Fibers and Polymers 2007, Vol.8, No.6, 629-634

Evaluating Antistatic Performance of Plasma-treated Polyester

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(Received August 22, 2007; Revised November 7, 2007; Accepted November 27, 2007)

Abstract: Use of low temperature plasma treatment has been attempted in the textile industry and there the has been some success in the dyeing and finishing processes. In this paper, an attempt was made to apply low temperature plasma treatment to improve the antistatic property of polyester fabric. The polyester fabrics were treated under different conditions with low temperature plasma. An orthogonal array testing strategy was employed for obtaining the optimum treatment condition. After low temperature plasma treatment, the polyester fabrics were evaluated with different characterization methods. Under the observation of scanning electron microscope, the surface structure of the polyester fabric treated by low temperature plasma was found to be seriously altered which provided more capacity for polyester to capture moisture and hence increased the static charges dissipation. The relationship between moisture content and half-life decay time for static charges was studied and the results showed that the increase in moisture content would result in shortening of the time for static charges dissipation. Moreover, the antistatic property of the low temperature plasma treated polyester fabric was greatly improved. In addition, the antistatic property of the polyester fabric treated by low temperature plasma was compared with that of the polyester fabric treated with a commercial antistatic finishing agent.

Keywords: Low temperature plasma, Polyester, Antistatic, Moisture content

Introduction

Static is non-movable, and generated static charges are not able to be removed and it is localized on the surface of the materials [1-3]. For conductive material, e.g. metal, the charges may be conducted to some places else and leak in the air. For textile material, the textile fibres are non-conductive in nature, and generated static charges would stay on the surface for a long time and hence create serious static problem [4,5]. The static problem is commonly found in synthetic fibre, especially polyester fabric, and is significant in dry and low humidity condition [6,7]. Static charges is generated by motion, such as rubbing fabric, walking on a carpet, sitting down, etc. During this movement, the fabric surfaces contact with each other, and positive charges are generated on one surface and negative charges on the other surface. The generated and accumulated charges will stay on the fabric and make the human body uncomfortable. The dust suspended in air always adheres to static charged fabrics and causes stain problems. Static charges may generate sparks and cause fire explosion in some cases [5].

Generally speaking, natural fibres have little static problem than synthetic fibre. There are some evidences to show that natural fibres have a higher degree of amorphorous region than synthetic fibre, which greatly increases the charge dissipation in air. For polyester, it has small amorphous region and high degree of crystalline region, and thus its moisture regain is small. Therefore, polyester has the most significant static problem. There are two basic methods for eliminating or solving the static problem. One method is to inhibit the charge generation on the fabric, and this can be done by coating a conductive polymer or layer on the textile surface [8]. On the contrary, the other method is to increase the rate of static charges dissipation in air. In this paper, low temperature plasma treatment is employed for modifying the surface of the polyester fabric [6,7] as it is the most popular textile materials for daily use, e.g. sport wear, and hence to improve the moisture content properties of the polyester fabric in order to increase the rate of static charge dissipation in air [9-11].

Therefore, the aims of this paper were to study the effect of low temperature plasma treatment on the static property of polyester fabric and also to find out the optimum treatment condition for obtaining the best antistatic property. In addition, the comparison of the antistatic properties was made between the polyester fabric treated by low temperature plasma and the one treated with a commercial antistatic finishing agent.

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Experimental

Preparation of Materials

100 % white polyester plain weave fabric of 77 g/m^2 with 49 ends/cm (8.4 tex) and 38 picks/cm (8.7 tex) was used. The fabric was washed with 2 % non-ionic detergent at pH 7 and 40 ^{o}C for 20 minutes, and then rinsed with deionised water for about 5 minutes so as to remove any oil or impurities that might be scattered on the fabric surface randomly during the manufacturing processes. The clean fabric samples were conditioned under standard condition of 65±2 % relatively humidity and 21±1 ^{o}C for at least 24 hours prior to all experiments.

