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The Role of Fiber Charging on Co-electrospinning and the Resident Life of the Residual Charges from the Electrospinning Process

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Introduction

Electrospinning (ES) is a process that makes nanofibers with the diameter in the range of 10 nm to 10 μm from polymer solution or melt by electrostatic force. More than 50 polymer types have been electrospun and the results have been elucidated [1]. Electrospun nylon [2] and polycarbonate [3] have been applied for making filter media. It has been shown by Tsai, et al [4] that there is a superiority of filter efficiency (FE) of ES media over other fibrous materials, such as spunbond, meltblown and needle-punched media. Schreuder-Gibson, et al. [5] have characterized a series of melt blown fabrics used in combination with ES layers for protective clothing. It has also been reported [6] that the ES fibers carry residual charges in the fibers from some polymer resins. This paper presents the effect of charges in the fibers from single or multiple nozzles with and without ionizing conditioning for stationary and rotating collectors on the fiber stream, on the fiber formation, and on the retention life of the residual charges.

Experimental

Different types of polymers, polyethyelene oxide (PEO), Estane ® thermoplastic polyurethane (PU), Nylon (PA), polycarbonate (PC), polycaprolactone (PCL), polyacrylonitrile (PAN) and polystyrene (PS), with polar and non-polar properties were investigated in this study. Power supplies (manufactured by SIMCO ®) of positive and negative polarities with 50 kV and 2 mA were employed as the voltage source for the ES process. A SIMCO ® ionizing blower was applied to neutralize the charges in the fibers between the nozzle and the collector.

A microsyringe pump from the Orion Company was used to control the throughput of the polymer solution. Stationary plates (18 x 24 inches) and rotating drum of 12 inch diameter and 26 inch width were used as fiber collectors. A capacitive probe with aperture of 0.07 inch attached on a scanning table was interfaced with an A/D board as shown in Figure 1 to measure the surface charge potential of the ES fabric. Syringe and needle were used as the ES nozzle. The sketch of an ES is shown in Figure 2. An aerosol generator and detector, the TSI 8130 was used to measure NaCl filtration efficiency (FE) of the ES fabrics. The NaCl particle had a number average diameter of 0.067 μm with geometric standard deviation (GSD) of 1.6. The filtration velocity was 5.3 cm/s.

Results

Non-polar polymers, PS, PC and PAN, retained the residual charges after ES as shown in Figure 3 through a period of time. However, the charges diminished with time. The polarity of the residual charges was determined by that of the applied voltage, i.e., positive voltage generated positive residual charges and vice versa.

The residual charges in the polar polymers, Nylon 6 and 66, PU, PEO, and PCL, were near zero as shown in Figure 4. This indicates that polar materials have a higher degree of moisture content and become more conductive, resulting in lower long-term residual electrostatic charge. This fact agrees with our previous research on the charge retention life on different types of polymers by corona charging [7]. However, the polar polymers held charges right after the fibers are formed between the spinning nozzle and the collector. This evidence is shown in Figure 5 where nylon fibers from a single nozzle are spread out to cover an area around 24 x 24 inches in the collector with a distance of 9 inches between the nozzle and the collector (DNC). Shown in Figure 6 are two zones of nylon fibers from two spinning nozzles separated at by a gap of 1 and 5/8 inches for the same DNC as in Figure 5. Nylon fibers spread out to cover a larger area in the collector than other polymer fibers. For example, PU, as shown in Figure 7, with fiber diameter of 656 nm as shown in Figure 8 of SEM photomicrograph, has less spread. Nylon is more spread out over the collection area, and nylon fibers also have a much smaller fiber diameter of 78 nm as shown in the SEM photomicrograph in Figure 9. The smaller fiber diameter held higher charge density; therefore, they produced stronger repelling forces.

If the rotating collector is used, DNC can be reduced, e.g., from 9 inches to 4 inches on a stationary collector, without the problem of inter-fiber fusion because the fibers dry rapidly by the rotation action of the collector. The fibers are spread across a smaller area in the collector at a shorter DNC (4 inches) as shown in Figure 10. The fabrics are uniform in the machine direction but three distinct collection stripes are formed from the three spinning nozzles by the fiber repelling force. When an ionizer is applied between the nozzles and the collector, the charges in the nylon fibers are neutralized to a certain extent. Therefore, the three stripes as shown in Figure 11 are more diffused and less distinct. However, it appears that the ionizer is not powerful or fast enough to thoroughly neutralize the charges in the fibers. The fiber spinning in the ES process may be distorted and collection may be more diffused if a more powerful ionizer is available and employed.

