A New Mechanism for the Electrospinning of NanoYarns

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ABSTRACT: A new electromechanical mechanism for spinning "core electrospun nanoyarn" is researched, designed, and implemented. SEM images have shown that the deposited nanofibers were wrapped helically around the core filament resulting in a core electrospun nanoyarn. The parameters of this mechanism such as feed-in angles, twist rates, and take-up speeds are analytically investigated. Twist rates of 500 to 750 revolutions per minute, core feed-in angle of 0°, and take-up speed of 1.5 cm/s were found optimum for successfully producing core electrospun nanoyarn. This nanoyarn is expected to find many applications in industrial and medical textiles. J Appl Polym Sci 124: 195–201, 2012

Key words: nylon; fibers; nanotechnology

INTRODUCTION

A core spun yarn is defined as "a structure made of a separable core constrained to be at the central axis permanently and surrounded by fibers, which act as a sheath."[1] The mechanical behavior of such structures is governed by fiber characteristics such as length, fineness, tenacity, breaking extension, and friction and by the core spun yarn characteristics such as fiber deposition and arrangement, core to sheath proportion of fibers, frequency of wraps around the core, twist angle of the fibers, packing, mass variation, etc.[2] The manufacturing process mainly consists of feeding the filament to a conventional spinning unit, where it is covered by natural or synthetic staple fibers by a suitable mechanical arrangement. Cotton spandex (elastane) yarns that are composite yarns consisting of elastane core wrapped helically by cotton staple fibers are a well known example of elastic yarns widely used in the textile industry.

The physical properties of core spun yarns depend on the sheath properties such as the fiber length, its fineness, and the type of fiber. In other words, sheath constructed of small diameter fibers that must be wrapped by the same length of fibers, will result in a higher number of wrapping turns.[3,4] This will lead to a higher surface area and to a higher volume ratio, and thus more uniform morphology and higher yarn strength. Although there is some prior research in which the core electrospun yarn principle is introduced, the mechanism used rendered the nanofibers to randomly cover the core without producing orderly structured yarn.[5,6]

In this study, we have designed a new mechanism and via extensive experimentation and optimization of this system. We are able to produce an ordered nanoyarn that can be defined as "a composite nanoyarn structure made of a separable core in the central axis and surrounded helically by electrospun nanofibers that act as a sheath." With this new mechanism, we were also able to analyze the effects of the nanofiber twist, the feeding angle of the core filament "core feed-in angles," and the take-up speeds on the structure of the resultant nanoyarn.

A new mechanism for spinning continuous nanoyarn

From our recent continuous nanofiber yarn mechanism, which forms the basis of this development,[7] we have designed a new mechanism for producing continuous core electrospun nanoyarn. Our aim is to wrap helically the deposited nanofibers on the feeding core filament, resulting in a core electrospun nanoyarn with a structure similar to the core ring spun yarn as shown in Figure 1.

EXPERIMENTAL

Materials and electrospinning operation

Nylon 6 solution of 20 wt % concentration was prepared by dissolving the polymer in 98% formic acid. The viscosity, electrical conductivity, and surface tension of the 20 wt % nylon 6 solution were

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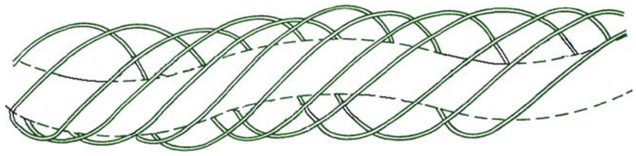

Figure 1 Morphological structure of the aimed core electrospun nanoyarn, which constructed of the man-made filament core with the sheath of nanofibers, drawing was reprinted from.[8] [Color figure can be viewed in the online issue, which is available at wileyonlinelibrary.com.]

reported to be 3.358 Pa. sec, 294 mS/m, and 48.5 mN/m, respectively. The nylon 6 solution was fed through a 5 mL capacity syringe to a vertically orientated (25-gauge) blunt-ended metal needle (spinneret) via Teflon® tubing and the flow rate was controlled using a digitally controlled, positive displacement syringe pump (M22 PHD 2000 Harvard apparatus, Edenbridge Kent, UK). The needle was held by one electrode connected to a high voltage DC power supply (MK35P2.0-22 Glassman, NJ). Typical operating regimes were applied; flow rates of 0.2 ml/h, voltage of 15 KV, and a working distance of 8 cm. These operation parameters were used for producing uniform distribution diameter nylon 6 nanofibers, based on our previous work.[9] A single polyester filament (Rhone Poulenc viscosuisse, South Africa) with count of 88 dtex and diameter of 90 μm was fed via the tension roller to the center of the holed twist disk, then to the take-up disk and finally to the winder. Figure 2 shows a schematic drawing of the mechanism with its changeable parameters.

