Observation of Thermal Cathodic Hot Spots in a Magnetically Rotating Arc Plasma Generator

Cheng Wang, Wanwan Li, Xiaoning Zhang, Mengran Liao, Jun Zha, and Weidong Xia

***Abstract*— At atmospheric pressure, cathodic arc root tends to shrink to a luminous hot spot, which limits arc column expanding and accelerates cathode ablative rates. To obtain a nonconstricted cathodic arc root, we built a magnetically rotating arc plasma generator that mainly consists of a cylindrical graphite anode chamber, a concentric lanthanum tungsten cathode, and a solenoid coil for producing an axial magnetic field (AMF). Evolution of self-organized multihot spots on cathode end is observed in this study. Results show that with the AMF, arc currents, or/and cathode temperature increasing, the spot's quantity gradually increases, and at last multispots evolve into a diffuse annular one. When the arc column is constricted, the arc moves on the spots periodically. Thus, a single constricted cathodic root is formed. By controlling the axial gas flow, the constricted arc converts into a diffusive one which covers all spots simultaneously, and then multiroots or diffuse annular root are developed. The cathodic spots and roots formation mechanism are proposed, and experimental results support the prediction of *nonlinear surface heating model*.**

***Index Terms*— Cathodic root, cathodic spot, magnetically rotating arc plasma.**

I. Introduction

AT ATMOSPHERIC pressure, cathodic arc root tends to shrink to a spot (constricted cathodic arc root), which limits the expanding of arc plasma. Moreover, the spot's temperature may be even higher than the cathode material melting temperature, resulting in severe electrodes erosion [1], [2]. With the increase in arc currents or/and decrease in working pressure, the constricted cathodic arc root abruptly transforms into a diffuse one in which the plasma covers the whole end of cathode. Previous literatures have already proved that the diffuse root reduces the highest temperature of cathode and then elongates the electrodes lifetime [1]–[6].

Besides the constricted arc root and diffuse one, a self-organized multispot mode (multicathodic arc roots) has been theoretically proposed in [7] and [8] using *nonlinear surface heating model*, in which the arc plasma is decoupled from the cathode sheath. This theory agrees well with diffuse and spot modes on cathodes of high-pressure arc discharges [1]–[6] and self-organized steady-state spot patterns on cathodes of glow microdischarges [9]–[12]. Nevertheless, most research about cathodic arc roots were operated under the conditions of low current (<10 A) and small-diameter cathode (<2 mm). As the cathode size increases, the power that was removed by heat conduction increased sharply, leading to the difficulty in obtaining diffuse cathodic arc root [1], [4].

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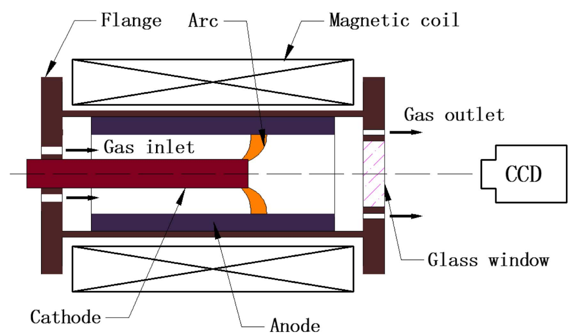

Fig. 1. Schematic of the experimental equipment.

To approach a nonconstricted cathodic arc root or even a diffuse one, a heating route by magnetically rotating arc was developed for the cathode [13]. Luminous multispots and a diffuse annular spot on the graphite cathode end were observed by a high-speed charge-coupled device (CCD) camera in a magnetically rotating arc plasma generator [14]–[16]. Owing to the high emissivity of graphite, the spots and cathode are so bright that the arc plasma could not be observed, and the state of arc connecting to the cathodic spots could not be identified. Thus, the thermal cathodic hot spot may represent a thermal trace of arc root that has occurred a short while ago rather than a current arc root.

In this study, a magnetically rotating arc plasma generator is constructed to investigate the properties of cathodic hot spots. To observe cathodic spots and arc plasma simultaneously, a lanthanum tungsten cathode is used. The material owns lower work function, thus it can reduces the cathode temperature and brightness effectively. The constricted or diffuse state of arc plasma is controlled by axial gas flow. Evolution of various cathodic hot spots and the states of arc connecting to the spots are observed and discussed.

