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Preparation of continuous nanofiber core-spun yarn by a novel covering method

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ABSTRACT

A novel covering method to fabricate nanofiber core-spun yarn has been developed. Effects of span distance and rotation speed of disks on morphology, covering effect, abrasion resistance, wicking property, and mechanical property were mainly discussed in this investigation. Results showed that span distance had a significant effect on covering effect, and nanofiber core-spun yarn with a perfect covering effect could be prepared at the span distance of 2 cm with covering rate and abrasion growth rate of 30% and 142.3%, respectively. Alignment direction of nanofibers on the surface of nanofiber core-spun yarn was affected by rotation speed of disks, and would lead to the changes of wicking property and mechanical property. When the rotation speed of disks was 200 rpm, wicking property of nanofiber core-spun yarn was relatively better with the wicking effect of 7.6 cm. Breaking strength was decreased first and then increased with the increase of rotation speed.

1. Introduction

Electrospinning is a simple and efficient method for fabrication of nanofibers, which possess a huge specific surface area, nano-sized diameter and high porosity [1,2]. Therefore, they have great application value in filters, wound dressings, composites, tissue engineering scaffolds, protective clothing, electronics, sensors, and drug delivery materials [3–6]. Generally, repulsion between charges makes polymer jets unstable under high-voltage electric field, resulting in deposition of nanofibers on the collector in a random state. However, the randomly oriented non-woven mat has relatively low mechanical strength, which has limited its applications in some fields [7,8]. In order to solve this problem, it can be considered to use a traditional yarn as the core covered by nanofibers to prepare the nanofiber core-spun yarn, which will have a enough strength to be woven into a functional fabric.

Approaches to cover nanofibers on the traditional yarn surface by using rotary disk or funnel were commonly used. Scardino [9] prepared the continuous nanofiber core-spun yarn by using helical-vortex air current to apply nanofibers on the core yarn surface randomly. Zhou [10] electrospun nanofibers on the surface of parallel monofilaments with the diameter of 50 μm, and a number of nanofiber-covered monofilaments were then twisted into a composite nanofiber yarn by a conventional nozzle-type electrospinning setup. Dabirian [11] used two charged oppositely-placed needles and a neutral plate to produce the nanofiber core-spun yarn. He [12] produced the nanofiber core-spun yarn by covering nanofibers on the surface of a core yarn through a multi-nozzle air jet electrospinning set-up and a rotating funnel, which were further used to prepare four kinds of carbon nanofiber yarns through thermal stabilization and carbonization [13]. Liu [14] prepared the nanofiber core-spun yarn by adoption of the blown bubble spinning, and nanofiber bundles could be formed and twisted in one step. Najafi [15] produced core-sheath yarn by using an aluminum drum as the temporary collector, in the surface of which there was a hole for core yarn entering the collecting area, where nanofibers were formed from two opposite spinnerets. However, above existing methods to prepare the nanofiber core-spun yarn through electrospinning were either complicated or failed to consider the alignment of nanofibers covering on the core yarn.

Based on the method to prepare aligned electrospun nanofibers through parallel electrode method proposed by Teo [16] and Zhao [17], a novel covering method was designed to prepare the nanofiber core-spun yarn through electrospinning. A conventional yarn was placed between two parallel aluminum flakes to twist aligned nanofibers on the surface of core yarn, and then a novel nanofiber core-spun yarn is formed. Effects of span distance (distance between two parallel

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aluminum flakes) and rotation speed of disks on covering effect, abrasion resistance, wicking property, and mechanical property of the resultant yarn were investigated.

2. Experimental

2.1. Materials

Poly acrylonitrile (PAN) ($M_w = 70{,}000$ g/mol) (Hangzhou Bay Acrylic Fiber Co., Ltd., China) solution with the concentration of 12 wt% was prepared by dissolving it in *N*,*N*-dimethylformamide (DMF) (Tianjin Kermel Chemical Reagents Co., Ltd., China). PAN and DMF were used without further purification.

2.2. Electrospinning process

Collecting distance (distance between spinneret tip and upper edges of two parallel aluminum flakes), applied voltage and flow rate were set at13cm, 17 kV and 0.8 mL/h, respectively. Rotation speed of rollers (30 rpm) was constant during every electrospinning process. In order to explore the effect of span distance on covering effect of the resultant nanofiber core-spun yarn, different span distances including 2 cm, 3 cm, 4 cm, 5 cm, and 6 cm were selected. Effect of rotation speed of disks on alignment of nanofibers on the surface of core yarn, wicking property, and mechanical property of nanofiber core-spun yarn was studied. Rotation speeds of disks were selected as 200 rpm, 350 rpm, 500 rpm and 700 rpm, respectively. All the experiments were carried out at 20 ± 2 °C and 65 ± 5 RH%.

2.3. Measurement

2.3.1. Characterization of morphology of resultant nanofiber core-spun yarn

Morphology of the nanofiber core-spun yarn was characterized by a field emission scanning electron microscope (FESEM) (Quanta-450-FEG, FEI, England). Optical images and videos of electrospinning process were recorded by a digital camera (HDR-SR11E, SONY, Japan).

2.4. Measurement of performance of resultant nanofiber core-spun yarn

Covering effect: The obtained nanofiber core-spun yarn was cut into 10 sections with the equivalent length of 2 m, which were weighed by an electronic balance(Sartorius CP 225D, Germany, with the precision of 0.00001 g) to calculate the covering rate (R_c) of the resultant nanofiber core-spun yarn.

$$Rc = \frac{W_1 - W_0}{W0} \times 100\% \tag{1}$$

where R_c is covering rate, %; W_0 is the weight of core yarn, g; W_1 is the weight of nanofiber core-spun yarn, g.