The principle of the core electrospun nanoyarn mechanism

The continuous core electrospun nanoyarn mechanism involves feeding a tensioned single core filament through the center of a *Y*–*Z* plane holed disk, which we call "twist disk," to a *X*–*Z* plane disk, which we call "take-up disk," to the winder. The distance between the two perpendicular set of disks at *Y*–*Z* and *X*–*Z* planes forms the spinning zone in which the nanofibers are deposited on the feeding core filament in a controllable manner, as shown in Figure 2.

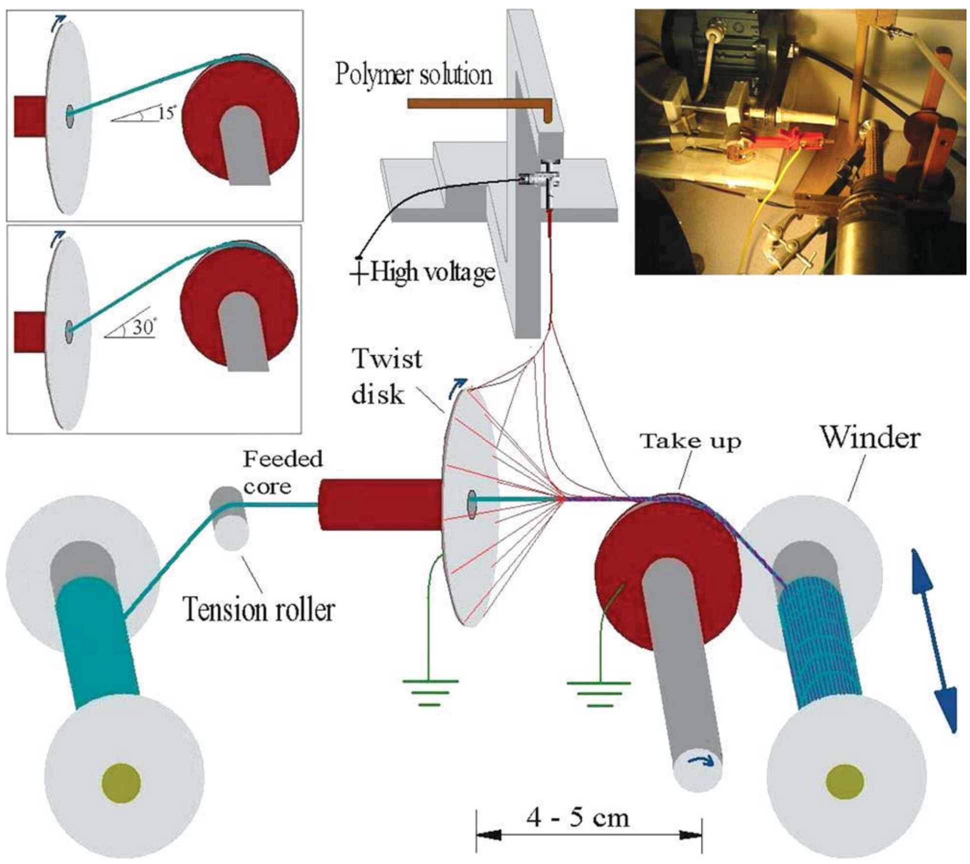

Figure 2 A schematic illustration of the mechanism used for spinning core electrospun nanoyarn. The spinning distance between the two disks was 4–5 cm. The twist disk was rotated around its axis by connecting it to a controlled motor speed and the core nanoyarn was wound on the winder through the take-up disk. The take-up disk was placed at three different horizontal levels against the twist disk to form three core feed-in angles of 0, 15, and 30°. [Color figure can be viewed in the online issue, which is available at wileyonlinelibrary.com.]

