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Novel Method for Nanofibre Yarn Production Using Two Differently Charged Nozzles

Abstract
In this study a new method of yarn production from electrospun nanofibres is discussed. This method is an innovation in electrospinning, using two differently charged nozzles and a collector travelling through the air to form yarn continuously. In this project PAN electrospun nanofibres were used to produce twisted yarn with a linear density of 2.1 tex at laboratory scale. The tensile properties of these yarns were then investigated. With this method it is possible to produce yarns with different polymers and linear densities.

Key words: *nanofibre yarn, tensile properties, charged nozzle, linear density, electrospun.*

Introduction

Electrospinning has been known for almost 70 years as a simple and effective technique for producing continuous ultra fine polymeric fibers with diameters from several to hundreds of nanometers. It is based on the use of electrostatical forces to drive a jet of polymer solution to form nanofibres. Electrospun nanofibres from a variety of polymers have been employed in filters, composites, tissue engineering scaffolds, protective clothing, electronics, catalysis, ceramic fibers, wound dressing, drug delivery materials and many other applications [1]. The principles of electrospinnig are simple and include four main parts: a metallic capillary as a needle which is connected to a high voltage source; a pump which controls the output flow of the polymer solution; and a collector grounded or charged to a negative voltage. In this technique only a small amount of polymer solution is needed [2]. Also, various methods have been used to obtain aligned electrospun nanofibres such as spinning onto a rotating drum [3], spinning onto the sharp edge of a thin rotating wheel [4], using a metal frame as the collector [5], a collector based pair of split electrodes [6]. There have been many attempts to align electrospun nanofibres. Moreover, a great deal of attention has been paid to produce yarns from these nanofibres, which has led to the introduction of various techniques.. One of these methods involves using multi field electrospinning apparatus with vertically oriented rings connected in series and charged at the same polymer jet voltage coming from a syringe needle. In this method, the travelling path of nanofibres was limited to a cone shape just before collecting onto a collector, which is achieved by applying an electrical field to these rings to prevent spun nanofibres from spreading. Consequently, electrospun nanofibres are collected on the wooden frame and form a yarn. As the wooden frame width is 1 inch, it is possible to produce yarns of only1 inch length [7]. Another method is based on the use of an oscillating metal grounded frame of high frequency as a collector. The bundle of electrospun nanofibres which is collected on this frame has a high degree of alignment of nanofibres within; but a drawback of this method is that only relatively short tows of aligned fibers can be obtained, and there has been no report detailing the mechanical properties of these yarns [8]. The use of two grounded rings as collectors which collect and align electrospun nanofibres is reported. In other techniques aligned fibers are twisted around one another by rotating one of the rings and forming a yarn. Although such twisted yarn has the advantage of a high degree of fibrealignment within it, it is very vulnerable as it has a diameter of about 4 micrometers, indicating poor stability [9]. The technique of spinning polymer onto a water reservoir collector is another method of yarn production from electrospun nanofibres and was referred to in an abstract presented at a conference in 2001 in which yarn of PAN electrospun nanofibres was obtained on the surface of water [10]: electrospun nanofibres came into contact with the surface of the water while they were travelling toward a grounded plate placed under the water. The initial non-woven web of nanofibres formed on the surface of the water was then drawn and pulled out to form a continuous yarn, which was done with the aid of a take-up roller rotating at constant speed [11]. Using the latter method showed that PLC yarn formed from PLC electrospun nanofibres had a lower strength than yarns formed by other techniques [12]. Twisting PAN electrospun nanofibres using a rotating drum as an electrical twister was reported by Fennessey *et al*, which led to the formation of a bundle of aligned PAN nanofibres with dimensions of 2 × 32 cm. The maximum strength and modulus of yarns obtained by this meth-

