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Nanofiber deposition by electroblowing of PVA (polyvinyl alcohol)

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Abstract Electrospinning provides a relatively versatile method of creating a variety of ultrathin nanofibers. One of the well known problems in electrospinning is low productivity. To increase the inherently low productivity in electrospinning, an assembly of multi-needles has been widely introduced. This process may be enhanced by introducing the electroblowing process that combines air blowing and electrospinning. In this study, the effect of electroblowing on web deposition was explored via the simultaneous and separate application of two forces: an electrostatic force and an air blowing-induced shear force, which are adjusted by the applied voltage and the air blowing pressure, respectively. The image filtering technology was used to evaluate the web deposition. The application of the shear force significantly affected the web deposition, especially at low voltage.

Introduction

Electrospinning is a term used to describe a class of nanofiber forming processes by which electrostatic forces are employed to control the production of nanofibers. The electrospinning process was first demonstrated by Zeleny and patented by Formhals [1–3]. Electrospinning provides a relatively versatile method of creating a variety of ultrathin nanofibers. Nanofibers with some specific properties can be prepared if appropriate solution parameter or processing parameters are performed [4]. However, electrospinning generally has relatively low productivity compared to other spinning processes, because the polymer solution has to be fed at comparatively slow rates and only electrostatic forces are used to obtain the ultrathin fibers [5]. A unique blowing-assisted electrospinning process, that blows air around the spinneret, has been demonstrated recently for the fabrication of nanofibers [6, 7]. The combination of the air blowing-induced shear force and the electrostatic force is capable of overcoming the high surface tension of the polymer solution. The blowing air can accelerate the solvent evaporation process, a necessary condition for the fiber formation before the jet reaches the ground collector during the process. The deposition amount and the diameter distribution of the nano fibers, which are important factors to control the properties of the nanoweb, can be adjusted by the air blowing pressure and the applied voltage. It is therefore expected that many useful polymers, which previously could not be electrospun, can now be processed by using the new electroblowing process approach. Furthermore, the electroblowing process increases the production rate and will therefore increase the functionality of mass production plans.

In this study, the effect of the electroblowing process on the web deposition is explored by applying two forces (an electrostatic force and an air blowing-induced shear force) simultaneously and separately. The image filtering technology is used to evaluate the amount of electroblown polymers. The diameter distribution of the deposited

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nanofibers and the bead formation are investigated according to the location on the ground collector.

Experimental

In a typical synthesis, 6.0 g of poly (vinyl alcohol) (PVA, average molecular weight: 65000, hydrolysis: 85.5–86.5, Dongyang Chem., Korea) was added to 94.0 mL of distilled water under continuous stirring (MS3040, Tops, Korea) and heating (MSH-1, Changshin, Korea) until dissolution was indicated by the formation of a clear solution.

The air blowing system was attached to the electrospinning apparatus so that the modified apparatus could provide both an electrostatic force and a shear force for the fabrication of the nanofibers from a polymer solution (Fig. 1). The dual nozzle that functioned as an electrode in this experiment consisted of a sheath nozzle of 19G (ø 0.75 mm) and a core nozzle of 25G (ø 0.25 mm). The solution was fed into the inner nozzle. The blown air induced a pressure ranging from 0 to 0.5 kg_f/cm^2 and was blown into the outer nozzle by an oil-less compressor (Von-air, Fusin). The collecting plate that functioned as an opposite electrode was stainless steel. The distance between the spinneret and the ground collector was set at 15 cm. A DC power source that can generate 0–50 kV was used for electrospinning. To examine the effects of variations in the voltage and air pressure on the electroblowing process, the drop behavior and web deposition were observed by two charge-coupled device (CCD) cameras under given voltages with a long working distance lens to minimize the electric field distortion induced by the external conducting materials of the image capturing system. The ejected jets were deposited on the thin black paper on a ground collector for 5 min. The image of the deposited web was analyzed by filtering the gray scale light intensity with the criteria of low and high passes. The diameter distribution of the deposited nanofibers was analyzed by scanning electron microscopy (SEM).

