Needleless Electrospinning and Direct Electrospinning of Nanofiber Yarns

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Electrospinning is a simple, but efficient and versatile, technology to produce polymeric nanofibers for widely diverse applications in both textile and non-textile areas [1]. This technique has been shown many advantages such as universality in processing polymeric materials, eases of controlling the fiber diameter and functionalizing nanofibers through adjusting solution composition for electrospinning, and flexibility to generate fibrous membranes of various geometries. Although the novel applications of electrospun nanofibers have been extensively explored [2], the technology development for mass electrospinning of nanofibers has been hampered.

In most cases, nanofibers are electrospun in the form of nonwoven webs. Nanofiber bundles that have long continuous length and interlocked fibrous structure, or nanofiber yarns, are expected to create new opportunities to develop more complicated nano fibrous structures with well-defined three-dimensional architectures and better mechanical performance, which will lead to many new applications. It remains a challenge to produce nanofiber yarns that have continuous length and controlled twist structure directly from an electrospinning process.

In this report, our recent works on needleless electrospinning for mass production of nanofibers and direct electrospinning of highly-twisted continuous nanofiber yarns are introduced.

NEEDLELESS ELECTROSPINNING

In an effort to increase the productivity of electrospinning, we have recently developed new needleless electrospinning systems (Fig 1). Disc was initially chosen as fiber generator and compared with cylinder [3]. The disc fiber generator needed a relatively low applied voltage to initiate the fiber formation, and the fibers were mainly formed on the disc edges. By comparison, nanofibers electrospun from the cylinder showed a higher dependence on polymer concentration and the applied voltage. The fibers were initiated from the cylinder ends first, and then from the entire cylinder surface only if the applied voltage was increased to a certain level. With the same polymer solution, the critical voltage to generate nanofibers from the disc was lower than that from the cylinder. Both electrospinning systems could produce uniform nanofibers, but the fibers produced from the disc were finer than those from the cylinder when the same voltage was applied to both. More recently, a spiral coil was used as fiber generator, which showed finer fibers with narrower diameter distribution, but much higher productivity than the disc system [4].

As listed in Table 1, nanofibers produced by the disc are finer with narrower diameter distribution (better quality). A thin disc (diameter 8 cm and thickness 2 mm) could produce nanofibers at a similar rate to a cylinder of the same diameter but 100 times wider (i.e. 20 cm long). However, the coil that has the same length and the diameter to the cylinder are double in the production rate, but the produced fibers are finer with narrow diameter distribution.

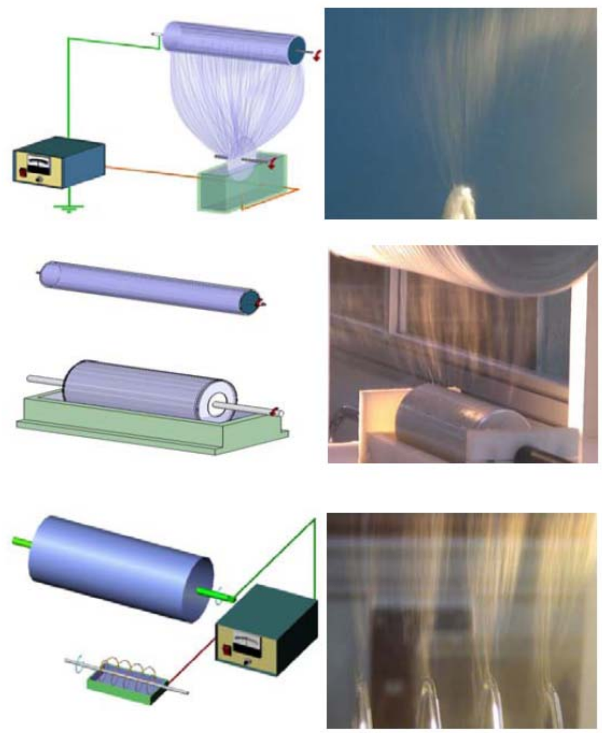

FIGURE. 1 Schematic of disc, cylinder and coil electrospinning systems and electrospinning processes.

TABLE. 1 A comparison between disc, cylinder and coil systems

	Cylinder	Disc	Spiral Coil
Dimensions	Φ=80 mm, Length=200 mm	Φ=80 mm, Thickness=2 mm	Φ=80 mm, Length=200 mm
Critical voltage (fibre-generating area)	47 kV (two top ends); 57 kV (top ends + top middle)	42 kV (top disc edges)	45 kV (top coils)
Diameter	334±118 nm	256±86 nm	237±78 nm
Productivity	7 g/hr (60 kV)	7 g/hr (60 kV)	14 g/hr (60 kV)

In comparison with the conventional needle electrospinning, the cylinder or the disc electrospinning system produced coarser nanofibers, but the dependency of fiber diameter on the polymer concentration showed a similar. However, for the coil system, it produced even finer nanofibers with narrower diameter distribution than the conventional electrospinning system. In addition, the crystallinity of polymer in needleless electrospun nanofibers was higher than that of nanofibers produced by conventional needle electrospinning.