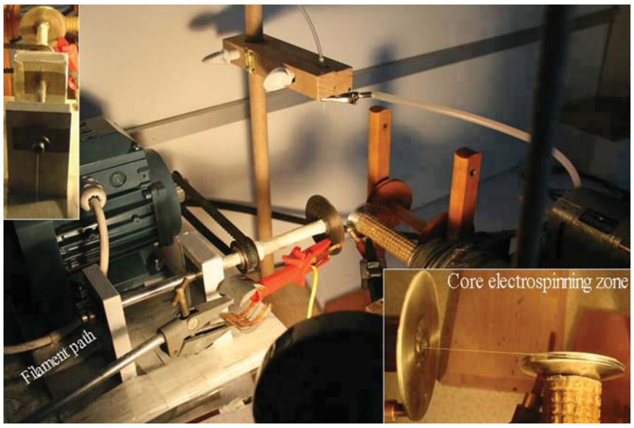

Figure 3 A photograph of the installed continuous core electrospun nanoyarn mechanism used in our experiments for twisting in helical form highly aligned nylon 6 nanofibers on a feeding polyester single filament at 0° feed-in angle. Each disk is earthed and attached to a motorized insulated shaft to run at a given rotational speed. However, changing the feed-in angle into 15 and 30° requires setting the horizontal level between the twist disk and the take-up disk as shown in Figure 2. [Color figure can be viewed in the online issue, which is available at wileyonlinelibrary.com.]

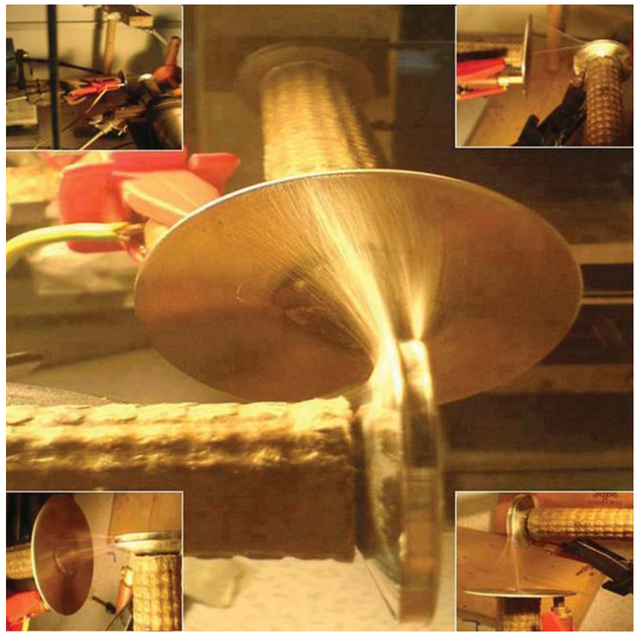

Figure 4 A photographs of aligned nylon 6 nanofibers deposited in the gap between the perpendicular twist disk and take-up disk for producing continuous core electrospun nanoyarn. These nanofibers covered the feeding polyester filament in three dimensional conical architecture. By rotating the twist and take-up disks the flying nanofibers deposited helically on the filament to form core electrospun nanoyarn. [Color figure can be viewed in the online issue, which is available at wileyonlinelibrary.com.]

The two disks are circular; the first disk "twist disk" is 60 mm in diameter and earthed. It has 1 mm thickness and 5 mm inside hole diameter. The second disk "take-up disk" is a wider earthed disk, 40 mm in diameter and 4 mm thickness, separated by a distance of 4–5 cm from one another. The twist disk is rotated around its axis by means of a motorized insulated shaft/gear arrangement attached to it, capable of setting the rotational speed for twisting the deposited nanofibers on the core filament. The core electrospun nanoyarn was wound onto the winder through the take-up disk, which is also attached to a motorized insulated shaft/gear set at a given rotational speeds, as shown in Figure 3.

Manufacturing parameters were altered to investigate the effect of the twist of the nanofiber bundle, the core filament feed-in angles, and the take-up