II. Experimental Apparatus

Fig. 1 shows a schematic of generator, which mainly consists of a cylindrical arc chamber (graphite anode,

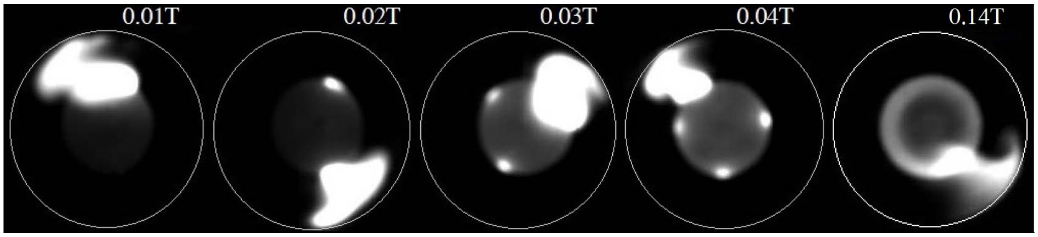

Fig. 2. Cathodic spots on the cathode end with one constricted arc column. The outer white line represents the plasma chamber. 0 Nm^3/h gas flow, 5000 frames/s. Frames 1–4: $I = 100$ A, 1 μs shutter. Frame 5: $I = 200$ A, 0.5 μs shutter.

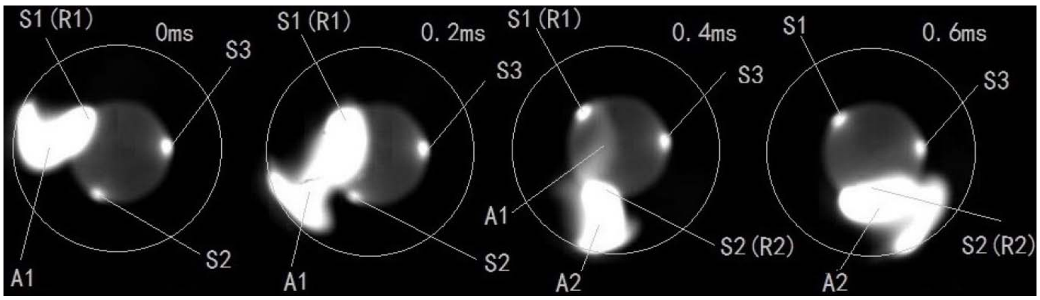

Fig. 3. Consecutive images of a constricted arc column hopping on multispots. $I = 100$ A, $B = 0.03$ T, 0 Nm^3/h gas flow, 1 μs shutter, and 5000 frames/s (S = spot, R = root, and A = arc column).

20-mm diameter, and 160-mm length), a concentric cathode (W-La alloy, 2% wt lanthana, 10-mm diameter, and 80-mm length), and a solenoid coil that produces an axial magnetic field (AMF) of a few hundred milliteslas. A flange covers one end of the anode chamber, while the cathode is arranged at the center of the flange. Around the cathode, axial gas inlets are uniformly distributed through the flange. Another end of the chamber is covered with a glass window, around which gas outlets are distributed axially uniformly. A high-speed CCD camera (Photron company, FASTCAM SA5 1000K-M3) is used to record the end-on projection of arc plasma. The recording frame rate ranges between 1000 and 100 000 frames/s and the exposure time ranges between 0.5 and 100 μs. Each frame consists of 256 $\times$ 256 pixels with 256 gray levels. To weaken the cathode radiation, a narrowband filter (centered at 416 nm, Ar-I line) was placed between the CCD camera and the chamber. To reduce its reflection, the inner surface of the cathode flange is painted black. A modulated 0–200 V dc power supply is applied to the generator. A voltage divider and a 50-kHz wideband Data Acquisition card are employed to obtain the arc voltage signals. The working gas used in this study is pure argon (99.999%).

III. Result and Discussion

A. Constricted Cathodic Root

As shown in Figs. 2 and 3, the arc shape is a single constricted column when the pressure of the chamber arrives to atmosphere pressure and no inlet gas is imposed. Driven by 0.01–0.04 T AMF, the arc column anticlockwise rotates rapidly, and luminous multispots appear on the cathode end. The arc column hops on the multispots periodically (frames 1–4 in Fig. 2, and frames at 0, 0.2, and 0.6 ms in Fig. 3). In the meantime, the arc shunting occurs between two adjacent spots, such as s1–s2 (frame at 0.4 ms in Fig. 3). This mode is called as *multispots with a single root* mode because only one arc attachment is observed in majority time. The cycle time of arc column heating each spot under 0.03 T AMF is about 1.5 ms, which is much less than the decay time of tungsten radiation (>5 ms) [17]. Before the spot is extinguished, the rotating arc heats the spots repeatedly, so that they can stay hot and luminous. Thus, the experiment confirms that the thermal cathodic hot spot may represent the thermal trace of arc root that has occurred a short while ago rather than a current arc root.