In this study, we confirmed previous experimental results showing that positive charge potential was measured on the residual charges of the PS fibers spun from positive nozzle [6]. When negative PS fibers from negative nozzle are spun upon the positive fibers, a net negative charge potential is measured. This bipolar material did not result in better charge retention life as shown in Figure 12 although one would expect better charge retention because the negative and positive charges in the material attract each other. It was also observed from the charge decay of the ionized PS that these charges behaved as unionized ones in terms of initial amount of charge and charge decay rate for both positive and negative charges as shown in Figure 12. However, the ionized PS fibers landed on a more concentrated area in the collector than un-ionized PS fibers as shown in Figure 13 and 14 for positive and negative polarities, respectively.

When two polarities of voltage are applied to two spinning nozzles, one polarity on one nozzle and the other polarity on the other, the charges arched over across the nozzles with a gap of 1 1/8 inch before the fibers were formed. If the nozzles were separated further apart, e.g., 2 ¼ inch, fibers could be formed before arching occurred but the fibers were attracted to each other to form ropes as shown in Figure 15.

When a positive voltage is applied to two nozzles of different polymer types, e.g., PC and PAN, the PC was distorted and formed a smaller area on the left while PAN was not noticeably affected and formed in a larger area on the right as shown in Figure 16. This is due to the fact that PAN had finer fibers of .24 μm than PC of 1.1 μm and therefore higher charge density. Therefore, the PAN fibers had stronger repelling force as observed in nylon fibers. Listed in Table 1 are the diameters of the fibers spun from different polymer types in this study, in which nylon had the smallest fiber size of about 0.07 μm and others had similar fiber size around 1 μm.

The filtration efficiency (FE) of positively charged PS was 42.1%, negatively charged was 31.7%, and negatively charged fibers spun upon positively charged fibers was 37.3%, for the same weight of the fabrics with a pressure drop of 0.3 mmH_2O. This behavior indicated that the NaCl carried negative charges because the positively charged fibers had higher FE than the negatively-charged fibers. These filtration results also indicate that the combined positive /negative fiber filter media has both positive and negative charges. Similar bipolar material generally has higher FE when challenged with neutral particles, but it was not the case for the NaCl particles.

Finally, microsize activated carbon particles can be embedded in the ES fibers as shown in Figure 17 for 6 μm carbon particles in 0.66 μm PU fibers. The appearance of the carbon-loaded fabric is shown in Figure 18, in which another layer of PU was sprayed on the carbon-loaded layer to secure the carbon particles in position.

Conclusions

Eight different polymer solutions were electrospun at both negative and positive polarity. Polar polymer fibers were found to have nearly zero residual charge after electrospinning. The non-polar fibers retained significant electrostatic charge, up to 1,000 volts in some cases, which diminished to 0-200 volts after 100 hours. Fiber collection from the electrospinning process was studied on a stationary, grounded collector and on a rotating drum. Polymers that produce fine fiber diameters, such as the nylons, exhibited a large diffuse spread of collection area, while larger fiber diameters produced from

polyurethanes resulted in smaller, more focused collection areas. The larger collection areas may be due to a higher charge density on the smaller diameter fibers, producing a stronger inter-fiber repelling force. Application of an ionizing condition on electrospinning PS focused fiber collection into a smaller area when spinning from either positive or negative polarity. Collection of the fibers on a rotating drum produced less inter-fiber fusion at shorter collection distances from the solution nozzle, and also resulted in smaller, tighter collection area (bands) of fiber. Application of an ionizer during electrospinning helped to widen the collection bands in the case of nylon fibers, but the strength of the ionizer was not sufficient to completely eliminate the collection banding on the rotating drum.