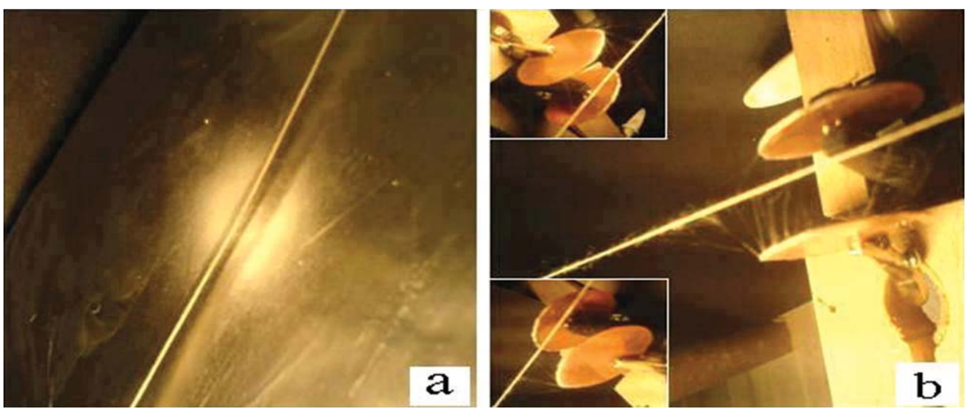

Figure 5 Recorded photographs showing the concept of the core electrospun nanoyarn mechanism developments. (a) A filament was placed between the spinneret and the surface collector, nanofibers covered the upper part of the filament and (b) the filament was placed between two circular disks in which the nanofibers covered the upper part of the filament. From these photographs, it is necessary to think how we rotate the filament under a continuous linear motion for completing the covering of the nanofiber sheath. [Color figure can be viewed in the online issue, which is available at wileyonlinelibrary.com.]

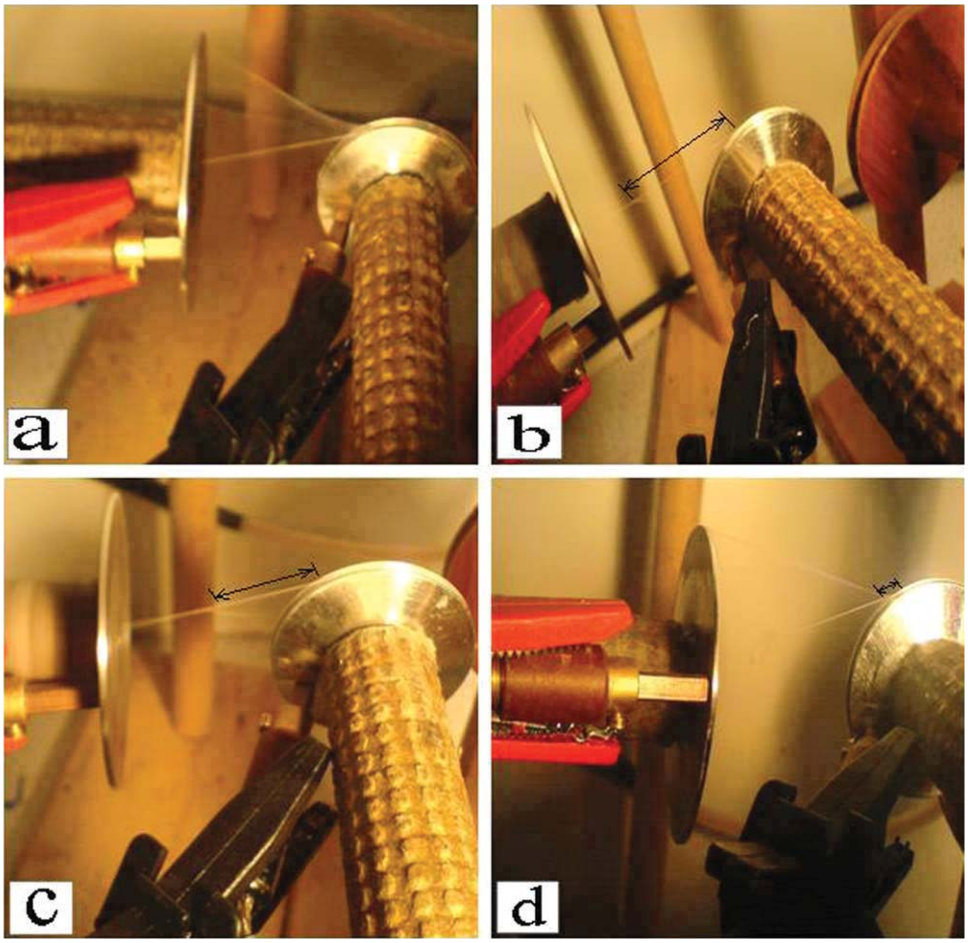

Figure 6 Live photographs show three different feed-in angles 0, 15, and 30°, of the polyester filament into the spinning zone. (a) Deposited conical nanofibers onto the stationary twist and take-up disks, (b) applying twist to the deposited nanofibers at filament feed-in angle of 0°, (c) applying twist to the deposited nanofibers at filament feed-in angle of 15°, and (d) applying twist to the deposited nanofibers at filament feed-in angle of 30°. It is easy to observe by the indicating arrows that as the feed-in angle decreases the deposited nanofibers coverage increases on the core filament. [Color figure can be viewed in the online issue, which is available at wileyonlinelibrary.com.]