With the increase in AMF from 0.01 to 0.04 T, the spot's amount increases from 1 to 4. The more luminous cathode indicates the cathode temperature ascends, which should be attributed to the fact that the heating effect on cathode is enhanced in larger AMF [13], [14]. In rotating arc plasma generators, the formation of new cathodic arc root is very likely governed by the restrike process between arc column and cathode [18]. On the one hand, with the increase in AMF, the back flow of plasma on the axis of chamber is enhanced, so that the arc shifts toward the cathode end more obviously [19]. As a result, the arc becomes closer to the cathode end. On the other hand, the hotter cathode reduces the restrike threshold voltage because the hotter cathode offers higher thermionic emission. Both factors promote the restrike process on the cathode, so that the new arc root occurs more frequently. Since the cathodic hot spot represents the thermal trace of arc root, a greater amount of spots are generated under larger AMF. In addition, the amount of spots is fixed for a certain arc current and AMF.

As the AMF and arc currents increase up to 0.14 T and 200 A, the multispots evolve into a diffuse annular spot, as shown in frame 5 in Fig. 2. It is also found

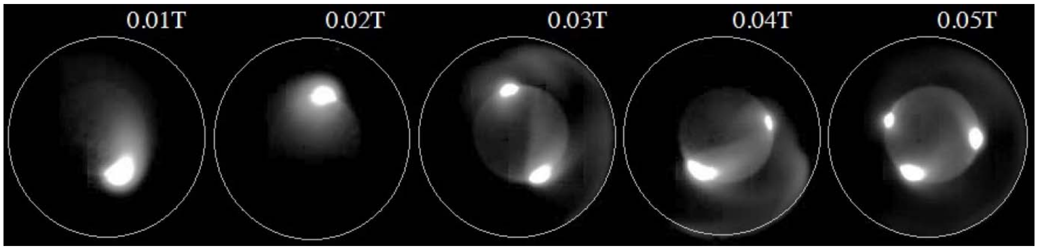

Fig. 4. Cathodic spots on the cathode end with DAP. $I = 100$ A, 1 Nm^3/h gas flow, 1 μs shutter, and 5000 frames/s.

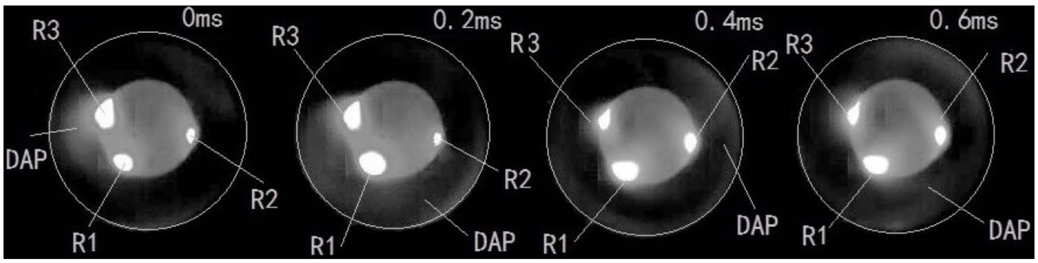

Fig. 5. Consecutive images of DAP attaching on multispots. $I = 100$ A, $B = 0.05$ T, 1 Nm^3/h gas flow, 1 μs shutter, and 5000 frames/s.

that the arc rotationally slides along the annular spot at about 2000 r/ s. We regard this mode as a *diffuse spot with a constricted root* mode. Hence, [14], which regarded all luminous spots or diffuse spot as multicathodic roots or diffuse root, may be incorrect, owing to the invisible arc plasma.