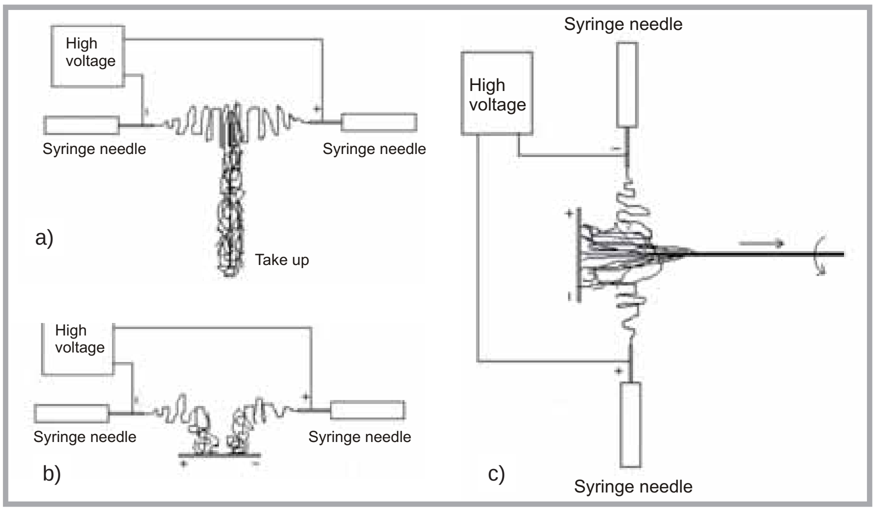

***Figure 1.** Schematic of the mechanism of: a) strand formation (Type A), b) yarn formation (Type B), c) yarn formation (Type C).*

od are 5.8 GPa and 163 MPa, respectively [13]. A system has been invented for collecting electrospun nanofibres which is able to deposit nanofibres over a large area by omitting the collecting surface and using two differently charged nozzles [14]. Also, Li *et al.* [15] introduced a similar method which could obtain aligned electrospun nanofibres within the yarn at higher speeds of the collector cylinder. A novel technique for generating uniaxially aligned electrospun nanofibres yarn is presented in the current study, which contains some changes to the two-nozzle electrospinning method.

Experimental

Materials

Commercial PAN polymer powder of 100,000 (g/mol) molecular weight and 70,000 numerical molecular weight was supplied by Poly Acryl, Iran. The solvent used was DMF from Merck Company. A polymer solution of PAN in DMF with a concentration of 13.5% was prepared by dissolving and stirring the above mixture at a constant speed at room temperature. It was then kept at 70 °C for 2 hours to complete the dissolution.

Methods and equipment

Electrospinning setup

As part of the innovative method, two different charged nozzles were placed opposite each other and used for spinning nanofibres. Electrospun nanofibres charged with a voltage of the same value but opposite polarization came out from, the both nozzles attracted each other and discharged. A continuous strand of nanofibre was taken up by pulling out the discharged nanofibres that had accumulated between the two nozzles. ***Figure 1*** shows a schematic of the strand formation mechanism (Type A). It is not possible to call this strand of nanofibre a yarn due to the low orientation, strength and uniformity. A bulk strand of nanofibre obtained by this method is shown in ***Figure 2***. A novel method for producing continuous twisted yarn from electrospun nanofibres was invented using two differently charged nozzles. In this new method, a neutral surface was placed in the middle of the electric field so that electrons on the surface of the plate were displaced in such a way that half of them became positively charged and the others negatively charged. The jets of polymer solution coming from the charged nozzles moved slightly towards the part of the plate with an opposite charge and were collected on this plate. A schematic of a later electrospinning method is shown in ***Figure 1.b*** (Type B). Electrospun nanofibres came into contact with piece yarn placed in their path, and then the other end of the nanofiber was pulled towards the plate, making a spinning triangle. The nanofibres were then twisted by rotating piece yarn around its axis. It is also possible to continuously produce twisted yarn by taking it up during twisting. Electrospun nanofibres have a degree of alignment within yarn produced by this method. ***Figures 1.c*** & ***3*** show the mechanism of yarn formation (Type C) and an image of yarn produced, respectively.

Take-up setup

A take-up unit was used which was able to twist and take up yarn without any balloon formation. ***Figure 4*** is a schematic picture of such apparatus [16].