CONTINIOUS ELECTROSPINNING OF NANOFIBER YARNS

Figure 2 schematically illustrates the basic setup for electrospinning of nanofiber yarns, which consists of two needle nozzles, a rotating funnel collector, a cross winder, and a high-voltage DC power supply. Two nozzles were placed in front of either side of the funnel collector, and a yarn-winding system was set between the nozzles with a distance further than that between nozzle and funnel collector. During electrospinning, two needle nozzles were connected separately with positive and negative polarities of the DC power supply. Nanofibers electrospun from the oppositely charged nozzles were deposited onto the rotating funnel collector to from a fibrous membrane covering the funnel surface.

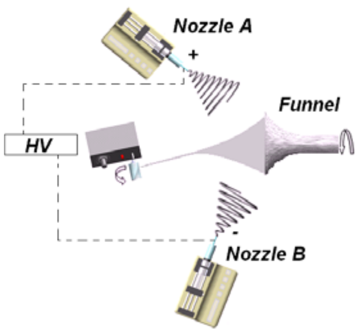

FIGURE 2. Schematic illustration of the basic setup for electrospinning of nanofiber yarns.

To form a nanofiber yarn, the nanofibers deposited were pulled off the funnel surface, while at the same time maintaining the funnel rotating constantly (Fig 3a). This led to the formation of a "cone" shaped fibrous membrane attaching to the funnel edge (Fig 3b). With continuously rotating and drawing the fibrous cone, a twisted fiber bundle was formed at the fibrous cone tip, which can be wound to form a continuous nanofiber yarn. Figure 3c shows the appearance of a nanofiber yarn produced by this process, which looks similar to that of conventional yarns, except that the fibers are on nanometer scales (with an average diameter of 486 nm in this study). In addition, most of the nanofibers within the yarn aligned in certain angles along the yarn length direction (Fig 3d).

Kilometers of a continuous nanofiber yarn can be directly withdrawn from the "cone" apex, with up to 7400 turns-per-meter of twists inserted through the rotation of the funnel. The maximum yarn production rate is 5 m/min, and the yarn twist level and fiber orientation can be controlled by the funnel rotating speed and yarn withdrawal rate. The nanofiber and yarn morphologies, yarn dimension, twist level and production rate are determined by both the operating parameters (e.g. applied voltage, electrospinning distance, flow-rate of polymer solution, funnel dimension and rotating speed, the distance between funnel and winder, and winding speed) and material properties (e.g. polymer, polymer concentration).

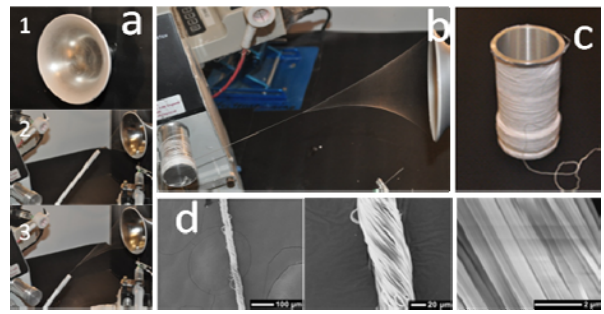

FIGURE 3. a) Frames of a video showing the formation of nanofiber cone with the aid of a plastic rod, b) Cone-shaped fiber deposition due to the rotation of the funnel collector and continuous drawing of nanofibers from the funnel, c) As-produced nanofiber yarns, and d) SEM images of a nanofiber yarn section. [Polymer: poly(vinylidene fluoride-co-hexafluoropropene) (*PVDF-HFP*)]

The tensile properties of nanofiber yarns were found to depend on the twist level. With increasing the twist level, both the tensile strength and the elongation at break increased. However, when the twist reached certain level, the tensile strength started decreasing, while the elongation at break maintained the increase trend. The maximum average tensile strength of the PVDF-HFP nanofiber yarn produced from this work was 60.4 MPa. Also, these yarns were further processed into braids and fabrics. The braided nanofiber yarns showed considerable improvement in tensile strength.

In conclusion, we have demonstrated the potential of using needleless setups to large-scale electrospin nanofiber nonwovens and dual-nozzle electrospinning setup to directly electrospin highly-twisted continuous nanofiber yarns. These nanofiber processing techniques may be useful for producing quality nanofibrous materials for various applications.

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