Non-polar polymers can be electrospun at opposite polarities: those produced by positive polarity retain a positive charge, and can be spun on top of a fiber mat produced by negative polarity. It was found that the positive fiber mats had the highest filtration efficiency against NaCl aerosol; the negative mats exhibited the lowest FE. A fiber mat containing positive fibers spun on top of a negative mat exhibited a mid-range FE, between the all-positive and all-negative fabrics against the charged NaCl aerosol challenge. Difficulties were observed when two different polymers were simultaneously electrospun, due to differences in surface charging of the fibers – high surface area fine fibers repelled each other more and "squeezed out" the larger electrospinning fibers into a tight collection area. Poor fiber mingling resulted. Physical embedment of carbon particulates into an electrospun polyurethane was achieved by commingling a stream of carbon particles with electrospinning PU to achieve an adsorbing filter fabric.

References

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3. Weghmann, A., "Production of Electrostatic Spun Synthetic Microfibre Nonwovens and Applications in Filtration," Proceedings of the 3rd World Filtration Congress, Filtration Society, London (1982).
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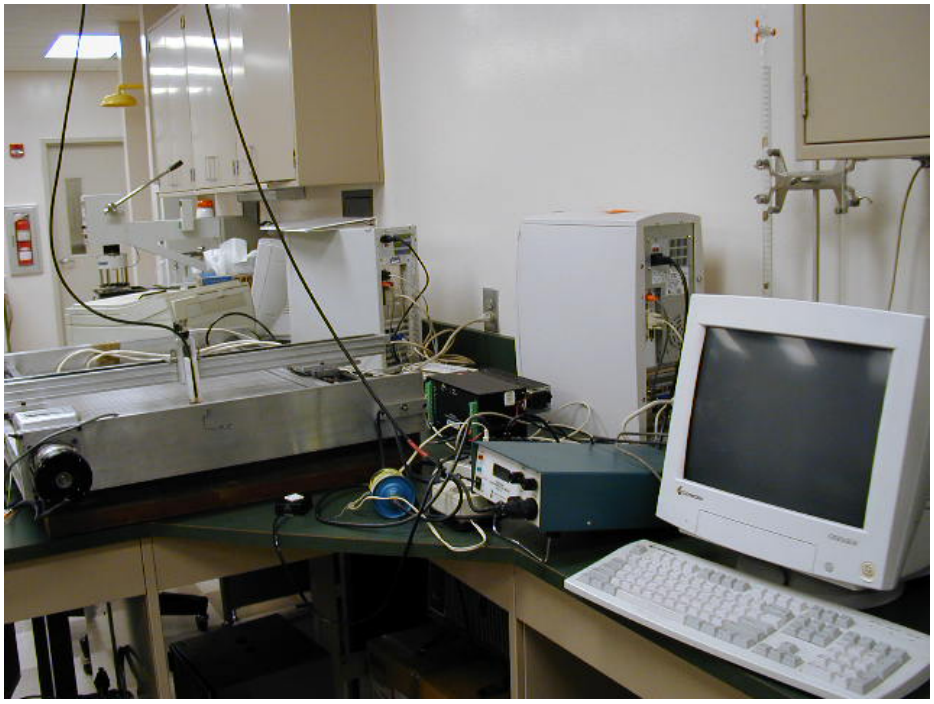


Figure 1. Photograph of surface charge potential measuring system.

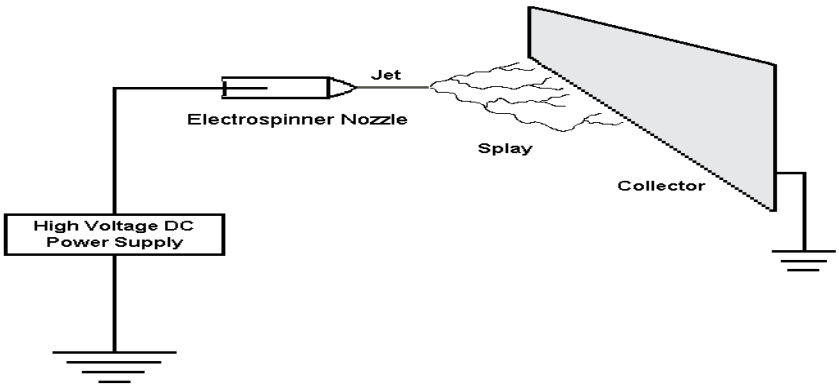


Figure 2. Sketch of ES process.

