Self-organized pattern on the surface of a metal anode in low-pressure DC discharge

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Abstract

Self-organization phenomena on the surface of a metal electrode in low-pressure DC discharge is studied. In this paper, we carry out laboratory investigations of self-organization in a low-pressure test platform for 100–200 mm rod-plane gaps with a needle tip, conical tip and hemispherical tip within 1–10 kPa. The factors influencing the pattern profile are the pressure value, gap length and shape of the electrode, and a variety of pattern structures are observed by changing these factors. With increasing pressure, first the pattern diameter increases and then decreases. With the needle tip, layer structure, single-ring structure and double-ring structure are displayed successively with increasing pressure. With the conical tip, the ring-like structure gradually forms separate spots with increasing pressure. With the hemispherical tip, there are anode spots inside the ring structure. With the increase of gap length, the diameter of the self-organized pattern increases and the profile of the pattern changes. The development process of the pattern contains three key stages: pattern enlargement, pattern stabilization and pattern shrink.

Keywords: self-organized pattern, low pressure, DC voltage, metal anode, pattern profile

(Some figures may appear in colour only in the online journal)

1. Introduction

Self-organized pattern, which is associated with instability and symmetry breaking is a fascinating and common phenomenon in physical, biological, chemical and economic systems [1, 2]. Pattern formation is also pervasive in gas discharge, which particularly occurs in the anode layer, and a variety of patterns could be observed in air discharge under different conditions [3, 4].

In recent years, many researchers have investigated the characteristics of the self-organized pattern in a wide range of electrical discharges. With regard to the morphological characteristic, Shirai et al investigated the anode pattern in atmospheric DC glow discharge with a liquid electrode [5–7], and Maszl et al observed this phenomenon experimentally on both liquid and metal anode surfaces [8, 9]. Astrov et al studied the formation of the self-organized pattern in dielectric barrier discharges [10–15]. Numerical simulation is an important method for understanding the origin of pattern formation. For example, Treles presented the first attempt to simulate the spontaneous formation of anode attachment spot patterns in high-pressure and high-current arc discharge [16, 17].

Although the characteristics and theories of self-organization phenomena have been investigated, the external characteristics of the self-organized pattern on the surface of a metal anode electrode under low-pressure condition have not been completely clarified. In this paper, the authors carried out laboratory investigations of self-organization in a low-pressure test platform for 100–200 mm rod-plane gaps with a needle tip, conical tip and hemispherical tip within 1–10 kPa, and analyzed the influence of the pressure, gap length and shape of the electrode on the profile and development process of the pattern.

2. Experimental configuration

Figure 1 shows the experimental configuration for the test. The gas used in the test was air. The ambient temperature and
relative humidity were constant at 20 °C and 35%, respectively. During the test, the temperature inside the discharge chamber was kept at 20 °C. This experimental system consists of a high-speed camera (54-kframes/s frame rates, 960 × 16 pixel resolution), power system, measurement system, pressure-control system, test chamber and electrode system. Figure 2 gives the schematic diagram of the arrangement of the camera and rod-plane electrode. The camera focused on the upper surface of the metal plane electrode to observe the ionization phenomena. The angle between the camera and the surface of the plane electrode is about 35°. The DC voltage was generated by an AC transformer (50 Hz, 20 kVA) and rectifier and filter, which was applied to the high-voltage rod electrode at 0.5 kV s$^{-1}$. The discharge voltage was the mean value of 20 times the test, and was measured by a resistance voltage divider and a digital oscilloscope (Tektronix DPO2012, 100 MHz, 1 GS s$^{-1}$). The discharge current was measured by a high-frequency current transformer (Pearson
2100, 20 MHz). In the measurement of the discharge process, we used current pulse trigger mode to record the process of pattern formation on the plane electrode for 400 ms. In order to make the charge distribute in the chamber adequately, the time interval for repeated discharges was set as 5 min. The pressure ranged from 1–10 kPa in the test chamber and was adjusted by vacuum needle valve and $\Delta P = 2$ kPa.

Figure 3 shows the chamber and electrodes. The effective radius of the stainless steel chamber and plane electrode are 400 and 200 mm, respectively, and the surface roughness of the plane is $1.6 \mu m$ [18]. The cylindrical stainless steel rod with a diameter of 10 mm with three kinds of tips are common electrode configurations in discharge tests. Table 1 shows the structure of the rod tip used in this experiment. The surface of the electrodes is cleaned by alcohol before the test.

### 3. Experimental result and discussion

#### 3.1. The dependence of pattern formation on external parameters

This research mainly aims at the characteristics of the self-organization phenomenon over a metal-surface electrode in low-pressure DC discharge with different electrode configuration. Figures 4(a)–(c) show the discharge voltage $U$ dependence of pressure $P$ for different rod tips with gap length increases from 100–200 mm. The pressure ranges from 1–10 kPa.

