Improvement of electrode erosion characteristics in diode-rectified multiphase AC arc

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Abstract: An innovative multiphase AC arc was drastically improved by diode-rectification technique. Conventionally, electrode erosion in AC arc originates from a lack of suitable electrode material because required properties for cathode and anode are different. To solve this problem, separation of AC electrodes into pairs of cathode and anode by diode-rectification was attempted. Diode-rectified MPA was then successfully established and erosion characteristics were drastically improved.

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

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 productivity. However, there are only few studies that have been reported since the multiphase AC arc is still new type of thermal plasma generating system. These studies have been on the arc stability [2], the temporal and spatial characteristics of the arc discharge [3], and the electrode phenomena [4-6]. In particular, electrode erosion is one of the most important issues to be resolved because it determines the electrode lifetime and purity of the products.

Electrode erosion in AC arc is of important issue. In general, 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 conductive material is suitable for anode as electron recipient. However, there is a lack of appropriate electrode material which satisfies required properties at both cathodic and anodic periods. In terms of the stable thermionic emission, tungsten based electrode are commonly used as AC electrode, although the thermal conductivity is not sufficiently high, resulting in sever erosion in conventional single-phase AC arc [7, 8] or MPA [6].

Electrode erosion mechanism in MPA has been investigated based on high-speed visualization [5, 6]. Erosion due to ejection of metal droplet larger than 100 μm in diameter is dominant at cathodic period, while evaporation is dominant at anodic period. The droplet ejection at cathodic period is basically caused by the electrode melting due to high heat transfer to electrode at anodic period.

To separate each AC electrode into pairs of cathode and anode could lead a breakthrough of the AC electrode erosion problem. Therefore, diode-rectification to separate AC electrodes are attempted. The purpose of the present work is to establish an innovative diode-rectified MPA (DRMPA) to improve the electrode erosion characteristics. Another purpose is to understand the electrode phenomena in DRMPA.

2. Experimental Setup

Schematic electric circuits for conventional MPA and DRMPA are shown in **Fig. 1**. Twelve diodes are placed between the electrodes and transformers. Thus. The electrodes were divided into pairs of cathode and anode, namely bipolar electrodes. **Figure 2** shows the schematics of the experimental setup with electrode configuration. 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. 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 Ar under atmospheric pressure.

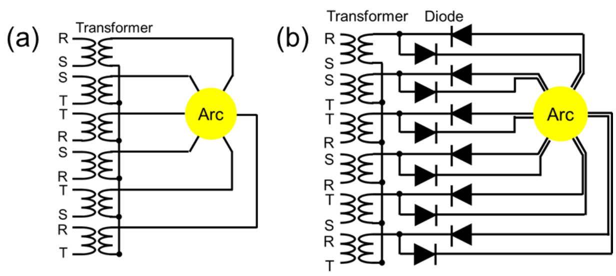

Fig. 1. Schematic electric circuits for conventional MPA (a) and innovative DRMPA (b).

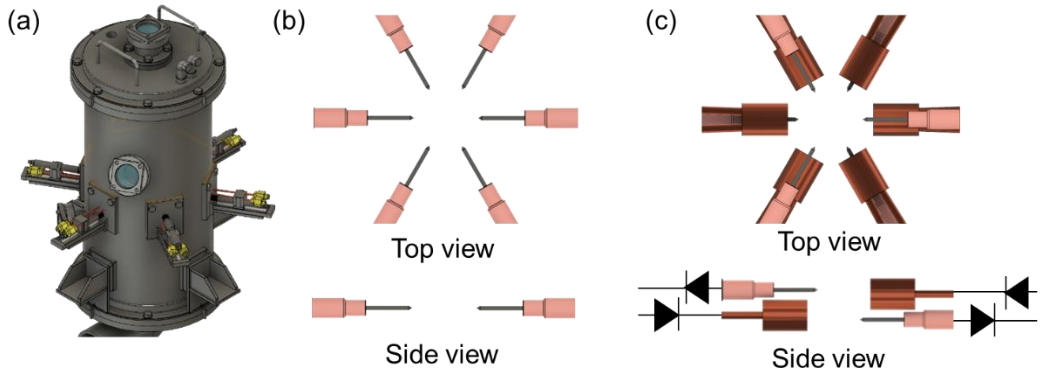

Fig. 2. Experimental setup (a) and schematic of electrode configuration for MPA (b) and DRMPA (c).

High-speed camera was (FASTCAM SA5, Photron Ltd., Japan) applied to visualize the fundamental phenomena in MPA with and without diode-rectification. Arc behaviour for MPA and DRMPA was recorded by the high-speed camera at a framerate of 1x10^4fps with a shutter speed of 2 μs. Electrode phenomena were visualized by high-speed camera.

Electrode temperature during discharge was measured by the same high-speed camera mentioned above. 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 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 and 880 nm. Then, surface temperature was measured on the basis of the two-colour pyrometry. Typical framerate was 1x10^4fps with shutter speed of 20-50 μs.

