Study on Glow Discharge Plasma Used in Polyester Surface Modification

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Abstract To achieve an atmospheric pressure glow discharge (APGD) in air and modify the surface of polyester thread using plasma, the electric field distribution and discharge characteristics under different conditions were studied. We found that the region with a strong electric field, which was formed in a tiny gap between two electrodes constituting a line-line contact electrode structure, provided the initial electron for the entire discharge process. Thus, the discharge voltage was reduced. The dielectric barrier of the line-line contact electrodes can inhibit the generation of secondary electrons. Thus, the transient current pulse discharge was reduced significantly, and an APGD in air was achieved. We designed double layer line-line contact electrodes, which can generate the APGD on the surface of a material under treatment directly. A noticeable change in the surface morphology of polyester fiber was visualized with the aid of a scanning electron microscope (SEM). Two electrode structures – the multi-row line-line and double-helix line-line contact electrodes – were designed. A large area of the APGD plasma with flat and curved surfaces can be formed in air using these contact electrodes. This can improve the efficiency of surface treatment and is significant for the application of the APGD plasma in industries.

Keywords: atmospheric pressure glow discharge (APGD), contact electrodes, polyester, surface modification

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

1 Introduction

Compared with the traditional surface modification method, the use of low temperature plasma as a kind of surface treatment technology has obvious advantages of being clean, highly efficient, and less pollution [1,2]. In reactions such as grafting, crosslinking, and polymerization, active particles with high chemical activity and high energy generated in the low temperature plasma can only modify the outermost layer of the material without interfering with its bulk properties [3]. At present, the glow discharge used for material surface treatment is mainly produced in a low-pressure environment. Compared with the low-pressure glow discharge, the atmospheric pressure glow discharge (APGD) can greatly simplify the production technology and reduce the operating costs while eliminating the use of vacuum equipment [4]. The APGD is typically generated in the form of a dielectric barrier discharge (DBD) [5,6]. At atmospheric pressure in air, the magnitude of the instantaneous pulse discharge current is high, and the discharge turns into a filament discharge, which causes damage to the material under treatment [7,8].

An effective method of achieving the APGD in air is to reduce the discharge voltage and inhibit the large instantaneous pulse discharge current by providing an initial electron in the discharge region [9]. In this study, a line-line contact DBD electrode structure is proposed, and the influence of its diameter on the discharge is discussed. In addition, a polyester surface is modified by the glow discharge generated by the double layer line-line contact electrodes. Scanning electron microscopy (SEM) was used to determine the effect of plasma treatment on the morphology of the polyester surface. In order to improve the processing efficiency of plasma modification, two types of electrode structures that can be used to generate large-area glow discharge plasma at atmospheric pressure in air are designed.

2 Generation of contact electrode glow discharge plasma

2.1 Experimental setup

Discharge experiments were conducted at atmospheric pressure in air by using the contact DBD electrode structure. The experimental system consisted of three components: a power supply, the electrode structure, and a measuring system. The power supply was a high-frequency, high-voltage sine wave generator with a voltage range from 0 to ±10 kV and a frequency range of 5-60 kHz (Fig. 1). The frequency used in this study was approximately 20 kHz. The electrodes were covered with a dielectric barrier material on both sides. The dielectric material was PTFE with a thickness of

0.25 mm, and the outer diameter of each electrode was 1.5 mm. The discharge voltage U across the electrode structure was measured with a Tektronix P6015A high-voltage probe. The discharge current I was determined by measuring the voltage across a resistor R in series with the electrode structure. Waveforms of the discharge voltage and current were recorded by a Tektronix digital oscilloscope (TDS1012B-SC).