It can be seen in figure 4 that with the increase of pressure, the adjacent $U$-$P$ curves of different gap length are further apart from each other, which means the influence of gap length increment on the breakdown voltage is gradually strengthened with increasing pressure. Furthermore, tip shape has a significant influence on breakdown voltage. The amplitude of breakdown voltage at the same pressure value and gap length shows ‘needle $<$ conical $<$ hemispherical.’ Therefore, tip shape may have obvious influence on the profile and development process of the self-organized pattern.

To research the dependence of pattern profile on pressure value and tip shape, we take a 200 mm rod-plane gap as an example. The effects of pressure and tip shape are shown in figure 5 and the diameter of the self-organized pattern varies with pressure, as shown in figure 6. With the increase of pressure, several transitions are observed obviously. With the needle tip at 1 kPa, the pattern presents irregular layer structure, and the structure of the pattern is unstable. With the increase of pressure within 1–3 kPa, the pattern enlarges and a ring-like structure gradually becomes visible, and the diameter of this pattern then gradually decreases with increasing pressure. When the pressure increases to 5 kPa, the pattern presents double ring and is constricted at the anode plane to a small spot at 9 kPa. It can be seen in figure 5(b) that the pattern has the obvious characteristic of ring-like structure. Within 1–6 kPa, the pattern enlarges and becomes a regular ring with increasing pressure. However, when the pressure

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**Figure 3.** Test chamber and electrodes. (a) Test chamber. (b) Plane and three kinds of rod tips.

<table>
<thead>
<tr>
<th>Tip structure</th>
<th>Needle</th>
<th>Cone</th>
<th>Hemisphere</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tip radius (mm)</td>
<td>0.05</td>
<td>0.5</td>
<td>5</td>
</tr>
<tr>
<td>Material</td>
<td>Stainless steel</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Surface roughness ($\mu m$)</td>
<td>1.6</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

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**Table 1.** Structure of the rod tip.
continues increasing, the ring-like structure gradually forms separate spots, which will subsequently develop into an anode streamer. The distinct difference between figures 5(b) and (c) is that distinct anode spots could be clearly observed inside the ring, and the luminance and the number of spots increase with increasing pressure. The outer ring forms separate spots within 6–7 kPa and is unable to form a regular pattern when the pressure increases to 8 kPa.

Thus, it can be concluded that the self-organized pattern on the surface of a metal anode under low-pressure condition depends on the shape of the electrode and the pressure value. An upper limit pressure of pattern formation between 8 and 9 kPa exists for 200 mm gap length. Within the pressure range of pattern formation, the diameter of the pattern increases and then decreases. However, the formation of different pattern profiles in figure 5 should be interpreted in terms of the formation mechanism of the self-organized pattern. Other studies have shown that every anode spot in the pattern represents a discharge filament, and filaments are ‘indistinguishable’ under low-pressure condition [19]. Figure 7 shows the discharge profile of a 200 mm rod-plane gap at 6 kPa, and the exposure time is set as 1000 μs. It can be seen in figure 7 that the discharge profile could be divided into the filament region and pattern region, and the holistic morphology of the filament region appears cone-shaped and ‘indistinguishable’. Therefore, we speculated that the influence of rod tip shape on the distribution of filaments within the filament region is the main reason for the different pattern profile with different rod tip. In consideration of the difficulty to observe the filament distribution inside the filament region, numerical simulation is needed in the future.

Therefore, the reason to form a different pattern profile could be explained as follows. Due to the sufficient time for electron diffusion at 1 kPa, filaments could occupy more electrode surface to form a layer structure [20]. Taking figure 5(b) as an example, the flocculent or liner structure in the middle of the ring-like structure at 3 kPa corresponds to the motion track of the discharge filament during the exposure time of the picture. When discharge filaments which appear randomly are too close to each other, they will interact with each other and move quickly to form the flocculent or liner structure. As for figure 5(c) within 6–8 kPa, the axial electric field of discharge filaments which form the outer ring of the pattern may inhibit other filaments, so the outer ring forms separate spots.

Figure 8 shows the influence of gap length on the profile of the self-organized pattern at 5 kPa. As shown in figure 8, the diameter of the pattern increases gradually with the increase of gap length. The possible reason for this phenomenon can be explained by the motion of free electrons. When free electrons move towards the anode electrode, the deviation to axis caused by thermal motion and elastic collision increases gradually, which in turn increases the ionization area on the plane [21, 22]. Besides, the profile of the pattern is also significantly affected by gap length. With the needle tip, the pattern changes from layer structure to ring structure with the increase of gap length. With the conical tip, ionized stripes with a more luminous ring on the outside are seen for the gap length between 100 and 150 mm, and the

Figure 4. $U$-$P$ curves of different electrode configurations. (a) Needle tip. (b) Conical tip. (c) Hemispherical tip.
pattern becomes single ring when the gap length is 200 mm. With the hemispherical tip, there are anode spots inside the ring structure, and the luminance and the number of spots increase with increasing gap length. Thus, it can be seen that, in the aspect of pattern profile, the effect of increasing gap length is similar to that of increasing pressure.
3.2. The development process of the self-organized pattern with a metal anode

It can be seen in section 3.1 that the self-organization phenomenon is observed on the surface of the metal anode within a certain pressure range. Hereafter, we take the 200 mm rod-plane gap as an example to describe the development process of the self-organized pattern.

