STUDY ON THE EFFECTS OF APPLICATION OF SURFACE TENSION ON THE STRUCTURE OF ELECTROSPUN NANOFIBER YARN

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Abstract:
A modified electrospinning setup has been used to produce a continuous twisted yarn from PAN nanofibres. A container partially filled with water, was placed underneath the two nozzles. This water media remained in static state and was acting as collecting surface. Nozzles were placed opposite of each other and are oppositely charged. Consequently an open-end nanofiber yarn is produced via converging point of constructed nanofibre spinning triangle. Studies were carried out on samples to assess the tensile behavior and surface morphology of sample nanofiber yarns. SEM evidences shows highly aligned nanofibers within the nanofiber yarns which is attributed to the surface tension between the nanofibers and water which in return could provide additional tension on the nanofibers during the nanofiber yarn formation.
Key words: Eectrospinning; Nanofibre yarn, nanofibre spinning triangle, polyacrylonitrile, stress-strain curve

1. Introduction
Electrospinning is considered as the most versatile method to produce continuous fibres from nanometer diameter up to submicron diameter and from a broad range of organic polymers [1-3]. After certain extent of applying a high voltage to the solution, the charged pendent drop of polymer solution is deformed into well known Taylor's cone. As the jet travels through the air, the solvent evaporates and bending instability causes the jet to get stretched in the electrostatic field. This will lead to the polymeric nanofiber formation which is consequently collected on the surface of collecting surface such as a grounded plate. Nanofibers have random orientation in the form of nonwoven mats called nanoweb[4,5].
Up to the end use, new generation of yarns can be engineered to be used in new fields such as tissue scaffolds and reinforcement materials in composites [6] which has different function from nanoweb that is used in certain applications such as filters, wound dressings and tissue scaffolds [7]. Collecting of nanofibers in arrays and inserting of twist to this bundle, initiates a new nano fibrous material as nanofiber yarn. Some of the nano yarn production techniques are only capable to produce a limited length of aligned fibres by means of different solid substrates as collector, such as a rotating disk [6], dual rings [8], and dual in-line blades [9]. Continuous nano yarns were produced by modifying the electric field in a limited linear density [10, 11]. Some of these techniques has used a liquid media, in a static [12, 13] or dynamic state [14], to produce a continues yarn. Poor arrangement of nanofibres about the yarn axis has led to a low tenacity yarn. As a result, further improvements are necessary to manufacture a twisted yarn from aligned electrospun nanofibres with continuously with high levels of orientation.
This study has applied a novel technique to produce a nanofibre yarn to fulfill the requirements of a stable nano yarn with high orientation of nanofibers. This method has combined the advantages of using two nozzles in opposite directions [10] and static water surface as collector[12,13]. Some mechanical properties of sample yarns are devalued and reported.

2. Experimental
Polyacrylonitrile (PAN) with weight average molecular weight (Mw) of 100000 g/mol was dissolved in dimethylformamide (DMF) to make a 15wt% solution at room temperature and under constant mixing for three hours. Then this solution was put in two syringes with an

inner diameter of 0.6 mm which were devised in opposite directions at a distance of 18 cm. Polymer solutions were pumped to needles by a dual syringe infusion pump and the polymer feed rate was set at 0.1ml/hr. A water bath (200 mm diameter × 15 mm depth) was placed 5.5 cm below the plane of nozzles. In an equal distance from each needle, an end of a piecing yarn was placed manually on a rotating drum, which was positioned at the top of the nozzles with a distance of about 20 cm from it, and then its end was placed in the water bath. Since high voltages of opposite potential (+13 kV, -13 kV) were applied to two needles separately, the jets were ejected simultaneously and formed a nano fibrous triangle at the open end of the piecing yarn, which is called here "nanofibre spinning triangle". By pulling the piecing yarn up via rotating the drum, produced nanofibres tend to stick on the yarn body and form an aligned strand of fibres that could be collected on the rotating drum. Take-up speed, was adjusted at a constant rate of 150 m/hr.

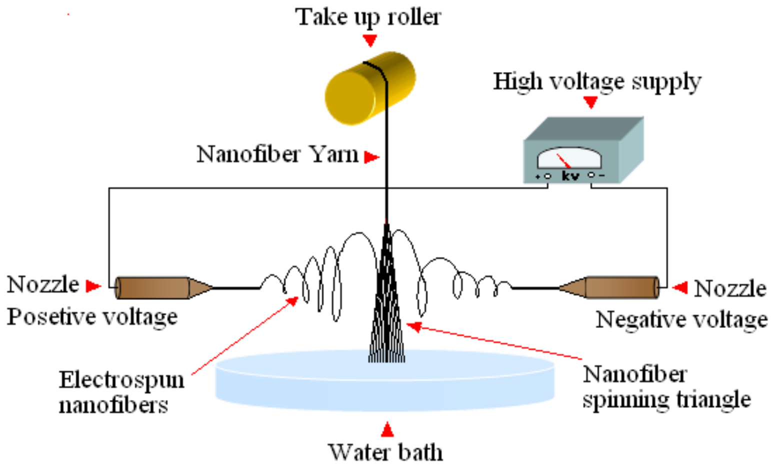

Figure 1. Schematic electrospinning setup to produce an open-end nanofiber yarn

Surface morphology of sample nanofiber yarns was studied with a Philips scanning electron microscope (XL-30) using an accelerating voltage of 20 kV.
Diameter of nanofibres and mechanical properties of yarn were were assessed by using the SEM micrographs and Instron tensile tester respectively.

3. Results and discussion

Stretched nanofibers were converged into the body of the piecing yarn and resulted in formation of the nanofibre spinning triangle which is shown in the figure 2(a). Since the nanofiber spinning triangle consists of both positively and negatively charged fibers, the whole body is neutral. SEM micrographs confirmed that nanofibers in spinning triangle were parallel as it can be seen in figure 2(b).