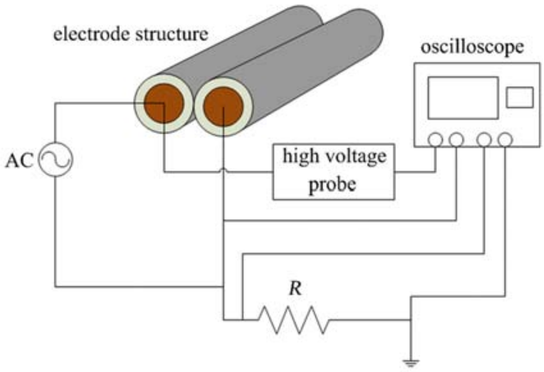

Fig.1 Schematic of experimental system

2.2 Generation characteristics of the plasma formed by the line-line contact electrodes

In the experiment, the voltage was increased slowly, and we assumed that when the discharge current was reached, the breakdown occurred and the peak voltage was the initial discharge voltage. The initial discharge voltage of the line-line contact electrodes was 3.2 kV. In order to make the discharge phenomenon more obvious and the plasma-generating area larger, the discharge voltage was increased up to 4 kV. Fig. 2(a) and (b) illustrate the discharge phenomena and the waveforms of the discharge voltage and current.

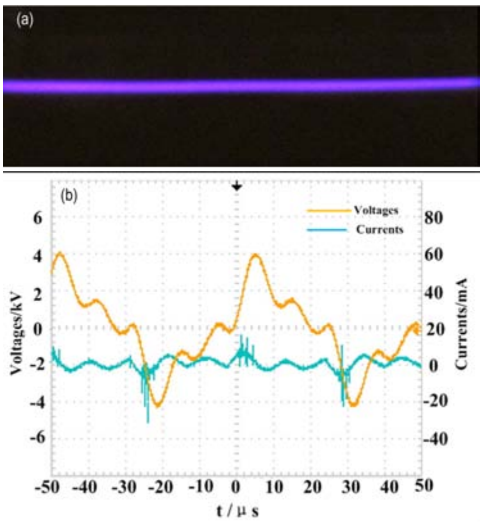

Fig.2 Discharge phenomenon and waveforms of discharge voltage and current of line-line contact electrodes, (a) Discharge phenomenon, (b) Waveforms of discharge voltage and current

The glow discharge generated in the groove was formed by two cylindrical electrodes. It can be seen that the glow covers the surface of two electrodes, and the light emission is uniform (Fig. 2(a)). Fig. 2(b) shows that the maximum instantaneous discharge current is 30 mA under an applied voltage of 4 kV.

The discharge phenomenon, in which the discharge is generally considered as a diffusion-type, with a discharge current on the order of milliamperes is known as a glow discharge. In other studies, a strict definition of glow discharge is used. By this definition, there is only one discharge process in both the positive and negative half cycles of alternating current, and there is only one peak in the current waveform. The discharge form in which many discharges were generated in the half cycle is called a like-glow discharge. The current density of the glow discharge is less than that of arc discharge or dielectric barrier discharge. Thus, the current magnitude and, in particular, the current density is the main basis for defining this as a glow discharge. The contact DBD has a lower discharge voltage and smaller electric field strength than a conventional DBD. Therefore, it can inhibit the rapid development of an electron avalanche and prevent the occurrence of a high transient pulse discharge current. The contact DBD produces a uniform discharge at atmospheric pressure in air. This phenomenon is consistent with the main features of a discharge current of the glow discharge. Thus, it can be considered as a glow discharge or like-glow discharge.

2.3 Effect of electrode diameter on discharge characteristics

The maximum electric field strength is the main factor that affects the initial discharge voltage. The curvature of the electrode increased as the outer diameter of the electrode was increased; hence, the maximum electric field strength decreased under the same applied voltage. To further analyze the influence of the size of the outer diameters of the electrodes on the maximum electric field strength, the electric fields of the line-line contact electrodes with different diameters were simulated by using Maxwell 3D software. The diameters of the metal electrodes were 1 mm, 2 mm, 3 mm, and 4 mm, and the corresponding outer diameters were 1.5 mm, 2.5 mm, 3.5 mm, and 4.5 mm. The maximum electric field strength of the electrodes under an applied voltage of 4 kV with respect to the outer diameters of the electrodes is shown in Fig. 3.