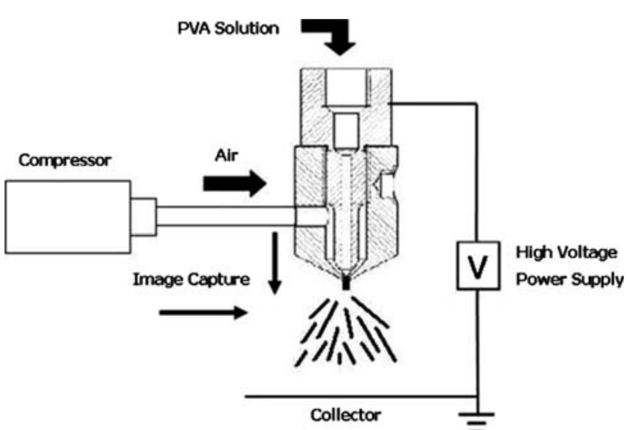

Fig. 1 Scheme diagram for electro-blowing setup used in this study

Results and discussion

Figure 2 shows the web deposition as a function of the air pressure and voltage. The ejected jet had been deposited on the thin black paper on the ground collector. The white image on the black background was formed from the diffused reflection of the deposited polymer.

The air blowing process without the electrostatic force produced only a few white spots, while the electroblowing process produced nanofibers. In the typical window of our experimental, the air blowing without the electrostatic force produced film-like spots on the ground collector, rather than a fibrous shape, as shown in Fig. 3a. A magnified image of the spots formed by the air blowing without the electrostatic force is shown in Fig. 3b. The spots are generally formed on a microscale with an irregular, film-like shape. The spots do not have enough specific surface area (surface area /volume) or reflecting angles to cause diffused reflection, compared to nanoscale fibers with round cross section. In addition to the geometrical features of the deposited polymer, the amount of the air blown polymer was relatively smaller than that of the electrospun polymer with air blowing. The polymer throughput was determined by the combination of the hydrostatic pressure, electrostatic force, and air blowing-induced shear force.

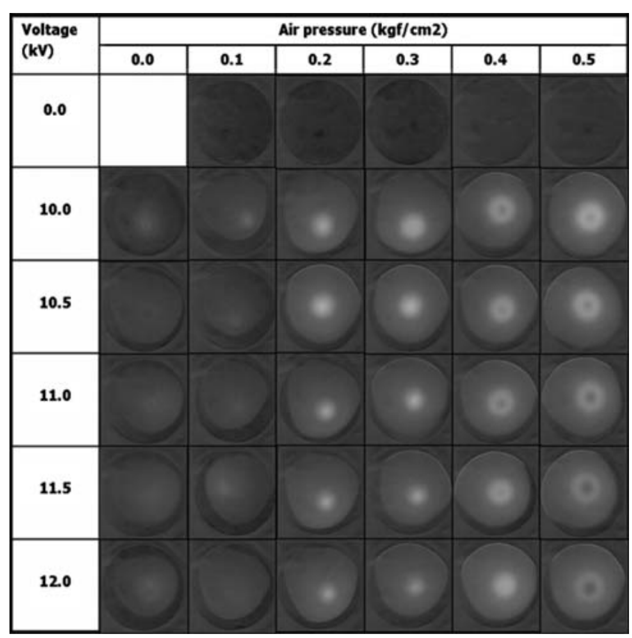

Fig. 2 Deposition patterns of electrospinning as a function of the air pressure and voltage