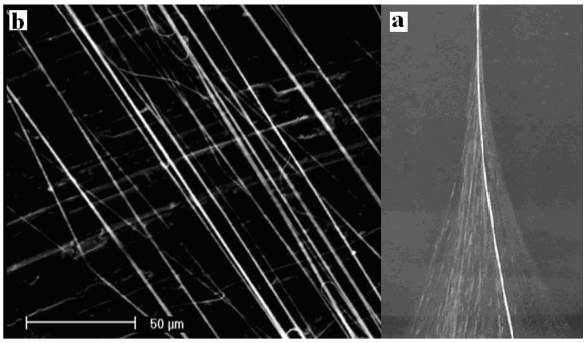

Figure 2. Spinning triangle image captured by a Nikon coolpix 5900 camera (a), SEM image of nanofiber orientation in the spinning triangle (b).

Since the principle of yarn formation in this method is analogous to the formation of yarn in the open-end spinning [15], the produced nanofibre yarn is called "open-end nanofibre yarn". Figure 4 demonstrates a SEM image of the electrospun nanofibre yarn with a linear density of 4.8 denier. A higher magnification of the yarn surface shows the fiber orientation in its outer structure. As it can be seen in figure 5 a large amount of nanofibres are parallel and aligned at the direction of the yarn axis. It seems that this high degree of orientation is resulted from the surface tension of nanofiber surface and water at the contact area. This extra tension seems to be enough to elevate the nanofiber orientation. Considering the high specific surface of nanofiber, surface tension will build up at its highest level.

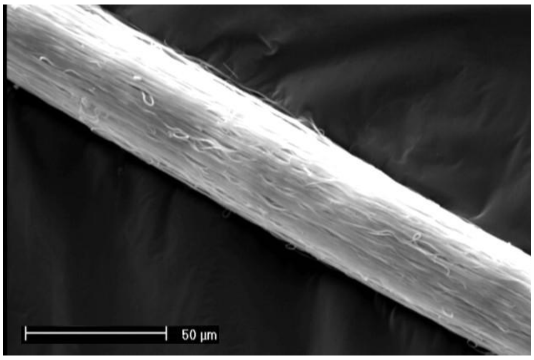

Figure 4. SEM image of the open-end nanofiber yarn.

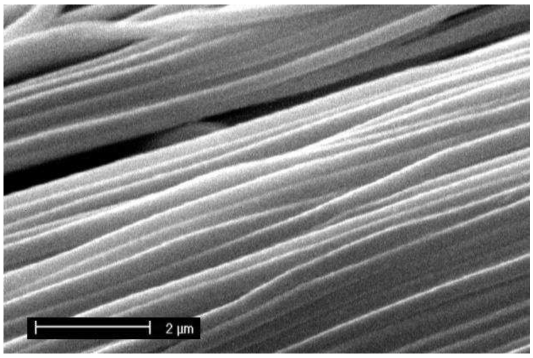

Figure 5. SEM image of fiber orientation in the open-end nanofiber yarn**.**

Evaluation of nanofibre diameter showed an average of about 400$\pm$55 nm. This study showed that by increasing the take-up speed of yarn, the average yarn diameter was decreased due to the drop in the number of nanofibers in the cross section of yarn.

Table 1 demonstrates the mechanical properties of nanofibre yarns. Regarding the tensile strength, the nanofiber yarns have proper mechanical properties for handling in some processes like weaving.

Table 1. Mechanical properties of nanofiber yarn

Property	Yarn Diameter	Tenacity	Strain at break	E-modulus
unit	μm	MPa	%	GPa
Mean value	44 ± 12	42 ± 10	38.1 ± 8	1.57 ± 0.2

Typical stress-strain curve of nanofibre yarn is shown in figure 6. As it can be seen in this figure, there is a plastic deformation before yarn breakage. The typical stress-strain behavior of the open-end nanofiber yarns appeared to be analogous to that of the open-end spun yarns from mirofibers [15].

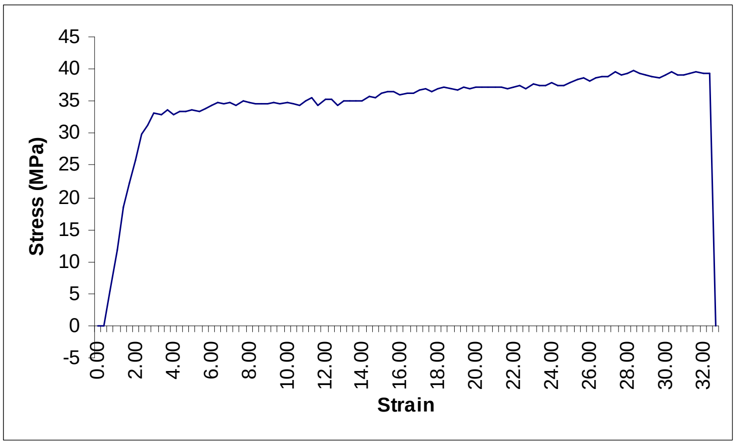

Figure 6. Typical stress-strain curve of PAN nanofiber yarn.

4. Conclusion

In this work, a novel method is proposed for producing an open-end nanofibre yarn in an electrospinning system. Open end nanofiber yarn was spun by applying a water bath as collecting surface and modifying the electrostatic field in a dual jet electrospinning process. The results demonstrates that take up speed and surface tension could affect the yarn formation and the orientation of nanofibres in the yarn. Higher orientation has lead to a nanofiber yarn with higher tenacity. SEM evidences confirms the highly aligned nanofibers within the nanofiber yarn structure.

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