Fig. 3(a) shows the electric field distribution for an electrode diameter of 1.5 mm. It can be seen that the local region of a strong electric field, which is formed in the tiny gap near the contact point of the two electrodes constituting the contact DBD electrode structure, provided the initial electron. Thus, the APGD plasma in the electron diffusion region was formed. It can be seen that the maximum electric field strength decreased when the outer diameter of the electrode was increased. However, there was little change in the magnitude of the maximum electric field strength (Fig. 3(b)) because, in the case of the electrode structure of the line-line-contact type, the maximum electric field strength depends almost entirely on the thickness of the dielectric material that covers the two metal electrodes. When we changed the outer diameters of each line electrode for a constant dielectric material thickness, the curvature radiuses of the electrodes changed, and the small gap near the contact point changed slightly. Therefore, the maximum electric field strength was approximately constant, and the outer diameters of the electrodes had little effect on the initial discharge voltage.

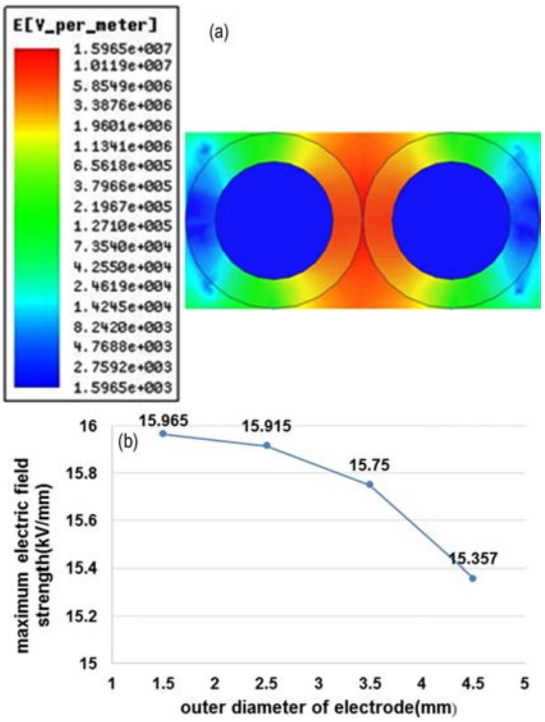

Fig.3 Influence of electrode diameter on electric field distribution, (a) Electric field distribution, (b) Maximum electric field strength of electrodes with different diameters

3 Polyester surface modification by the contact electrode

3.1 Influence of polyester on the discharge characteristics of the contact electrode

The glow discharge generated by the line-line contact electrode is mainly in the groove formed by the two electrodes. Thus, the polyester materials under treatment should be placed in this groove to ensure that the plasma can be effectively used in the polyester surface modification. Further analysis of the simulation and experiment results was performed in terms of the discharge characteristics of the line-line contact electrode. The original electric field distribution of the electrodes was changed after placing polyester, which is insulated, into the groove. The outer diameter of the electrode was 1.5 mm, the thickness of the PTFE was 0.25 mm, and the diameter of the polyester was 0.62 mm. The simulation results for an applied voltage of 4 kV are shown in Fig. 4.

The maximum electric field strength of the line-line contact electrodes after adding the polyester was 1.58×10^7 V/m (Fig. 4(a)). This was a relatively small change considering that the maximum electric field strength of the electrodes before adding the polyester was 1.59×10^7 V/m. However, the polyester surface produced a strong electric field when it was placed in the groove formed by the two cylindrical electrodes.

The minimum electric field strength of the polyester lower semicircular surface was 4×10^6 V/m, which was greater than the theoretical breakdown field strength of the air (3×10^6 V/m) under an applied voltage of 4 kV (Fig. 4(b)). Thus, when we apply enough voltage to the electrodes after adding polyester, plasma can be directly generated on the polyester surface, which then modifies the surface.