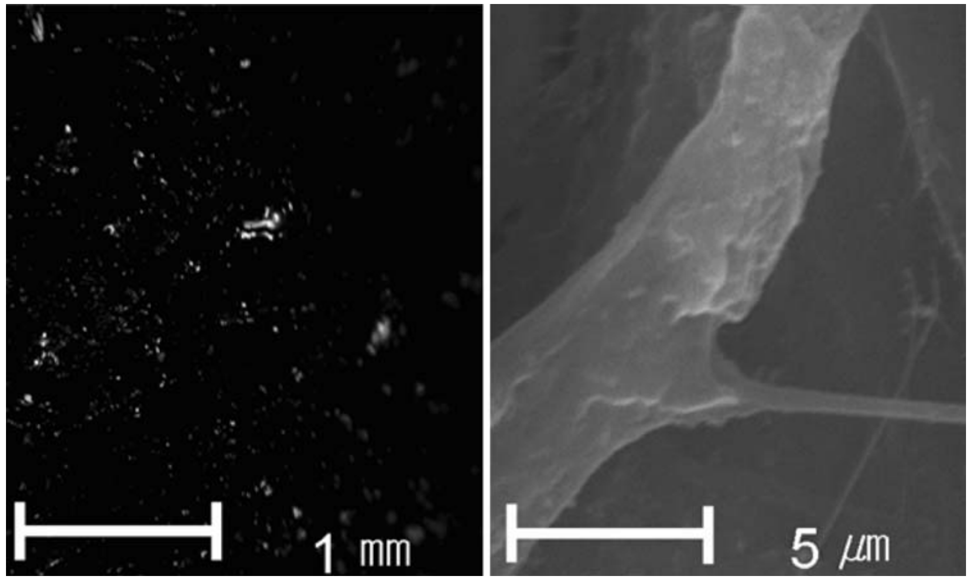

Fig. 3 SEM micrographs of air blown PVA at the air pressure of 0.5 kg/cm^2 without applying voltage

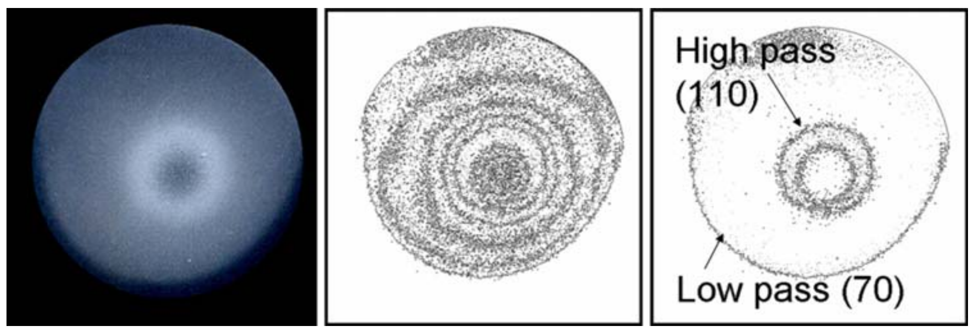

Fig. 4 Deposition pattern and its filtered images

The grayscale images were stored with 8 bits per sampled pixel, which allows 256 different grayscale intensities to be recorded. To evaluate the deposition amount, the gray scale light intensities of the image were filtered with the criteria of low (gray scale intensity 70) and high (gray scale intensity 110) passes, as shown in Fig. 4. The image filtered by the low pass represents the overall distribution, while the high pass is applied to evaluate the distribution in the middle. The deposition amount evaluated with the low pass criteria is not always proportional to the applied voltage, as shown in the Fig. 5. The deposition amounts at 11.5 and 12 kV were almost the same. Although the polymer throughput was increased with increasing applied voltage due to the strong electrical drawing force, this strong force may have caused the breakage of the drawn jet resulting in the intermittent electrospinning. Therefore, the deposition amount may have peaked before the highest voltage.

With increasing air blowing-induced shear force, in addition to the electrostatic force, the amount of the centered deposition at the lower voltage was larger than that at the higher voltage, as shown in Fig. 6. The increasing voltage without the air blowing decreased the drop volume, as shown in Fig. 7. The drop volume may have played a significant role in the electroblowing process.