speeds, on the morphological structure of the yarn. The effect of nanofiber twist angle was investigated at two rotational speeds of the twist disk, namely 500 and 750 rpm. The core polyester filament was fed into the spinning zone at three feed-in angles; 0, 15, and 30° by placing the take-up disk at three different horizontal levels against the twist disk as shown in Figure 2. The resulting core electrospun nanoyarn was wound onto the winder via the take-up disk at three take-up linear speeds; 1.5, 6, and 12 cm/s. These values were based on our previous published work[7,9] and initial experimental trials of this mechanism.

Characterization

Samples of core electrospun nanoyarn were collected on SEM stubs. These samples were sputter-coated with gold-palladium for 45 s at 18 mA. Yarns were examined using a Hitachi *S*-530 Scanning electron microscope (Berkshire, UK) at an acceleration voltage of 10 kV.

RESULTS AND DISCUSSION

Observations

Figure 4 shows different photographs of aligned nylon 6 nanofibers deposited on the gap between the perpendicular twist disk and take-up disk for continuous yarn spinning and how these nanofibers covered the feeding polyester core filament in a three dimensional conical architecture. Consequently, by rotating the twist and take-up disks the incoming nanofibers deposit onto the feeding filament gradually to form a helical structure and thus forming core electrospun nanoyarn.

This mechanism has been designed after careful consideration of literature and by investigating step by step the requirements for spinning continuous core electrospun nanoyarn, as shown in Figure 5.

Analytical investigation of the parameters of the mechanism on the core electrospun nanoyarn morphological structure

Figure 6 shows three different feed-in angles of 0, 15, and 30° of the polyester filament into the spinning zone. It has been found that as the feed-in angle decreased, the deposited nanofibers cover of the feeding filament per unit time increased. This resulted by electrospinning nanofibers from initially stationary disks, that is, no twisting, and by then rotating the twist disk to observe the conical twists of the nanofibers around the filament. It has therefore been confirmed that a core filament feed-in angle of 0° is the most suitable, under our mechanism, for producing orderly nanoyarn.