Parameters for Optimising Low Temperature Plasma Treatment

Low temperature plasma treatment was conducted using a glow discharge generator (Showa Manufacturing Co., Ltd.,

Table 1. Parameters and levels used in OATS

Level	Parameters		
	Discharge power (W)	System pressure (Pa)	Treatment duration (min)
I	200	100	3
II	100	50	2
III	50	25	1

Table 2. Experimental arrangement

Test run	Parameters		
	Discharge power (W)	System pressure (Pa)	Treatment duration (min)
1	I	I	I
2	I	II	II
3	I	III	III
4	II	I	II
5	II	II	III
6	II	III	I
7	III	I	III
8	III	II	I
9	III	III	II

Japan), which is a radio-frequency (13.56 kHz) etching system using oxygen as the plasma gas. In order to achieve the most excellent effect of low temperature plasma on the antistatic property of the polyester fabrics, the optimisation of antistatic property by low temperature plasma treatment was investigated. An orthogonal array testing strategy (OATS) technique was applied to analyse the optimum treatment condition [12-14]. Three variables in the low temperature plasma treatment, i.e. discharge power, system pressure and treatment duration, were used and the experimental arrangements were shown in Tables 1 and 2 respectively. After low temperature plasma treatment, the fabric samples were conditioned under standard condition with relatively humidity of 65±2 % and 21±1 °C for at least 24 hours prior to further evaluation.

Antistatic Property

The antistatic property of the fabric samples in both warp and weft directions was determined using resistance measurement by means of a STATIC voltmeter R-1020 (Rotchschild, Swiss). The fabric samples were first charged-up and then the elapsing time was measured. The elapsing time, termed as half-life decay time, is the time required for discharging half of the charge present in the fabric samples as accumulated during the charging-up process. The shorter the half-life decay time is, the better the antistatic property will be.

Moisture Content

The moisture content of the fabric sample was determined in accordance with ASTM D2654.

Antistatic Finishing

A commercial antistatic finishing agent, which is a hydrophilic polymer with hydroxyl-functional polysiloxane, was used for treating polyester fabric for comparison purpose. 20 g/*l* commercial antistatic finishing agent was prepared and was padded onto the fabric using a padding machine (Labortex Co. Ltd., Taiwan) with a pressure of 2.6 kg/m^2 and padding speed of 2.5 rpm to give a wet pick-up of 80 %. The padded polyester fabric was completely dried in an oven at 80 °C and then cured at 170 °C for 30 seconds. The treated fabric was conditioned under standard condition of 65±2 % relatively humidity and 21±1 °C for at least 24 hours prior further evaluation.

Scanning Electron Microscopy (SEM)

The surface morphology of the fabric samples was investigated by the Scanning Electron Microscope-Leica Stereoscan 440 (Leica Cambridge, England).

X-ray Photoelectron Spectroscopy (XPS) Analysis

The surface chemical composition of polyester fabric were analysed by XPS. The XPS spectra were obtained on a Perkin Elmer PHI 5600 spectrophotometer combined with an Al Kα X-rays emitter operated at 1486.6 eV, 350 W and working pressure of 7.3×10^{-9} torr. The peak positions were corrected for charging relation to hydrocarbon intensities of C_{1s} (285.0 eV) and O_{1s} (533.0 eV) were also measured.

Results and Discussion

Optimum Condition Analysis

Measurement of the half-life decay time is the most direct and simplest method to assess the antistatic property of the polyester fabric samples. The shorter the half-life decay time is, the better the antistatic property will be. Table 3 shows the half-life decay time (expressed in second) obtained from the nine trials generated by the OATS technique. Based on the measurement, it is noted that the values of half-life decay time in both warp and weft directions of the fabric were nearly same. Therefore, the values shown in Table 3 were the averaged half-life decay time values of the warp and weft directions.

From Table 3, it is observed that all the three operation parameters of low temperature plasma treatment, i.e. discharge power, system pressure and treatment duration, resulted in different effects on the half-life decay time of the low temperature plasma treated polyester fabric. The order of importance of these parameters is discharge power, treatment duration and system pressure. On the whole, the optimum condition for improving the antistatic property of polyester fabric by low temperature plasma treatment is developed. By calculating the results obtained from the nine trials, the optimum condition acquired for the low temperature plasma treatment for improving antistatic property is: discharge

Table 3. Orthogonal table for optimising the low temperature plasma treatment for improving antistatic property of polyester fabric

Test run	Parameters			Half-life decay time (sec)
	Discharge power (W)	System pressure (Pa)	Treatment duration (min)	
1	I	I	I	354
2	I	II	II	334
3	I	III	III	320
4	II	I	II	408
5	II	II	III	465
6	II	III	I	322
7	III	I	III	502
8	III	II	I	381
9	III	III	II	406