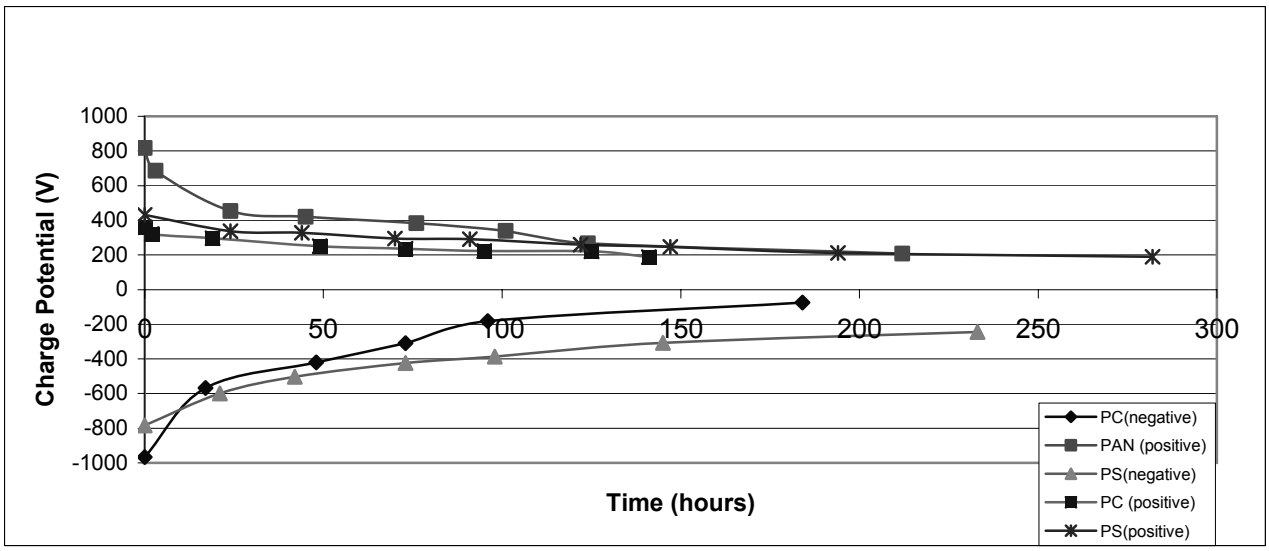


Figure 3. Resident life of residual charges on ES fibers of different polymers.

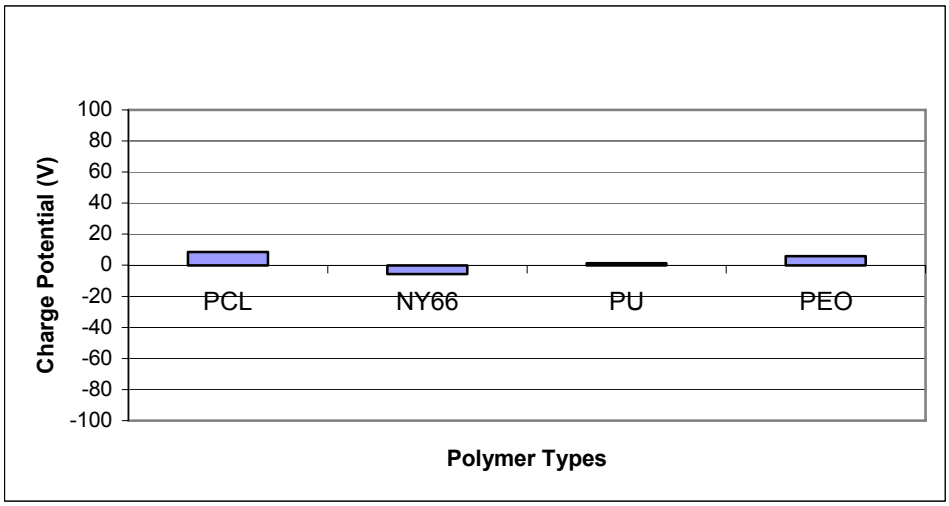


Figure 4. Charge potential of ES nonpolar polymers.