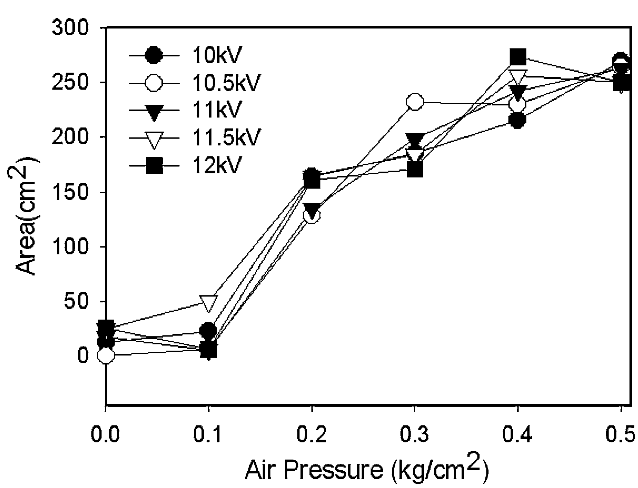

Fig. 5 Effect of the air pressure and voltage on the deposition amount (low pass 70)

The shear force between the drop surface and the air stream may have increased with increasing drop volume as depicted in Fig. 8. A higher shear force induced a greater

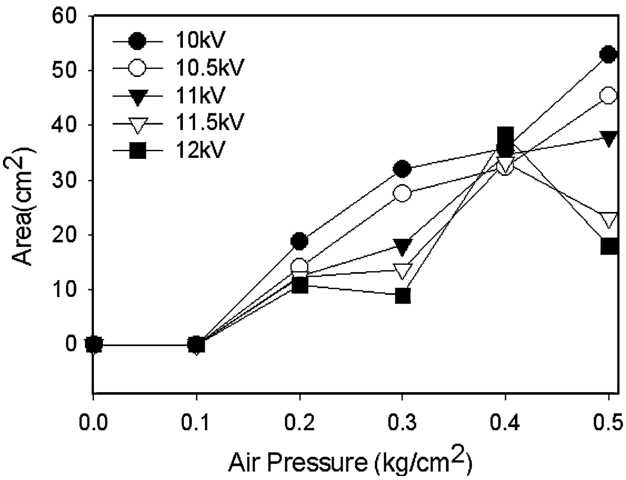

Fig. 6 Effect of the air pressure and voltage on the deposition amount (high pass 110)

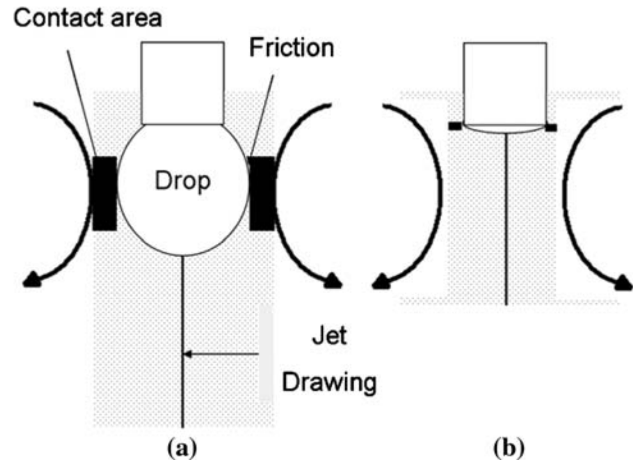

Fig. 8 Contact area between the air stream and jet stream at **a** the low voltage and **b** the high voltage

drawing effect in addition to the electrical drawing. Therefore, a greater air blowing effect was expected at the lower voltage. The maximum deposition by the electroblowing was determined by the combination of the shear and electrostatic forces.

The polymer deposition amount generally increased due to the increased shear force induced by the increasing air blowing pressure, as shown in Fig. 6. However, decreased depositions were observed at the highest air pressure at the high voltages of 11.5 kV and 12 kV, which was attributed to the intermittent electroblowing process caused by the aforementioned breakage of the drawn jet.