Figure 9 shows the development process of the self-organized pattern of a 200 mm rod-plane gap with a needle tip at 5 kPa. This process contains three key stages: pattern enlargement, pattern stabilization and pattern shrink. As shown in figure 9, the frame before seeing the pattern for the first time is set as \( t = 0 \) \( \mu \)s. At \( t = 604 \) \( \mu \)s, a small homogeneous spot is generated at the anode. During 604–11 461 \( \mu \)s, the spot gradually enlarges and reaches its maximum size at \( t = 11 461 \) \( \mu \)s. In terms of the profile of the self-organized pattern, the change of profile with the time increasing can be divided into three stages: small anode spot, ring-like structure and double-ring structure. During 11 461–17 493 \( \mu \)s, the diameter of the outer ring basically remains unchanged, but the diameter of the inner ring gradually decreases. The outer ring of the pattern begins to shrink from \( t = 18 099 \) \( \mu \)s and nearly extinguishes at \( t = 23 525 \) \( \mu \)s. Furthermore, the development process of the pattern is accompanied by the transformation from a pattern to a positive column. The degree of ionization at the outer ring increases during 12 046–19 303 \( \mu \)s, and some filaments gradually develop into positive columns with high charge density. More than one positive column could develop forward simultaneously, but when one positive column develops faster due to some accidental reason, its strong axial electric field may inhibit other positive columns and discharge filaments. Therefore, the pattern on the anode surface eventually disappears.

Figure 10 gives the voltage and current waveforms of a 200 mm rod-plane gap discharge with the needle tip at 5 kPa, and the region between the two dash lines corresponds to figure 9. The discharge voltage and peak current are 9.6 kV and 6.7 mA, respectively. As shown in figure 10, the development process of the self-organized pattern is accompanied by current. The chopped wave of voltage waveform represents the beginning of the pattern. In the subsequent process of voltage drop, the pattern experiences enlargement, shrinks and subsequently transforms from the pattern to a positive column. In addition, the elongation of the positive column is the main reason for the surge of the current.

In order to analyze the influence of tip shape on the development process of the self-organized pattern, figures 11–14 give the development process and waveform of the pattern formation with a conical tip and hemispherical tip at 5 kPa, respectively. As shown in figure 11, the profile of the pattern maintains a ring-like structure from its origin to extinction. The development process of the pattern also contains three key stages: pattern enlargement, pattern stabilization and pattern shrink. From this research, we believe that the formation of the positive column may be due to the accumulation of positive ions

**Figure 6.** Diameter of self-organized pattern of different electrode configurations varies with pressure.

**Figure 7.** Discharge filament of a 200 mm rod-plane gap with hemispherical tip. Exposure time is set as 1000 \( \mu \)s.

**Figure 8.** Self-organized patterns of 100–200 mm rod-plane gaps at 5 kPa. (a) Needle tip. (b) Conical tip. (c) Hemispherical tip. Exposure time is set as 350 \( \mu \)s.
in the pattern. The reason could be that during the shrink process of the pattern within 27 247–44 740 μs, positive ions in the ring-like pattern drift towards the center of the anode plane, which in turn strengthen the field strength of the area ahead of the center. As the formation of electron avalanches is significantly affected by the polarity effect, the positive column with high charge density will initiate from the center of the pattern. It can be seen in figure 12 that regions A, B and C correspond to the stage of pattern enlargement, pattern stabilization and pattern shrink, respectively. The change law of the pattern profile could be described as follows. The pattern increases with the decrease of voltage in region A. The voltage increases slightly when the pattern is stable and decreases again during the transformation from the pattern to the positive column. Two peak value
positions of current waveform correspond to the maximum size of the pattern and positive column, respectively.

It can be seen in figure 13 that the variations of pattern profile with a hemispherical tip include two aspects: the outer structure and inner structure. As for the outer structure, with the time increasing, the outer part of the pattern becomes a ring-like structure, which gradually forms separate spots and eventually disappears. In terms of the inner structure, the anode spots change from the separate state to connected state.

4. Conclusions

We carried out laboratory experiments to investigate the characteristics of the self-organized pattern on the surface of a metal electrode under AC voltage for 100–200 mm rod-plane gaps with a needle tip, conical tip and hemispherical tip within 1–10 kPa. The influence of the pressure, gap length
and shape of the electrode on the profile and development process of the pattern was analyzed. The following results were obtained.

1. The self-organized pattern can be observed only on the surface of the metal anode, and an upper pressure limit of pattern formation exists.
2. With increasing pressure, the pattern diameter first increases and then decreases, which means the size of the pattern has a maximum value.
3. With increasing pressure, the pattern presents a layer structure, single-ring structure and double-ring structure with a needle tip, and the ring-like structure forms separate spots with a conical tip. With a hemispherical tip, there are anode spots inside the ring structure.
4. With the increase of gap length, the diameter of the pattern increases and the profile of the pattern changes.
5. The development process of the pattern contains three key stages: pattern enlargement, pattern stabilization and pattern shrink.

Acknowledgments

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