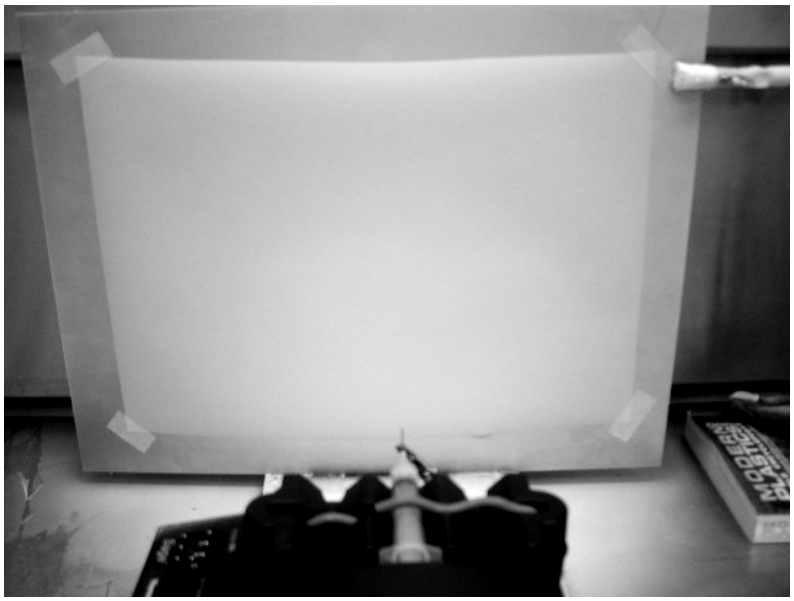


Figure 5. ES nylon system of single nozzle.

Figure 6. ES nylon system of twin nozzles.

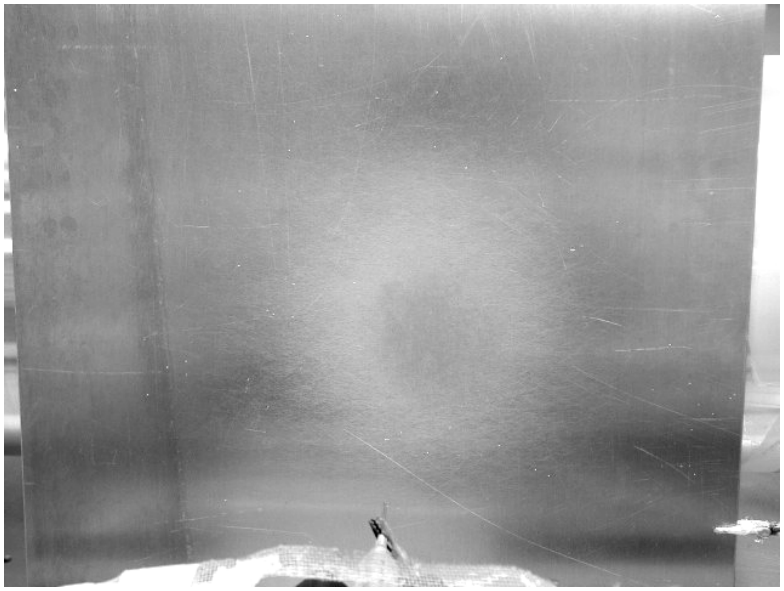


Figure 7. Small area formation of ES PU fabrics.

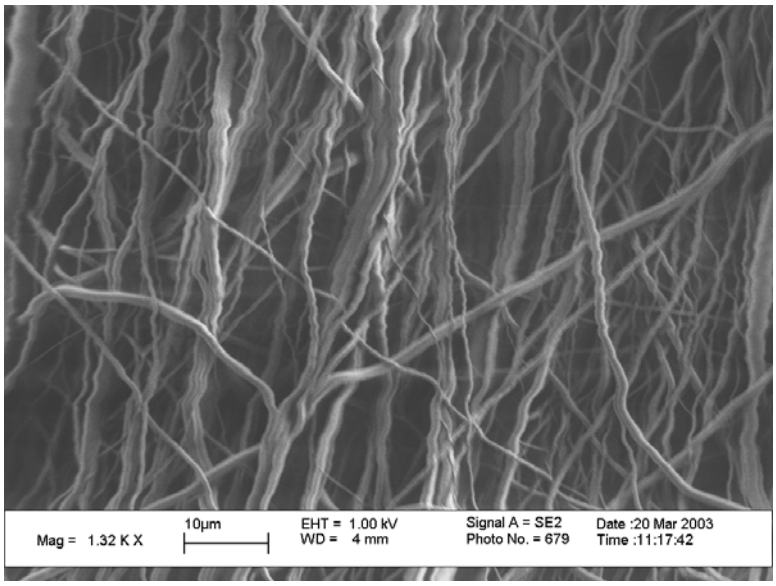


Figure 8. Photomicrograph of ES PU fibers.