B. Multicathodic Root

When 1 Nm^3/h argon gas is imposed, the luminous and constricted arc column which was shown in Fig. 3 evolves into a dim and diffusive plasma cloud, as shown in Figs. 4 and 5. The diffusive plasma cloud was proposed as *dispersed arc plasma* (DAP) [16], [20], [21]. The property and formation mechanism of DAP have been investigated in [21]. The DAP's rotation could be observed. Since the arc plasma is likely to connect to all multispots simultaneously, there may coexist several arc roots, such as R1, R2, and R3 in Fig. 5. This mode is called as *multicathodic arc roots* mode. Because the diffusive plasma is heterogeneous, the currents that are taken by the three cathodic arc roots are different. During the process of DAP's rotation, the currents change periodically. Consecutive images in Fig. 5 exhibit the cycle time is about 1.5 ms, which is about equal to the cycle of constricted arc hopping on hot spots in Fig. 3. Compared with constricted arc column, the spots amount in DAP is less under the same AMF and arc current. This phenomenon may result from the fact that the distorted constricted arc column produces higher restrike voltage than that the DAP does under the same arc currents and AMF [21]. Moreover, the arc plasma may become farther away from the cathode end in DAP owing to the imposed axial gas flow.

C. Arc Voltage and FFT Spectra

To obtain further confirmation of the DAP connecting to multispots, the arc voltage characters are discussed. Parts of synchronously measured arc voltage signals that correspond to CCD images in Figs. 3 and 5 are plotted in Fig. 6. The voltage wave of constricted arc is saw-tooth with a 5–8 V fluctuation. The arc voltage declines during the arc column shunting between two adjacent spots. When the arc column is elongated by the Lorentz force, the arc voltage ascends. Fast Fourier transformation (FFT) spectra of arc voltages show that there is a frequency peak of approximately 2000 Hz (f). This frequency is in accordance with that of arc column hopping on multispots (about 3 × 1/1.5 ms). When the arc is dispersed, the voltage fluctuation frequency is obviously not 2000 Hz, while Fig. 5 shows that brightness periodic fluctuation is still about 2000 Hz. Hence, it is deduced that there is no obvious restrike process between the arc and spots during spots

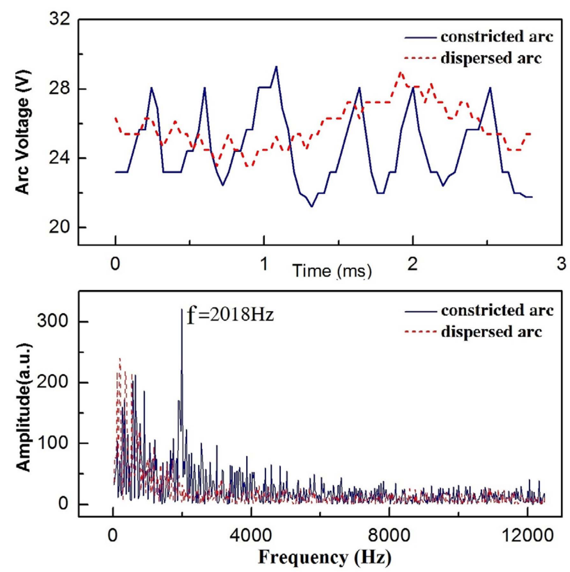

Fig. 6. Time-resolved arc voltage wave (top) and their FFT spectra (bottom). Constricted arc: $I = 100$ A and $B = 0.03$ T. Dispersed arc: $I = 100$ A and $B = 0.05$ T. Sampling frequency: 50 kHz.

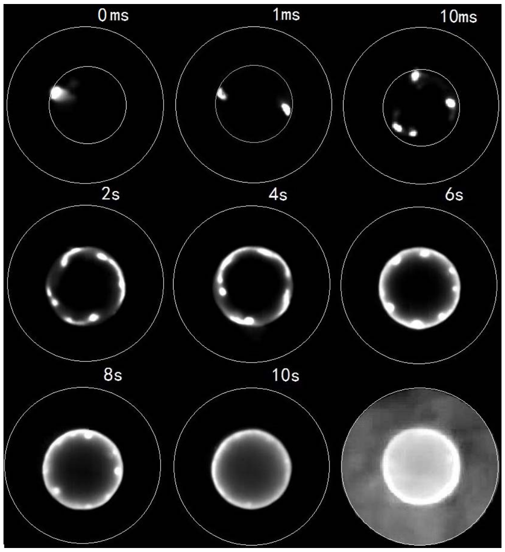

Fig. 7. Evolution of cathodic spots versus time in fully DAP after ignition. 1 Nm^3/h gas flow, $I = 200$ A, and $B = 0.14$ T. Frames 1–8: 0.5 μs shutter. Frame 9: 3 μs shutter.

luminance changing in the DAP. This conclusion proves that the DAP should attach on all spots. Besides, the DAP's valley voltage observed in this study is higher than constricted arc's, although previous research shows that the DAP owns lower arc voltage [21]. Thus the cathode voltage drop of DAP is higher than that of constricted arc. As a fact that the cathode voltage drop ascends with current density's reducing [22], [23], the character of cathode voltage drop indicates the DAP owns larger arc attachment areas.