Σ Change in half-life decay time (sec)	Parameters		
	Discharge power (W)	System pressure (Pa)	Treatment duration (min)
ΣI	**1008**	1264	**1057**
ΣII	1195	1180	1148
ΣIII	1289	**1048**	1287
Difference	*281*	*216*	*230*

Figure in **Bold** exhibits the smallest value among all the values shown in the levels of different factors used while the *Italic* shows the level of importance of each factor.

power=200 W, system pressure=25 Pa and treatment duration= 3 minutes. This optimum condition was then used for treating the polyester fabric for further evaluation.

The effect of discharge power of low temperature plasma treatment on the antistatic property of polyester fabric is shown in Figure 1. Figure 1 shows that when the discharge power increased, the half-life decay time decreased accordingly which means that a better antistatic property is achieved. When the discharge power increased, the plasma gas could obtain more energy for ionisation and could be ionised more easily. As a result, the concentration of active species would

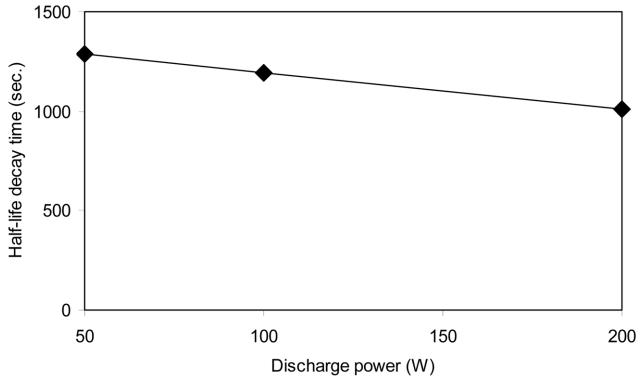

Figure 1. Effect of discharge power of low temperature plasma treatment on the antistatic property of polyester fabric.

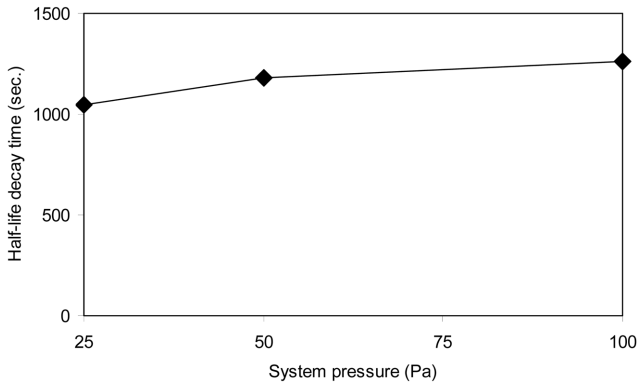

Figure 2. Effect of system pressure of low temperature plasma treatment on the antistatic property of polyester fabric.

be increased. On the other hand, the speed of the electron under a strong electric field would be accelerated, resulting in increment of kinetic energy of the electron. Both factors added together would greatly increase the action of the plasma on the fibre surface. The surface action would cause the introduction of surface roughness and oxygen polar functional groups in the polyester fabric which may increase the static dissipation [15,16].

The effect of system pressure of low temperature plasma treatment on the antistatic property of polyester fabric is shown in Figure 2. When the system pressure decreased, the half-life decay time increased accordingly which means that the antistatic property was adversely affected. When the system pressure is low, the number of collisions between the plasma species and other reactive species would be reduced. As a result the kinetic energy lost during collisions would be less and the species could carry a relatively high kinetic energy when interacting with the surface. This interaction would result in the modification of the polyester fibre surface and hence affect the physical and chemical compositions of the polyester fibre surface.