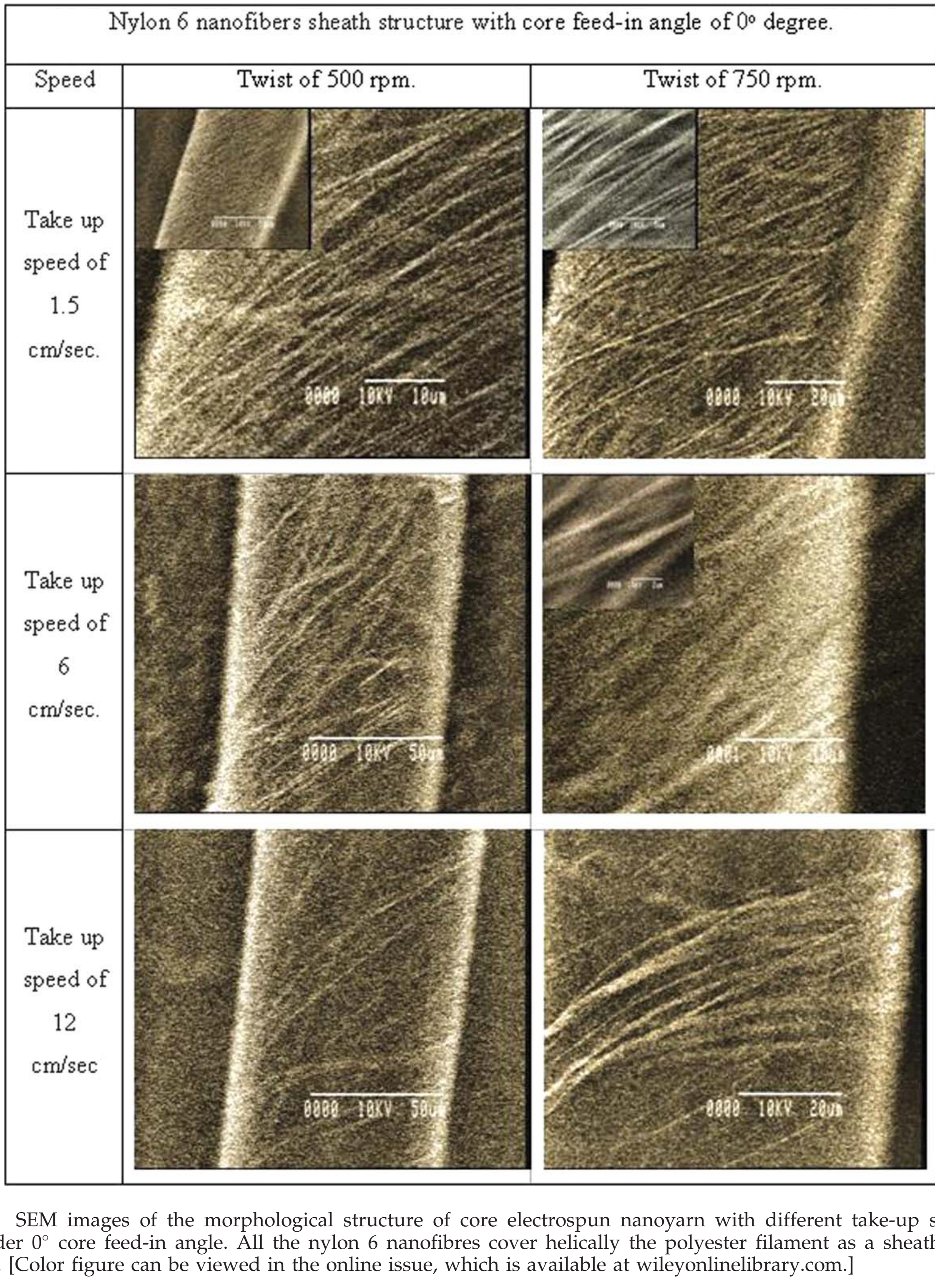

Figure 7 SEM images of the morphological structure of core electrospun nanoyarn with different take-up speed and twist under 0° core feed-in angle. All the nylon 6 nanofibres cover helically the polyester filament as a sheath in the *Z* direction. [Color figure can be viewed in the online issue, which is available at wileyonlinelibrary.com.]

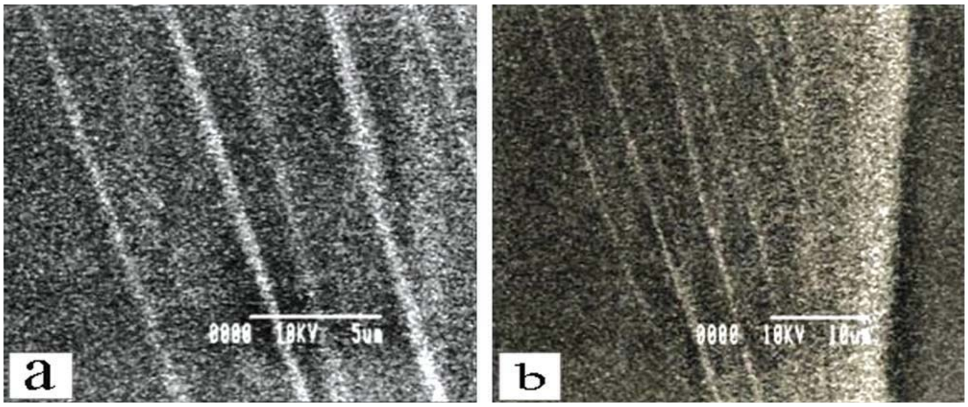

Figure 8 Electrospun nylon 6 nanofibers covered helically the polyester filament in the *S* direction. (a) Twist revolutions of 500 rpm and take-up speed of 6 cm/s and (b) twist revolutions of 500 rpm and take-up speed of 12 cm/s. [Color figure can be viewed in the online issue, which is available at wileyonlinelibrary.com.]

At an optimum core feed of 0°, Figure 7 shows SEM images of core electrospun nanoyarn morphological structures with take-up speeds of 1.5, 6, and 12 cm/s and twists at 500 and 750 rpm.