D. Evolution of Diffuse Root

Under this condition (0.14 T AMF, 200-A arc currents, and 1 Nm^3/h argon gas inlet), the constricted arc column that was shown in Fig. 2 is fully dispersed, as shown in the last frame of Fig. 7. The frames 1–8 show a temporal and spatial evolution of cathodic hot spots after ignition. Since the shutter of frames 1–8 is less than that of the last frame, the spots on the cathode end are more clearly visible, while the DAP cannot be observed. After ignition, a luminous spot in frame 1 (0 s) appears, then it splits into two spots at 1 ms, and then four spots at 10 ms, and at last a diffuse annular spot at 10 s. During this process, the fourth frame (2 s) shows about seven spots. Some spots exhibit arc-shape regions and some are linked together. The sixth and seventh frames (at 6 and 8 s) show that more luminous spots indistinctly emerge in a luminous annulus. At 10 s (frame 8), a homogenous luminous annulus appears around the edge of cathode end. The more luminous cathode means the cathode temperature obviously increases with time. Therefore, the rising of cathode end temperature is considered as the main factor causing the increase in spots quantity. Comparing with *a diffuse spot with a constricted root* mode in Fig. 4, the annular spot in Fig. 7 is brighter and more homogenous. Considering the DAP throughout the annular area shown in frame 9, *a diffuse annular arc root* is developed. This evolution is similar to [9], in which segmented plasma spots and a ring plasma formed in cathode boundary layer discharge in xenon. However, there still exists a significant difference between two evolution. This study shows that the diffuse annular arc root is the joint outcome of spot division and linking while [9] showed the plasma spots became elongated until segmented plasma spots formed. Moreover, the discharge pattern is quite different for both.

E. Discussion

In previous studies, multiple spots have been experimentally observed in glow microdischarges but not on cathode of high-pressure arcs [8]. This study confirms the existence of multiple spots on cathode in arc discharge. The phenomenon is a direct proof of Benilov's theory of *nonlinear surface heating model* [7], [8]. There still exists a significant difference in our conclusion yet. The hot spot in this study represents the thermal trace of arc root, thus its formation depends on the state of arc root. Furthermore, the arc root in rotating arc plasma generators is the coupling action result of arc column and cathode [18]. The fact that multispots in constricted arc are more crowded than those in DAP under the same AMF and arc currents has proved that the effect of arc column to the hot spot should not be neglected. This phenomenon seems to indicate that the hypothesis of Benilov's cathode theory, of which the cathode sheath is decoupled from the plasma, has a limitation.

The thermal cathodic hot spot represents the thermal trace of arc root, so the spot and root should be distinguished explicitly. The formation of multispots is much easier than that of multiroots because the latter are often limited by the arc configuration. In the constricted arc, the arc cross section is much smaller than the spot's occupied area. The arc's spreading is limited, so that the arc cannot cover to the whole hot spots. When the arc transfers to a large area diffusive plasma, which almost covers the whole spots area, the multispots or diffuse annular spot turns into multiroots or diffuse root (nonconstricted root). Thus, an arc column of large cross section is necessary for approaching a nonconstricted cathodic arc root.

IV. Conclusion

In the study, various configurations of cathodic hot spots are generated on a W-La cathode end in a magnetically rotating arc plasma generator. With the increase in AMF, arc currents, or/and cathode temperature, the spot's amount increases, and finally these spots evolve into a diffuse annular spot. Experimental results support Benilov's prediction of *nonlinear surface heating model*. It is worth noting that the multispots induced by constricted arc column are more crowded than those by DAP under the same arc currents and AMF. Moreover, under the conditions of constricted arc and DAP, constricted root and nonconstricted root are obtained, respectively. Results show that the multicathodic roots or diffuse root is dependent not only on the cathodic hot spot mode but also on the state of the arc plasma.

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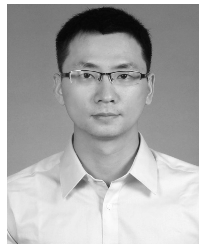

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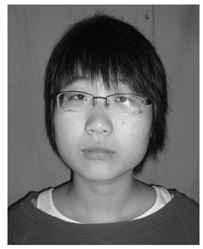

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