Three locations were used to determine the diameter distribution of the deposited nanofibers: the center of the ground collector (a), the middle between the center and the edge of the collector (b), and the edge of the collector (c), as shown in Fig. 9. Increasing air pressure increased the shear force on a jet and thus decreased the nanofiber diameter as shown in Figs. 10, 11, and 12. The nanofiber diameter was not significantly affected by varying the applied voltage under the air blowing condition. The air drawing effect by a shear force, that is directly proportional to the contact area between the air stream and jet stream, would have been high on the large diameter jet produced at the lower voltage. However, the electrical drawing is increased with increasing voltage. Thus, the diameter would be determined by the combination of the drawings by the shear and electrostatic forces. There was no significant difference in the diameter according to the deposition location because the jet at the edge featured a long flying path that provided sufficient time for nanofabrication while the electric field was weakened by the relatively long distance between the two electrodes.

The increased air pressure at the constant voltage increased the number of beads (Fig. 13). The unstable flow of the air stream may have enhanced the jet instability. The bead morphology changed according to the location on the

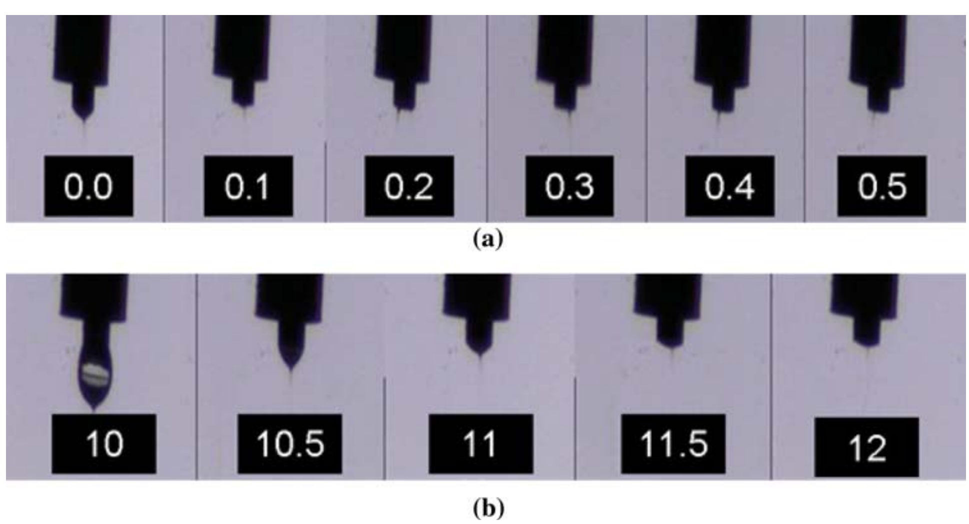

Fig. 7 Drop behaviors as a function of **a** various air pressures (kg/cm^2) without applying voltage and **b** various voltages (kV) without air pressure

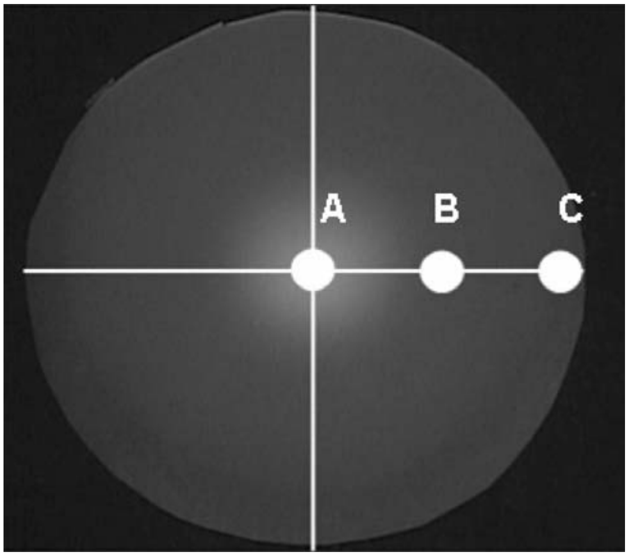

Fig. 9 Three deposition locations of the collector: the center of the collector (A), the middle between the center and the edge of the collector (B), and the edge of the collector (C)