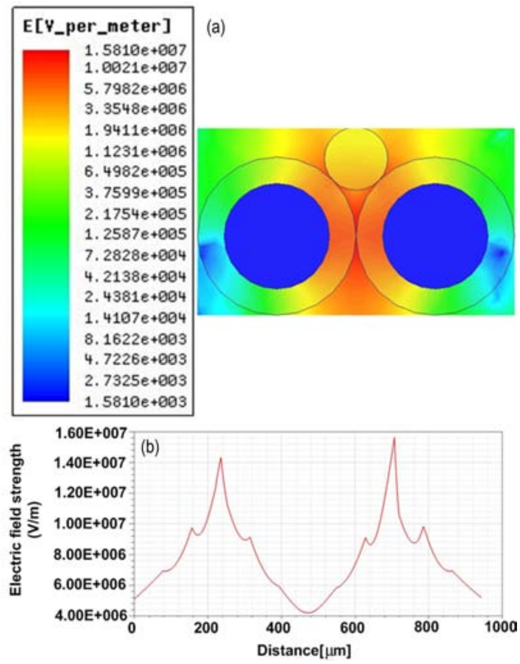

Fig.4 Electric field distribution of line–line contact electrode with polyester, (a) Electric field distribution, (b) Electric field strength along lower polyester surface

The maximum instantaneous discharge current was about 25 mA under an applied voltage of 4 kV, which was basically the same as the discharge current of the line-line contact electrodes before adding the polyester (Fig. 5).

3.2 Effect of polyester surface modification

For the line-line contact electrodes, a strong electric field along the surface of the polyester fiber was formed only on the lower half of the surface between the two electrodes. In order to form an electric field, with a greater strength than that of the air breakdown electric field on the entire surface of the polyester fiber, double layer line-line contact electrodes were designed based on the single line-line contact electrodes. The upper left and the lower right electrodes were the high-voltage electrodes, and the other two were ground electrodes (Fig. 6(a)). The outer diameter of the electrode was 1.5 mm, the thickness of the PTFE was 0.25 mm, and the diameter of the polyester was 0.62 mm. The simulation results for an applied voltage of 4 kV are shown in Fig. 6.

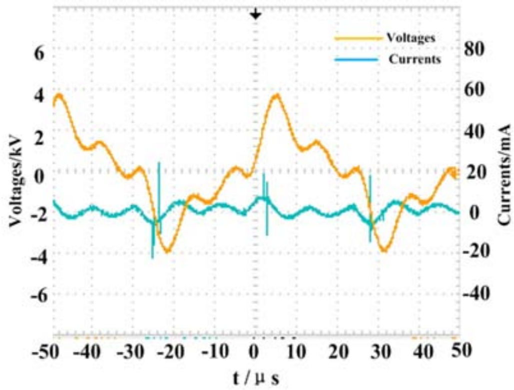

Fig.5 Waveforms of discharge voltage and current

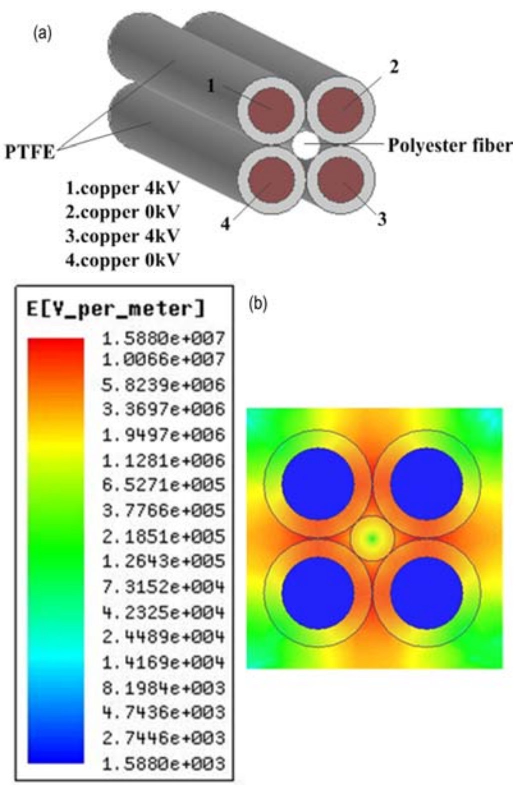

Fig.6 Electrode structure with double layer layout and its electric field distribution, (a) Electrode structure, (b) Electric field distribution

The maximum electric field strength of the double layer line-line contact electrodes was 1.5×10^7 V/m, which was basically the same as the maximum electric field strength of the line-line contact electrodes. The electric field distribution along the polyester fiber surfaces is shown in Fig. 7.