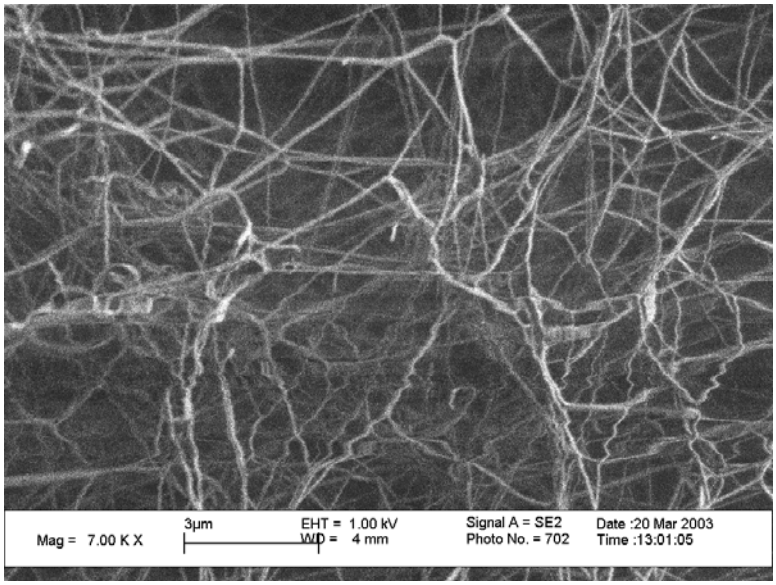


Figure 9. Photomicrograph of Nylon 66 fibers

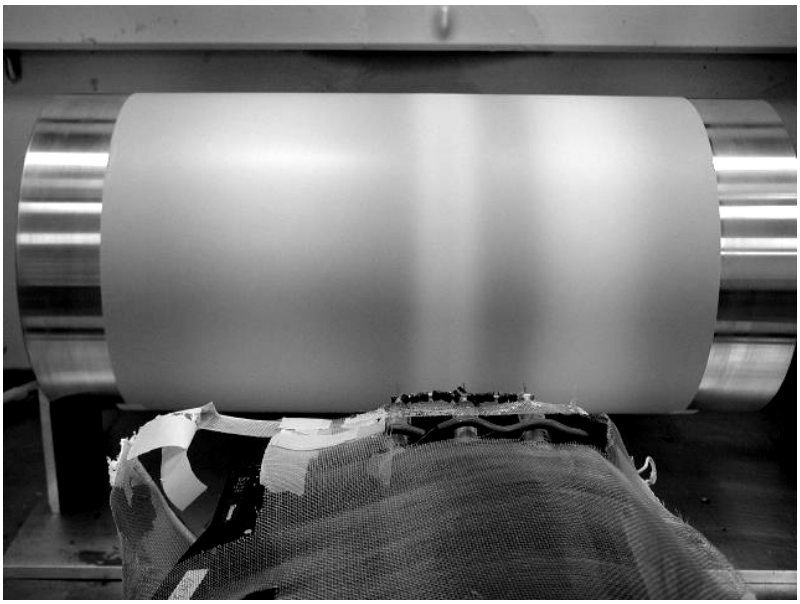
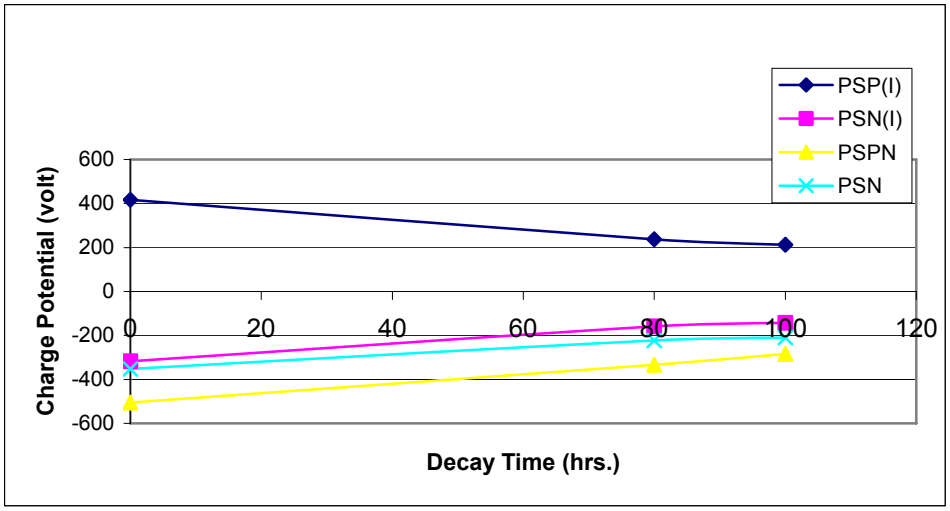