On the basis of our previous work, a mechanism for continuous nanofiber yarn,[7] we found that at twists of 500 and 750 rpm uniform and coherently tight nanofibers are wrapped around the core filament. At lower twisting rates of 500 rpm, the deposited nanofibers move to a higher angular displacement at a fixed take-up speed. Therefore, higher angular displacement leads to higher twist angles and consequently to lower twist per unit length of the core filament yarn. SEM images in Figure 7 show a twist angle of 45–60° at 500 rpm twist (disk revolutions) and at twist angle of 30–45° at 750 rpm twist (disk revolutions), respectively. The results obtained here are in agreement with those in the literature for conventional core spun yarn.[10,11] One of the great advantages of this mechanism is the ability of controlling twist direction. Core yarns were electrospun with *Z* direction as shown in Figure 7 and in *S* direction as shown in Figure 8.

In conventional core spun yarns, it is found that the critical sheath size is dependent on the fiber length, fineness, and type of fiber.[12,13] Contrary to this, the critical sheath size in our mechanism is dependent on the take-up speed rate. Take-up speed rate will affect the sheath size, sheath core ratio, adhesion, sheath number of layers, and the count of the core electrospun nanoyarn. The SEM images in Figure 7 show that as the sheath size increases, the sheath core ratio increases, producing best adhesion, and the highest yarn count, as the take-up speed decreases to minimum. Moreover, at low take-up speed, sheath fibers with more layers would be formed. These layers, because of their helical configuration, generate radial pressure on the core filament and thereby restrict slippage. In fact, this is expected as with take-up speed of 1.5 cm/s there is more time for fibers to adhere and form sheath layers. On the other hand, a take-up speed of 1.5 cm/s will produce the lowest core yarn production rate. Hence a balance between sheath size and production rate should be found for optimization of manufacturing.

Consequently, core electrospun nanoyarn has been developed at core feed-in angle of 0°, take-up speed of 1.5 cm/s, and twist at 500 rpm as shown in Figure 9 by a new mechanical arrangement.

Optimizing these parameters further requires knowing the velocity of the deposited nanofibers and their branching out. This has now being studied and will be discussed in another article. It can also be noted that increasing number of the spinnerets around the core filament in a circular plain geometry

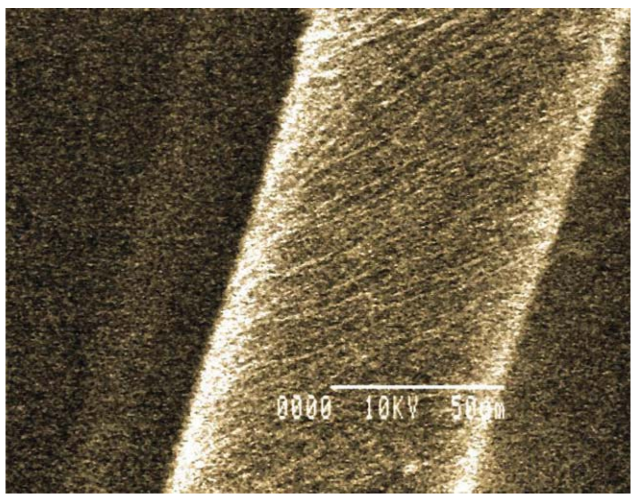

Figure 9 SEM image of polyester core electrospun nanoyarn covered with nanofibers in a helical sheath with core feed-in angle of 0,° take-up speed of 1.5 cm/s and twist of 500 rpm. [Color figure can be viewed in the online issue, which is available at wileyonlinelibrary.com.]

will provide the opportunity to increase the take-up speed and thus the core yarn production rate. It should also be mentioned that, to improve adhesion pretreatment of the synthetic core with plasma for instance will increase the adhesion and post-treatment of the nanofiber sheath with hydrophilic agents will achieve greater moisture absorption and release. Adding of more spinnerets, pretreating the filament and post-treating of the core nanofiber sheath are further issues under investigation.

CONCLUSIONS

In this research article, a novel mechanism for producing core electrospun nanoyarn has been designed, investigated, and implemented. Core filaments that can be used include polymer, carbon, glass and elastomeric filament, monofilament, textured filament, high tenacity filament, metallic wire, and staple yarn. Twist rates at 500 to 750 revolutions per minute at core filament feed-in angle of 0° and take-up speed of 1.5 cm/s were found to be the optimum parameters for producing nanoyarn under this new nanoyarn spinning mechanism.

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