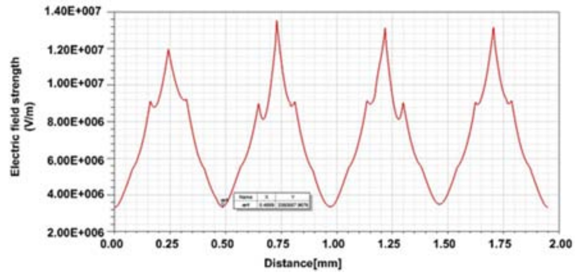

Fig.7 Electric field distribution along polyester surface

The minimum electric field strength on the entire polyester surface was 3.3×10^6 V/m, which is greater than the theoretical breakdown field strength of air. Thus, the glow discharge plasma could be generated on the entire polyester surface. The initial discharge voltage of the double line-line contact electrodes was 3.4 kV. The waveforms of the discharge voltage and current under an applied voltage of 4 kV are shown in Fig. 8.

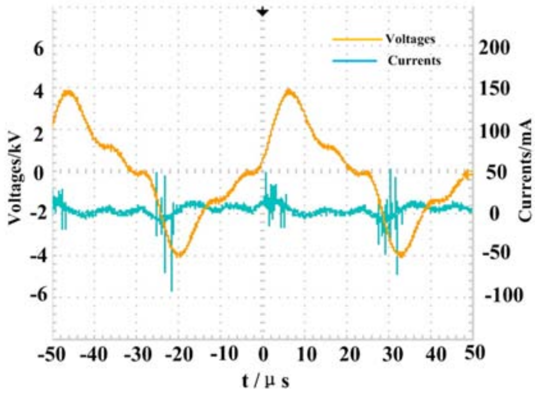

Fig.8 Waveforms of discharge voltage and current

The waveforms of the voltage and current in the positive half cycle and the negative half cycle of the voltage both exhibited multiple instantaneous short pulse current waveforms. However, the peak discharge current was only 90 mA, which is in accordance with the main characteristics of the glow discharge current. The plasma generated by the double line-line contact electrodes under an applied voltage of 4 kV treated the polyester for 60 s. SEM images were obtained in order to illustrate the alteration of the surface morphology of the untreated and treated polyesters with a magnification of 2,500 times, as shown in Fig. 9.

Fig. 9(a) shows that the untreated polyester fiber surface is very smooth and indicates no damage to the fiber surface. Fig. 9(b) shows convex deposits produced in the polyester fiber surface treated by plasma. Fig. 9(c) shows a few tiny grooves on the polyester surface treated by the glow discharge plasma. The rough surface can improve the wettability of the polyesters and increase the dyeing rate [10−12]. The energetic particles in the plasma strike the material surface and transfer their energy to the fiber material leading to sputter etching. Simultaneously, the free radicals of the plasma react with the surface molecules of the fiber material leading to a crosslinking effect. Thus, the surface morphology of the material is changed [13,14].

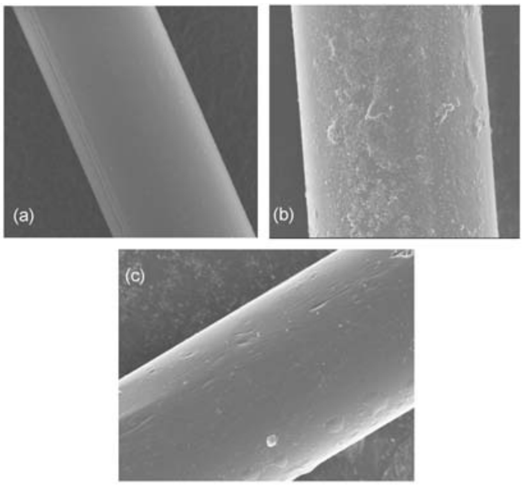

Fig.9 SEM images of polyester fiber, (a) Untreated, (b) Surface sediment after plasma treatment, (c) Surface etching effect after treatment