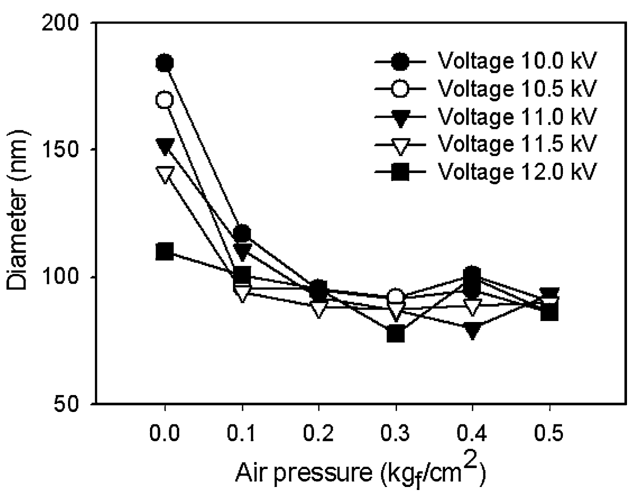

Fig. 10 Nanofiber diameter deposited at the center of the collector (A)

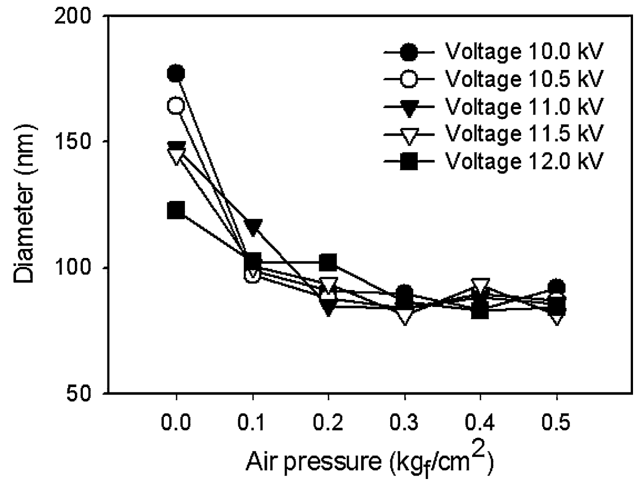

Fig. 11 Nanofiber diameter deposited at the middle between the center and the edge of the collector (B)

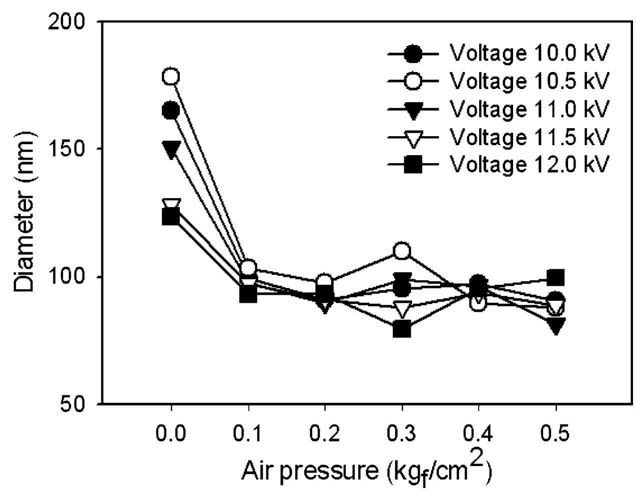

Fig. 12 Nanofiber diameter deposited at the edge of the collector (C)

ground collector. The bead became flat at the center of the ground collector, as shown in Fig. 14. The blown air hit the bead directly in the middle of the ground collector with a relatively higher air pressure. This phenomenon may be applied to enhance the bonding strength between nanofibers without an additional bonding process to produce a sufficiently strong web.

Conclusion

The effect of electroblowing on the web deposition was investigated by applying two forces, an electrostatic force and an air blowing-induced shear force, simultaneously and separately.

