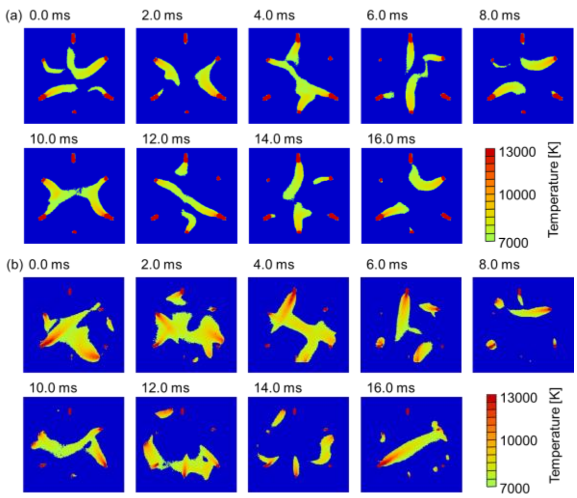

Fig. 8. Temperature fields of the MPA (a) and the DRMPA during one AC period (b). Indicated time corresponds to that in Fig. 7.

region in the furnace is lower than the 10,000 K. The temperature in the centre region is important because most of the treated powders are injected into this region.

Figure 9 presents the temperature fluctuation in the centre region of the furnace, which were estimated from the obtained temperature fields. Results indicated that the arc temperature in the DRMPA was higher than that in the MPA. The reason for this result is still unclear, but the relationship between the cathode jet and anode jet flow must have a strong effect on the temperature fluctuation. Cathode jet flow in the DRMPA was clearly dominant and extended to the centre region of the furnace. The arc temperature in the cathode jet region is higher than that in the anode jet region. Therefore, the arc temperature in the centre region for the DRMPA became higher than that for the MPA.

4. Conclusion

Fundamental phenomena in the diode-rectified multiphase AC arc has been successfully visualized on the basis of the high-speed camera system with appropriate band-pass filters. Electrode temperature fluctuation in the AC cycle was clarified. High-speed camera visualization also revealed the arc temperature fluctuation. Obtained results suggested that the diode-rectified multiphase AC arc is expected to be utilized in massive powder processing such as nanofabrication processes at high-productivity for a long time operation.

5. Acknowledgment

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6. References

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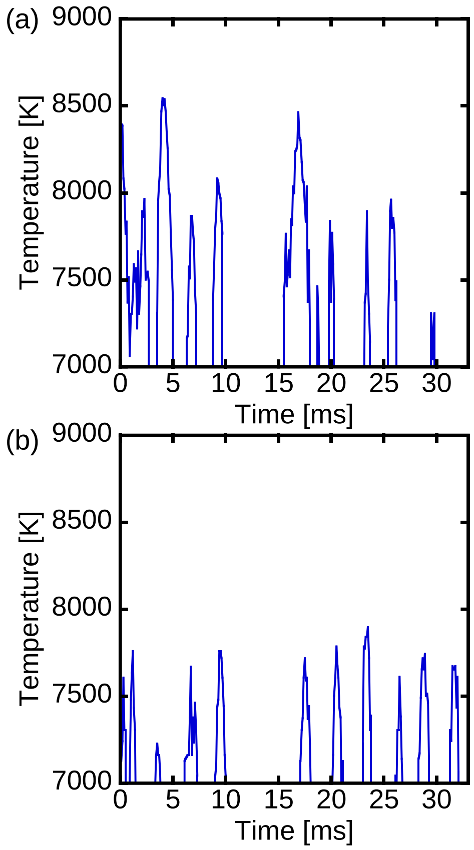

Fig. 9. Temperature fluctuation at the centre of the discharge region for the MPA (a) and the DRMPA (b)