3.3 Two kinds of electrode structure for generating large-area glow plasma

In order to treat many polyester threads simultaneously and improve the processing efficiency, multi-row line-line and double helix line-line contact electrodes were designed according to the discharge characteristics of the line-line contact electrodes described above. Thus, large-area APGD plasma could be generated. The line-line electrode structure was modified to form the multi-row line-line contact electrode structure by increasing the number of electrodes and discharge area to form a large flat area of discharge. The line-line electrode structure was modified to form the double helix line-line contact electrode structure by increasing the length of two electrodes and arranging them in a spiral shape forming a large curved area of surface discharge. The dielectric material was PTFE with a thickness of 0.25 mm, and the diameter of the electrode was 1.5 mm. The total length of both wires in the two electrodes was 1080 mm. The discharge under an applied voltage of 4 kV is illustrated in Fig. 10. Both electrodes formed even, large-area glow plasma.

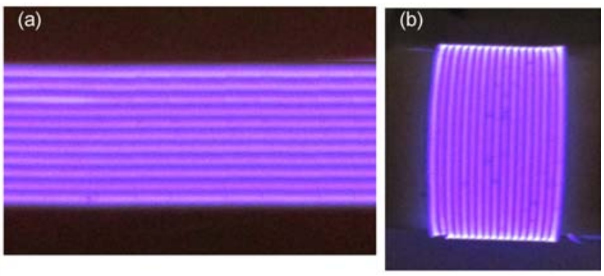

Fig.10 Diagram of discharge phenomenon, (a) Multi-row line-line electrode, (b) Double helix line-line electrode

The waveforms of the discharge voltage and current of the two electrode structures under an applied voltage of 4 kV are shown in Fig. 11. The electrode structure that occupied a large area had a higher capacitance than the single-front electrodes. This capacitance can be equivalent to that of a large number of capacitors and resistors in parallel. The discharge current waveform demonstrated a high displacement current owing to the capacitor and conduction current. The capacitive current fluctuated, whereas the pulse discharge current exhibited transient changes. The discharge current waveforms of the two types of surface discharge were similar.

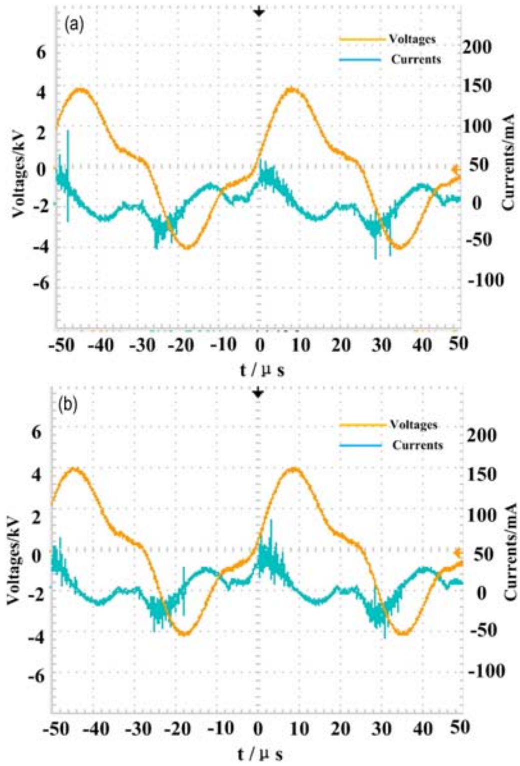

Fig.11 Waveforms of discharge voltage and current, (a) Multi-row line-line electrode, (b) Double helix line-line electrode

To calculate the discharge power of the two electrodes, the capacitance C in a series with the circuit loop was measured. Lissajous figures were produced by the U-Q method [15]. The Lissajous figures of the two electrodes at 4 kV are shown in Fig. 12.

The discharge powers calculated by using the Lissajous figures of the multi-row line-line and double helix line-line contact electrodes were 0.424 W and 0.328 W, respectively. The multi-row line-line electrode and double helix line-line electrode can both be arranged in double layers to treat multiple polyesters at the same time. The large area glow discharge plasma generated by these two electrode structures can be used to modify the surface of the polyester material in order to improve the processing efficiency and in other applications.