Instrument

After gold coating, the morphology of electrospun PANnanofibre yarns was observed with a Philips scanning electron

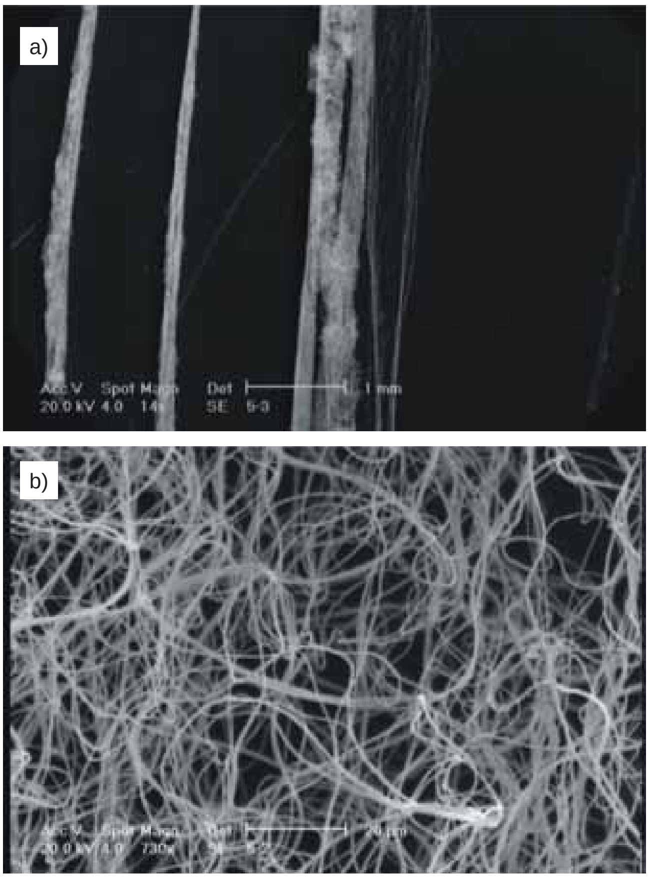

Figure 2. *(a) Image of bulk strand of nanofibre (b) Higher magnification SEM image of bulk strand of nanofibre.*

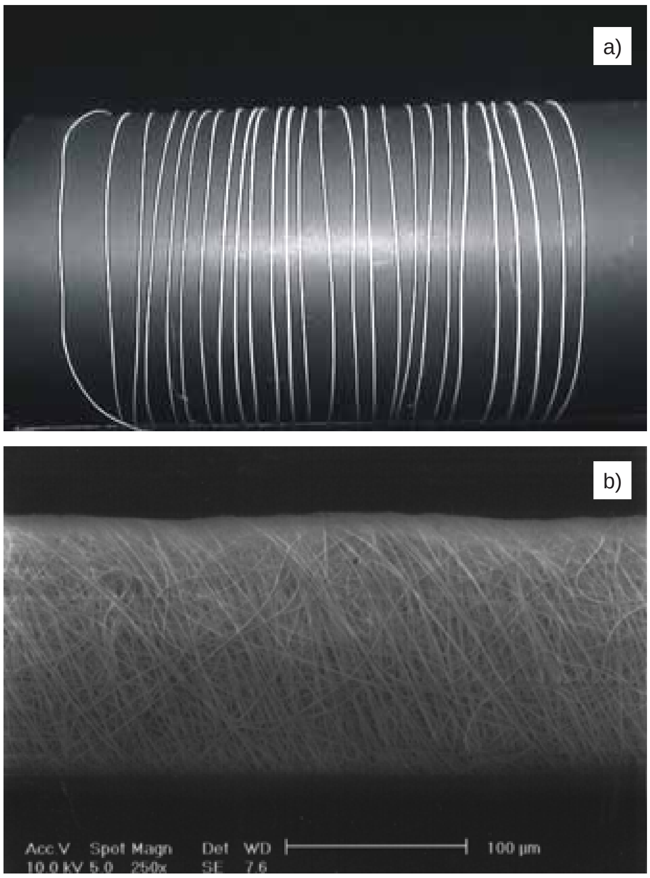

Figure 3. *Image of yarn produced. (a) Captured by digital handy cam; (b) SEM image of electrospun PANnanofibre yarn.*

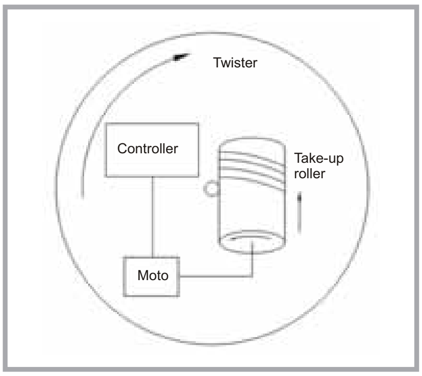

Figure 4. Schematic of take up unit.