3. Results and discussions

3.1 Arc behaviour in DRMPA

Arc behaviour in DRMPA was observed by high-speed camera system without band-pass filters. **Figure 3** shows the high-speed snapshots of DRMPA and the conventional MPA during an AC cycle. Electrode No. 1 was in the cathodic period from 0.00 ms to 8.33 ms, while electrode No. 4 was in the anodic 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

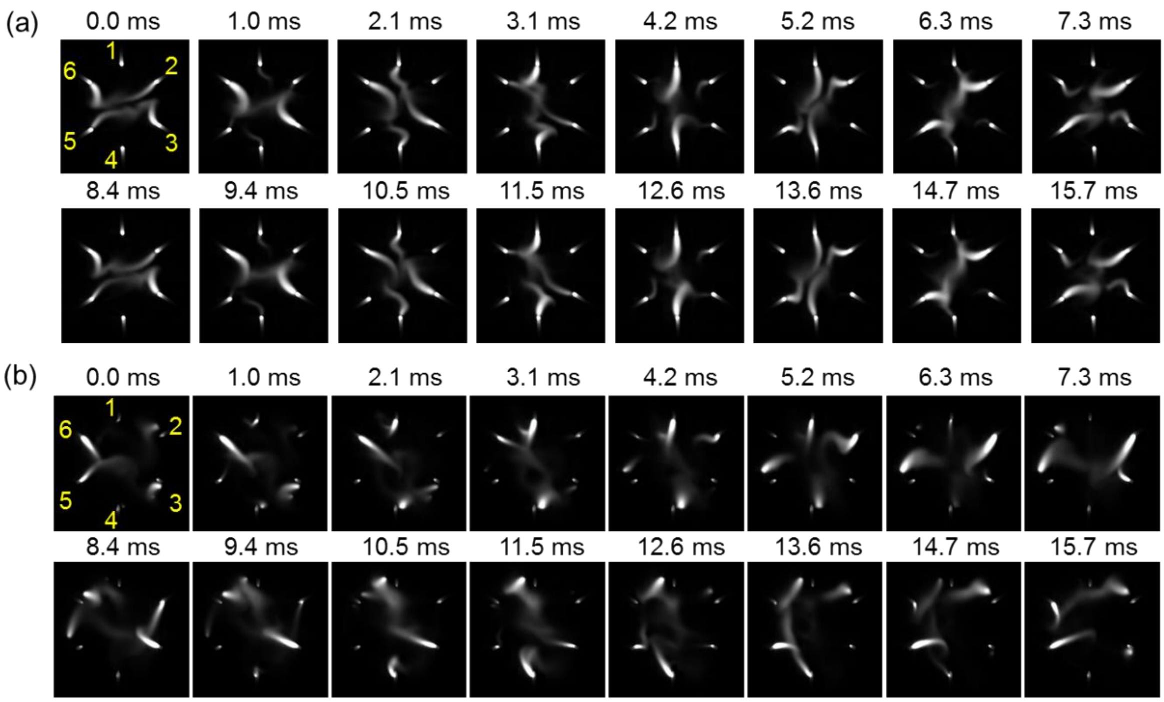

Fig. 3. High-speed snapshots of MPA (a) and DRMPA (b) during an AC cycle.

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. 3, 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.

Further analysis of the high-speed camera images was then conducted to understand the spatial characteristics of DRMPA. The high-speed snaps were accumulated during an AC cycle after binarization of each image by appropriate threshold value. Therefore, the accumulated images shown in **Fig. 4** express the distribution of arc existence time during an AC cycle. The obtained distributions for DRMPA exhibit widely-spread arc region. On the other hand, the MPA shows more concentrated distribution at the centre region among the electrodes. This difference originates from the different anode jet behaviour as mentioned in the previous paragraphs.

The obtained results about the arc behaviour suggested that the DRMPA was stably operated and was suitable heat source for thermal plasma processing such as nanofabrication due to its large volume of high temperature region.

3.2 Electrode erosion phenomena in DRMPA

Electrode erosion rates for DRMPA and MPA in different arc currents are presented in **Fig. 5**. The erosion rates in DRMPA were much smaller than that in the conventional MPA for all conditions in different arc currents. In particular, erosion rate of anode in DRMPA was drastically reduced. This is because the anode material in DRMPA was made of copper which has higher thermal conductivity than tungsten. Moreover, the erosion rate of cathode was also decreased than that in MPA. In order to understand the reason for this result, high-speed visualization of electrode phenomena during arc discharge was conducted.

Temperature distributions of tungsten electrode for MPA and DRMPA during arc discharge at 120 A of arc current are presented in **Fig. 6**. In the case of MPA, the electrode tip was melted at both anodic and cathodic periods, as shown in Fig. 4 (a) and (b). In contrast, the cathode tip in DRMPA was not melted. This is due to the absence of the anodic heat transfer from the arc to the tungsten electrode in DRMPA.