Figure 10. ES nylon system of triple nozzles without ionizer.

Figure 11. Three stripes are not apparent -- the uniformity of ES triple nozzle nylon fabrics improved by applying ionizer.



Note: PSP(I) - Positive PS with ionizer
PSN(I) - Negative PS with ionizer
PSPN - Negative PS on positive PS
PSN - Negative PS

Figure 12. Charge decay on PS fibers with and without ionizer.

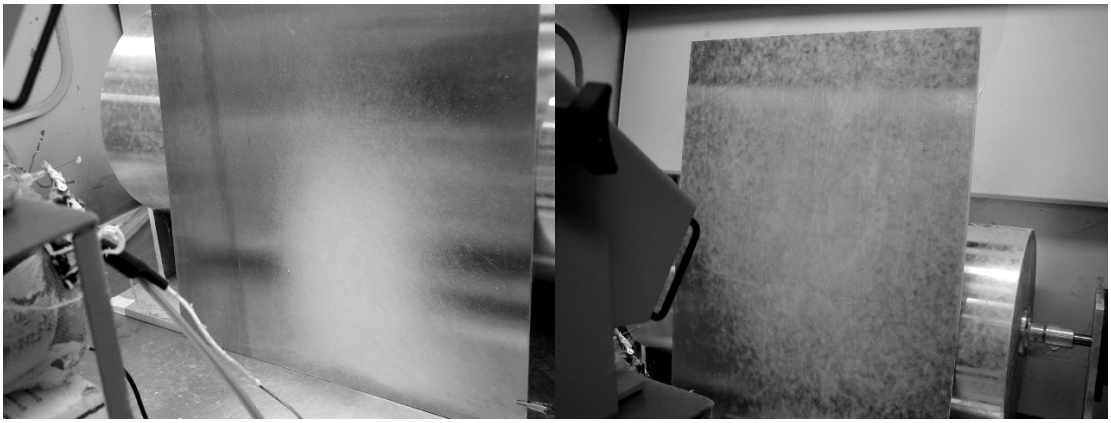


Figure 13. Different formation sizes of positive PS fabrics with (L) and without (R) ionizer.

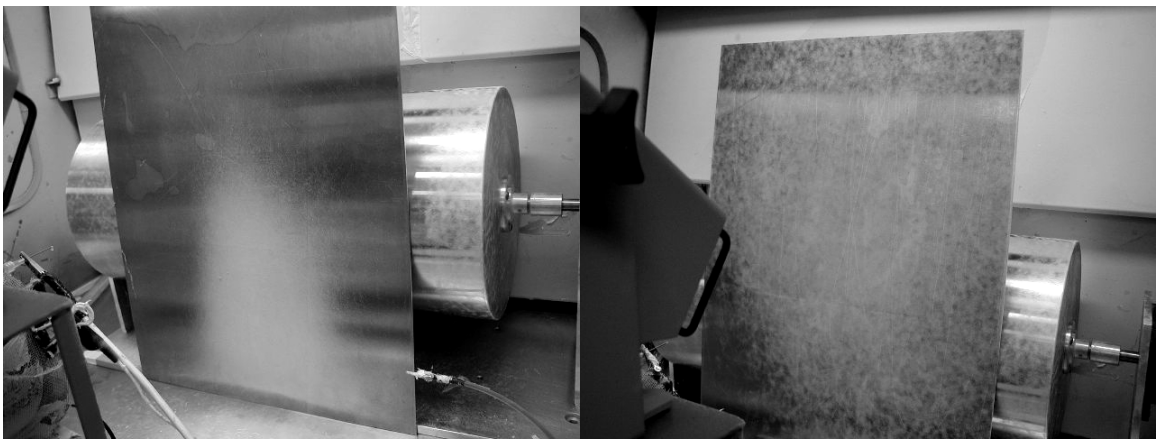


Figure 14. Different formation sizes of negative PS fabrics with (L) and without (R) ionizer.