The effect of treatment duration pressure of low temperature plasma treatment on the antistatic property of polyester fabric is shown in Figure 3. When the treatment duration

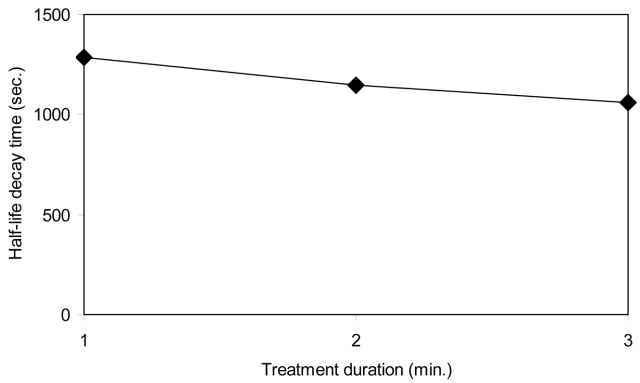

Figure 3. Effect of treatment duration of low temperature plasma treatment on the antistatic property of polyester fabric.

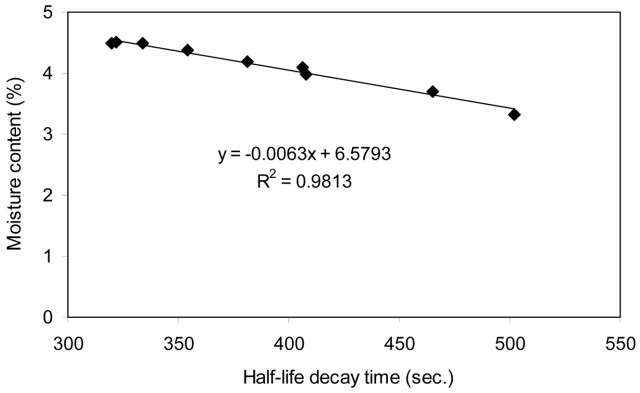

Figure 4. Relationship between half-life decay time and moisture content.

increased, the half-life decay time decreased accordingly which means that the antistatic property is improved with a longer treatment duration. When longer treatment duration is used, more interaction would occur between the fibre surface and the plasma species. As a result, the alteration on the fibre surface would become more significant.

Relationship between Half-life Decay Time and Moisture Content

Figure 4 shows the relationship between the half-life decay time and moisture content. A good statistical relationship of R^2=0.9813 was obtained. The increased in moisture content of polyester fabrics would reduce the half-life decay time, i.e. improved antistatic property of polyester fabric with statistical significance. As moisture contains water which is polar in nature, the conductivity of the water molecules is better than the polyester fabric, and therefore the localised static charge on the polyester fabric surface would leak away and thus static charges would be dissipated more easily. Also the moisture film formed on the polyester fabric surface may evaporate in air and at the same time sufficient amount of static charges were carried away from the surface and leaked into air. Therefore, the static charges were dissipated into the air, and the amount of static charges on the polyester fabric would thus be decreased. As the moisture content was inversely proportional to the half-life decay time of the polyester fabrics, therefore, the mechanism of the low temperature plasma treatment for improving the antistatic property of polyester is to increase the moisture regain of the polyester fabric and hence decrease the half-life decay time of the polyester fabrics.

Scanning Electron Microscopy (SEM)

SEM images were observed to comprehend the alteration of surface morphology of the polyester fabrics. The fibre surfaces of original polyester fabric, low temperature plasma treated and commercial antistatic finishing agent treated polyester fabric surfaces are shown in Figures 5, 6, and 7, respectively with a magnification of 30,000.

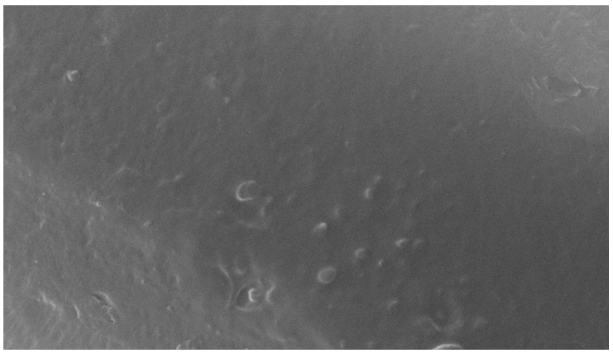

Figure 5. Scanning electron micrograph of original polyester fibre (×30,000).