***Table 1.** Mechanical properties of yarns produced with nanofibres.*

Number of test	n	30
R.P.M of the twister	R.P.M	320
Stress at break	ave.MPa	54.57
	CV%	16.86
Strain at break	%	60.81
	CV%	22.73
Work up to break	avg.Nmm	4.72
	CV%	34.97
E-Modulus	ave.GPa	1.44
	CV%	26.08

microscope (XL-30) and Sony digital handy cam (DCR-PC115E). The diameter of the nanofibres was measured from high magnification SEM images. The mechanical properties of the yarn were measured by Zwick 1446–60.

Result and discussion

In order to specify yarn tensile properties, the distance between the two nozzles and the distance between the neutral plate and centre of the electric field were set at 13 cm and 5 cm, respectively. The dimension of the plate was 6 × 12 cm. The diameter of the two nozzles was 0.7 mm with a length of 4 cm, and the distance between the two centers of the nozzles and the take-up unit was 25 cm. The voltage applied was 8 kV, while the speeds of the take-up and twisting operations were 5.79 m/hour and 320 rpm, respectively [16, 17].

Electrospun nanofibre yarns were cut into pieces of equal length and then kept in standard conditions of (20 ± 2) °C and 65% relative humidity in order to do a tensile strength test. This test procedure was performed using a Zwick tensile tester, with a gauge of 10 cm and elongation rate of 60 mm per minute. Some tensile properties including the stress at break, initial modulus, strain at break and work up to break of these yarns were indicated. Results are given in ***Table 1***. It is possible to improve the tensile properties by thermal treatment after production [17]. Typical force-elongation curves related to these yarns are shown in ***Figure 5***. An SEM image of electrospun nanofibre yarn is shown in ***Figure 6***, which indicates the degree of alignment of nanofibres and yarn twist. To measure the diameter of nanofibres, SEM images were taken of nanofibres within the yarn produced. 100 fibers were chosen and their diameters were compared with the image scale, then the average of the results was obtained. The average diameter of electrospun nanofibres within the yarn produced from the PAN solution of 13.5% concentration was about 474 nm.

Conclusion

Nanofibres have a great deal of applications in many fields; however, it is necessary to take advantage of some processes to produce yarn from nanofibres in order to improve their application in textiles. In this work, a new method of yarn production from electrospun nanofibres has been introduced, accompanied by yarn property specifications. The average stress and initial modulus were 54.57MPa and 1.44 GPa with a twist of 3316 per meter. This kind of yarn could be used for many potential applications, such as the preparation of carbonnanofibre and the support of cell culture. The results show that it is possible to use different polymer solutions to produce yarn using this method.

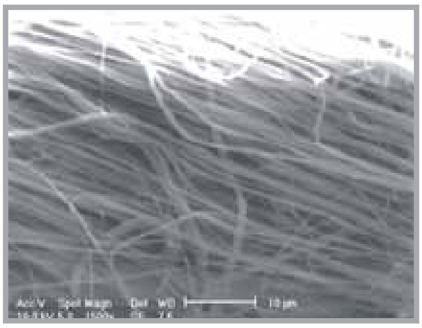

***Figure 6.** Higher magnification image of yarns produced with nanofibres.*

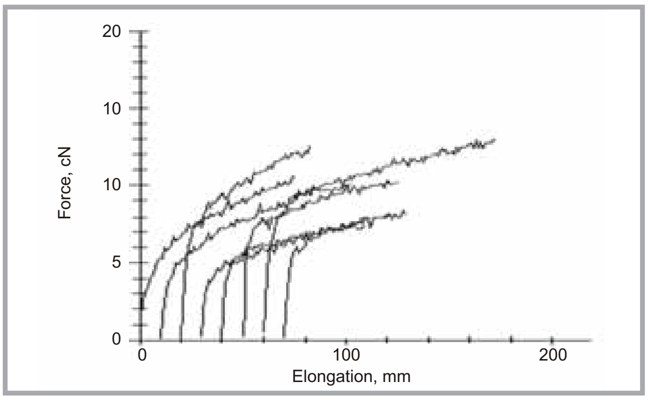

***Figure 5.** Typical force-elongation curves.*

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