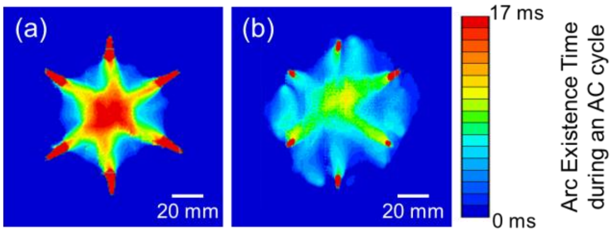

Fig. 4. Existence time of MPA (a) and DRMPA (b) during an AC cycle.

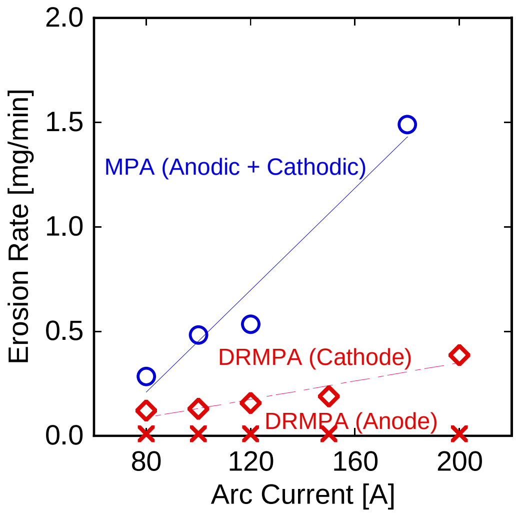

Fig. 5. Effect of arc current on electrode erosion rate in MPA and DRMPA.

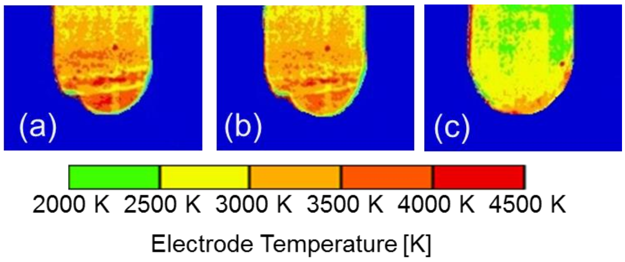

Fig. 6. Surface temperature distributions of MPA electrode at anodic period (a) and cathodic period (b), and cathode in DRMPA (c).

Time variations of electrode tip temperature for DRMPA and MPA during AC cycles with corresponding waveforms of the arc current are shown in **Fig. 7**. Temperature peaks originated in the maximum instantaneous values of the arc current during AC cycles. At all times during AC cycle, electrode tip temperature in MPA was 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.

4. Conclusion

An innovative multiphase AC arc with diode-rectification are established. Stable arc operation was confirmed even in the case with diode-rectification. Erosion characteristics of electrode in multiphase AC arc was drastically improved. High-speed camera visualization provided the arc behaviour in DRMPA. Moreover, high-speed camera technique with band-pass filter system revealed that the temperature characteristics of electrode in DRMPA. Separation of AC electrode into pairs of tungsten-based cathode and copper anode by diode-rectification 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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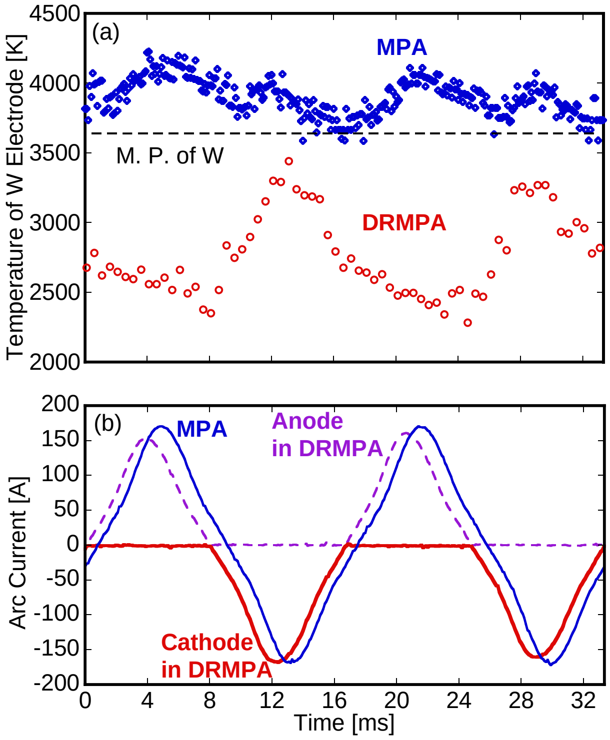

Fig. 7. Time variation of tungsten electrode temperature during an AC cycle (a) and corresponding waveforms of arc current (b).