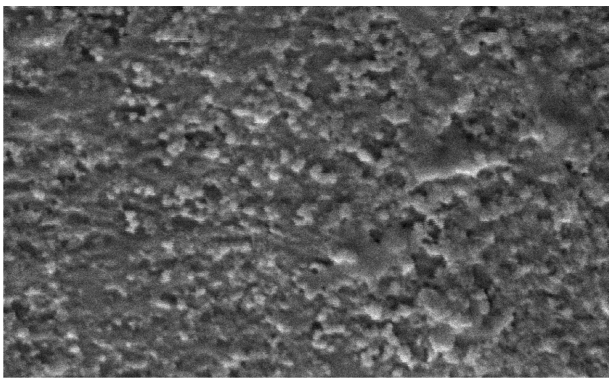

Figure 6. Scanning electron micrograph of low temperature plasma treated polyester fibre (×30,000).

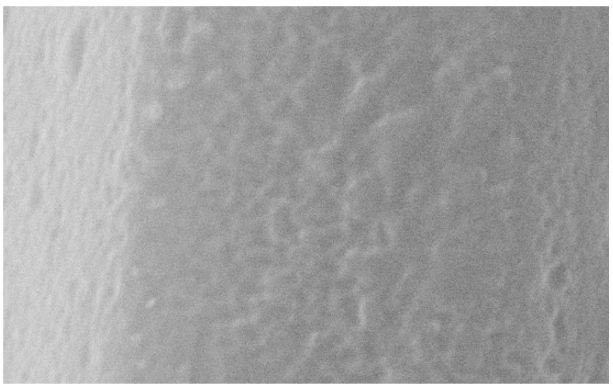

Figure 7. Scanning electron micrograph of commercial antistatic finishing agent treated polyester fibre (×30,000).

Figure 5 demonstrates the SEM image of untreated polyester fibre, while Figure 6 displays the SEM image of low temperature plasma treated polyester fibre. Figure 5 clearly demonstrates that the untreated polyester fibre surface is smooth and free from roughness indicating that no damage occurs on the fibres surface. This smooth outer surface of polyester will not enhance the absorption of moisture and hence the moisture regain of the polyester fabric was generally very poor. However, in Figure 6 the SEM image of

Table 4. Elemental composition (wt%) of polyester surfaces determined by XPS measurement

Polyester sample	Elemental composition (%)		O/C ratio
	O	C	
Without low temperature plasma treatment	22.7	77.3	0.29
With low temperature plasma treatment (under optimum condition)	36.6	63.4	0.58

Table 5. Comparison of half-life decay time and moisture content between differently treated polyester fabric

Sample	Half-life decay time (sec)	Moisture content (%)
Untreated	1675.5	1.009
Low temperature plasma treated (under optimum condition)	286	4.99
Antistatic agent finished	157.5	1.41

fabric sample treated with low temperature plasma illustrates a change in the fibre surface morphology with voids and pores. When compared Figure 6 with Figure 5, the low temperature plasma treatment imparted a significant alteration on the fibre surface due to its etching action on fibre surface causing surface roughness [11,15-17]. Hence, the rough surface can provide more capacities for capturing moisture in the air and subsequently moisture could be easily penetrated into the polyester fibre. Therefore, the moisture content of the polyester would increase, and improve the antistatic property of the polyester fabric. In the case of commercial antistatic finishing agent as shown in Figure 7, it is shown that the antistatic finishing agent was adhered on and well covered the fibre surface to perform its function. Therefore, based on the surface morphology of the differently treated polyester, it could be concluded that the low temperature plasma treatment and commercial antistatic finishing agent have different mechanism for improving the antistatic property of polyester fabric.

XPS Analysis

Table 4 shows the XPS elemental composition data for different polyester fabric surfaces. The evolutions of oxygen to carbon ratio, O/C ratio are also presented. The change in the O/C ratio relation to the untreated polyester fabric sample was used for studying the surface modification due to the low temperature plasma treatment. It is observed that the O/C ratio was increased after low temperature plasma treatment. The increment of the O/C ratio clearly shows that the surface has higher oxygen content than prior to low temperature plasma treatment because a large number of oxygen polar functional groups are introduced into the polyester fabric surface [10,11,17]. Thus the adhesion of moisture on the hydrophilic polyester fabric surface will be increased after the low temperature plasma treatment.

Antistatic Finishing

Table 5 shows a comparison of half-life decay time and moisture content between differently treated polyester fabric.