Figure 15. Formation of ropes by applying opposite polarities on PAN(+) and PC(-) fibers.

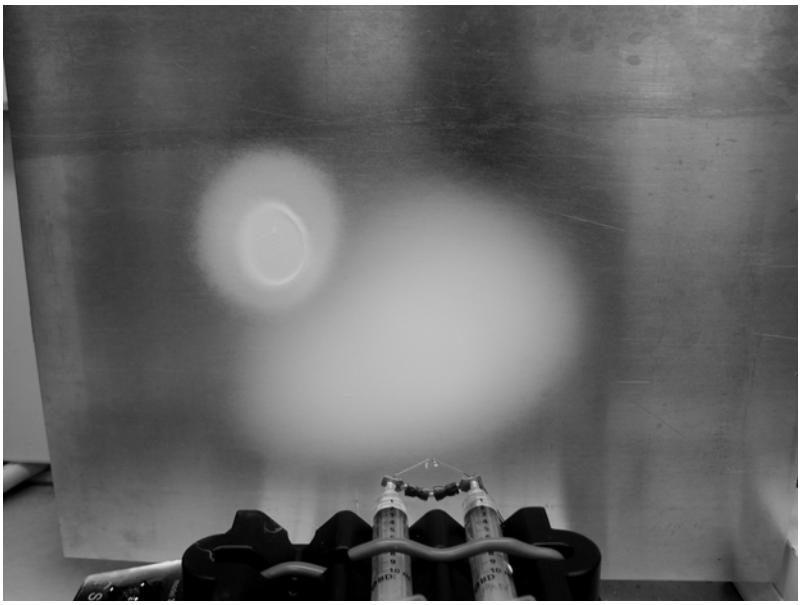


Figure 16. Distortion of PC (L) fibers by PAN (R) fibers.

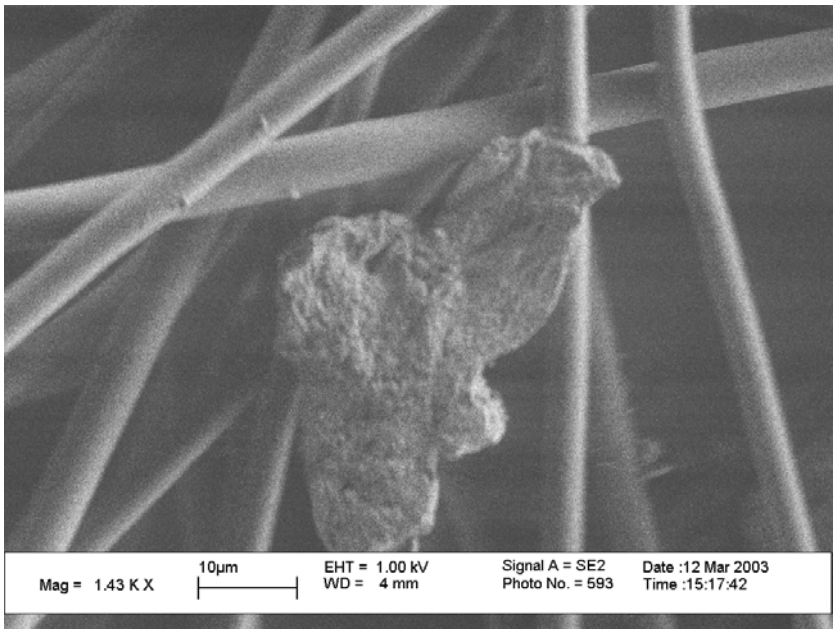


Figure 17. Photograph of carbon particles embedded in ES PU fibers.

Figure 18. Photograph of the carbon-loaded ES PU fabrics.

Table 1. ES and MB fiber diameter from different polymer types.

	Mean	***C.V.(%)***
ES PU	656 nm	61.71
MB PU	19 μm	27.69
ES Nylon6	68.1 nm	30.99
ES Nylon 66	77.9 nm	33.15
MB Nylon 6	6.76 μm	23.72
ES PAN	235 nm	53.81
ES PCL	1.77 μm	62.83
ES PC	1.08 μm	48.74