The deposition amount was successfully evaluated from the gray scale light intensities of the image filtered with the low and high pass criteria. The polymer deposition amount was generally increased due to the additional shear force induced by the increasing air blowing pressure. Especially, the shear force significantly increased the web deposition at the low voltage application.

The increased air pressure at constant voltage increased the number of beads. The bead in the middle of the ground collector was flattened. This phenomenon may be applied to enhance the bonding strength between nanofibers without any additional bonding process being required to produce a sufficiently strong web.

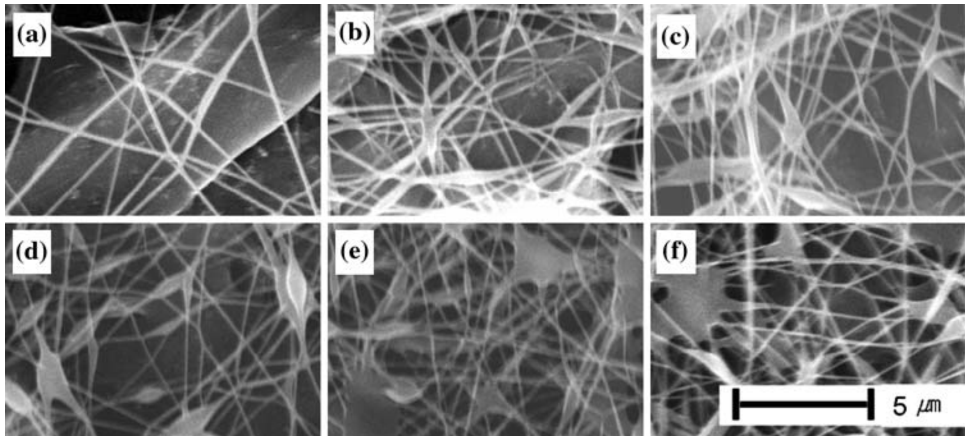

Fig. 13 SEM micrographs of electroblown at the various air pressures of **a** 0.0 kg/cm^2, **b** 0.1 kg/cm^2, **c** 0.2 kg/cm^2, **d** 0.3 kg/cm^2, **e** 0.4 kg/cm^2, and **f** 0.5 kg/cm^2 with a constant applied voltage of 10 kV

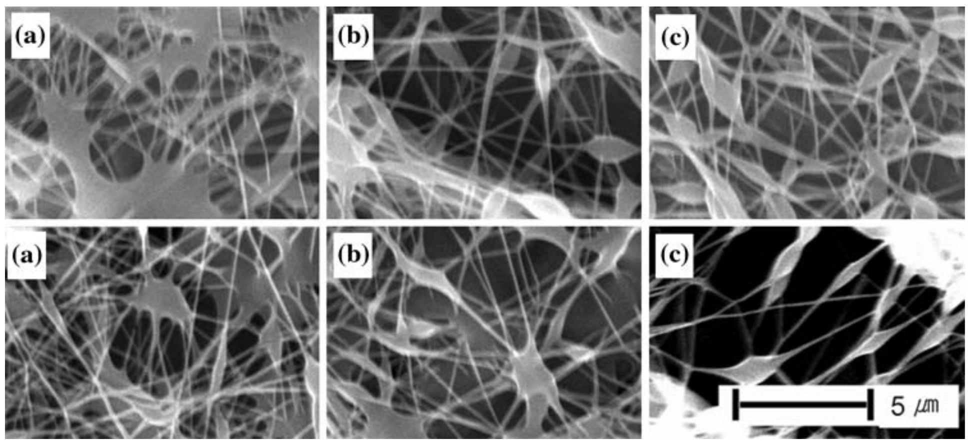

Fig. 14 SEM micrographs of nanofibers deposited at three deposition locations of **a**, **b**, and **c** with a constant applied voltage of 10 kV and two air pressures of 0.4 kg/cm^2 (upper) and 0.5 kg/cm^2 (lower)

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