As shown in Table 5, the half-life decay time of polyester fabric after low temperature plasma treatment and antistatic finishing are greatly improved from average 1675.5 s to 286 s and 157.5 s, respectively. Therefore, a lesser static problem would occur in the differently treated polyester fabric. When taking the moisture content into consideration, the moisture content between the untreated polyester and the commercial antistatic agent finished polyester were not significantly different. However, this is not the case for the low temperature plasma treated polyester fabric as the moisture content is increased significantly. This means that the improved antistatic property on polyester fabric based on low temperature plasma treatment and antistatic finishing agent had a different antistatic mechanism.

The antistatic finishing agent used in this study was a hydrophilic polymer with hydroxyl-functional polysiloxane which will adhere to the polyester fabric surface, as shown in Figure 7, to increase fibre surface conductivity by forming an intermediate layer on the surface. This layer is typically hygroscopic with the presence of mobile ions which may lead to higher conductivity [8,18] and hence improves the static charges dissipation.

In the case of low temperature plasma treatment with oxygen, based on the experimental results, the surface wettability can alter the antistatic property of the polyester fabric. Surface wettability is directly related to surface energy, and more energetically stable surface results in less wettable surface. It is now established that low temperature plasma modification of the fibres results in oxidation and degradation (voids and pores formation) of the fibre surfaces. The oxidation creates oxidized functionalities, which lead to an increase in surface energy, while the degradation mainly changes surface morphology of the fibres [19,20]. SEM images have shown that low temperature plasma treatment causes the increase of surface roughness. According to Wenzel equation ($\cos\theta^{\text{qrouth}}=r\cos\theta_0$) [16], the roughness of the surfaces influences the contact angle [21, 22]. θ^{qrouth} is the contact angle on a surface of sample, θ_0 is the contact angle on the smooth surface, and r is the roughness (ratio of the actual area of the interface to the geometric surface area). When the surface having a contact angle smaller than 90°, increasing surface roughness probably reduces the contact angle and will contribute to the improved surface wettability. Water is a conductor of electricity. Therefore, the improved surface wettability will decrease the accumulation of electrostatic charges.

The increase of surface roughness also induces the increase in the specific surface area [23]. The increased specific surface area will lead to a more moisture-rich surface, which

enhances the conductivity of the fibres. The low temperature plasma treatment not only causes the increase in surface roughness but also introduces the hydrophilic groups onto the fibre surface. XPS analysis has shown that the oxygen content has been increased on the fibre surface after low temperature plasma treatment. Thus, there have the possibilities of introducing oxygen-containing polar groups such as -OH, -OOH and -COOH on the fibre surface after low temperature plasma treatment [23-25]. There are two possibilities of generating the polar groups: (i) generated by reacting with the ambient gas during the low temperature plasma treatment and (ii) generated when the polyester samples are exposed to air after low temperature plasma treatment, i.e. low temperature plasma treatment produces a considerable amount of unsaturated bonds and then the unsaturated bonds are reacted with atmospheric oxygen to form polar groups on the polyester fabric surface.

As low temperature plasma treatment increases the amount of oxygen-containing polar groups on the polyester fibre surface. These polar groups will incorporate with moisture through hydrogen bonding and help moisture penetration and binding on the fibre surface [16]. Under the action of water molecule, these polar groups will generate ionisation and lead to a structural layer of conducting electricity on the fibre surface, which enhances the electrostatic dissipation. Therefore, the half-life decay time of the fibres decreases after low temperature plasma treatment.

Conclusion

After the low temperature plasma treatment with oxygen, the half-life decay time of polyester fabric was greatly reduced. The optimum condition of the low temperature plasma treatment for improving the antistatic property of polyester fabric in this study was discharge power=200 W, system pressure=25 Pa and treatment duration=3 minutes. The findings showed that the discharge power and treatment duration had an inversely proportional relationship with the half-life decay time while the system pressure had a directly proportional relationship with the half-life decay time. The mechanism of the low temperature plasma treatment was to alter physical structure and chemical composition of the polyester surface and hence the surface would become more opened. Thus the specific surface area would be increased for capturing moisture from air and subsequently increased the dissipation of the accumulated static charges.

A comparison on antistatic property of low temperature plasma treated polyester fabric and commercial antistatic finishing agent treated polyester fabric was made. Both treated fabrics had an improved antistatic property but they got different values in the moisture content. The difference implied that the mechanism of antistatic for the antistatic finishing agent and low temperature plasma treatment on the polyester fabric was not the same.

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