4 Conclusion

This study proposed contact DBD electrodes. The discharge characteristics and electric field distribution

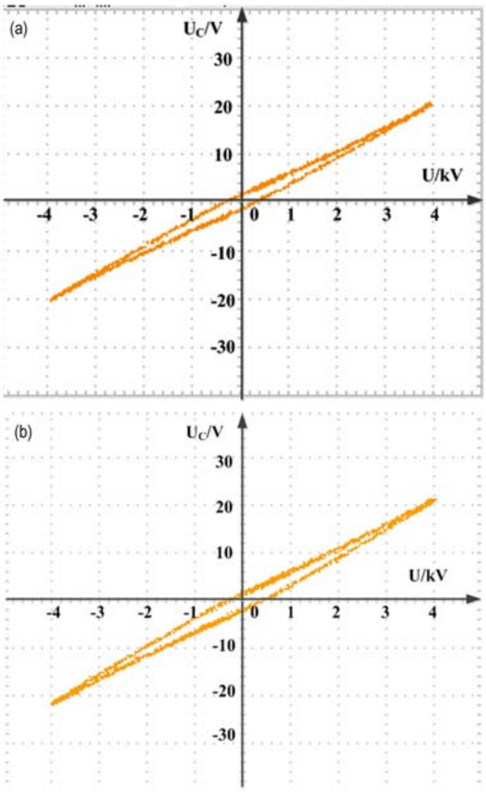

Fig.12 Lissajous figures, (a) Multi-row line-line electrode, (b) Double helix line-line electrode

of the electrodes under different conditions were studied. The surface of the polyester was modified by the designed electrodes. The following conclusions can be drawn:

a. This study proposed a special line-line contact electrode structure. A wide range of APGDs was generated using this electrode, which can form a region with a strong electric field to provide the initial electrons for the whole discharge area and reduce the initial discharge voltage.

b. The polyester was treated by the double layer line-line contact electrodes. The APGD can be generated on the surface of the polyester directly. The SEM images show that the polyester surface can be modified effectively by the glow discharge plasma generated along the surface of the material.

c. In order to treat many polyester threads at the same time and improve the processing efficiency, we proposed a multi-row line-line contact electrode structure, which can form a large flat area of discharge, and double helix line-line contact electrode structure, which can form a large curved area of surface discharge. These two kinds of electrode structures have potentially wide applications.

References

1 Zhang Chunming, Fang Kuanjun. 2009, Surface & Coatings Technology, 203: 2058
2 Mráček A, Lehocký M, Smolka P, et al. 2010, Fibers & Polymers, 11: 1106
3 Wang Chunying, Wang Chaoxia. 2010, Fibers & Polymers, 11: 223
4 Liu Wenzheng, Jia Lingyun, Yan Wei, et al. 2011, Current Applied Physics, 11: 117
5 Li B, Chen Q, and Liu Z W. 2010, Apply Physics Letter, 96: 04150
6 Chiper A S, Rusu B G, Nastuta A V, et al. 2009, IEEE Transaction on Plasma Science, 37: 2098
7 Shi J J, Liu D W, Kong M G. 2006, Apply Physics Letter, 89: 081502
8 Shi J J, Liu D W, Kong M G. 2007, IEEE Transactions on Plasma Science, 35: 137
9 Liu Wenzheng, Sun Guangliang, Li Chuanhui. 2014, Physics of Plasmas, 21: 043514
10 Wei Q F, Gao W D, Hou D Y, et al. 2005, Apply Surface Science, 245: 16
11 Krump H, Hudec I, Luyt A. 2005, International Journal of Adhesion & Adhesives, 25: 269
12 Sun D, Stylios G K. 2006, Journal of Materials Processing Technology, 173: 172
13 Raffaele-Addamo A, Selli E, Barni R, et al. 2006, Applied Surface Science, 252: 2265
14 Simora M, Rahel J, Cerna M. 2003, Surface & Coatings Technology, 172: 1
15 Marcin Holub. 2012, International Journal of Applied Electromagnetics and Mechanics, 39: 81

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