Abrasion resistance: All the obtained core-spun yarn with the length of 2 m were then used to obtain the abrasion resistance of nanofiber core-spun yarn by a abrasion tester (Y731D, China). Abrasion resistance can be characterized with abrasion growth rate (R_a) expressed as follows:

$$Ra = \frac{N1 - N0}{N0} \times 100\% \tag{2}$$

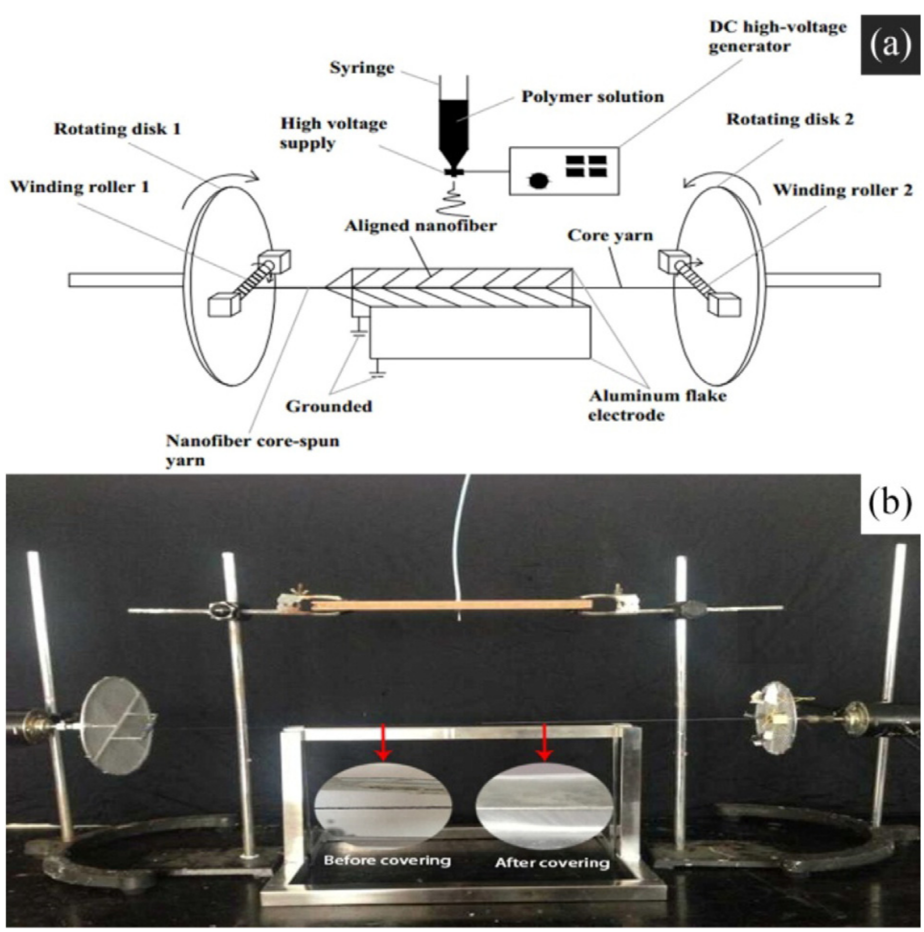

Fig. 1. (a) Schematic of the set-up used to prepare nanofiber core-spun yarn; (b) image of the self-designed setup.

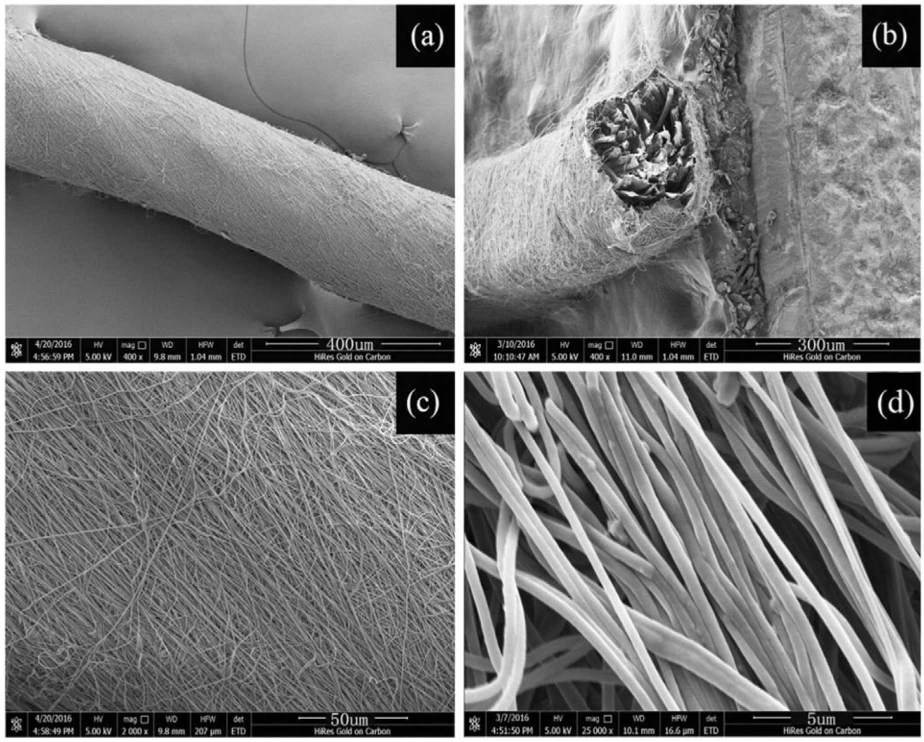

Fig. 2. SEM images of nanofiber core-spun yarn: (a) surface morphology of nanofiber core-spun yarn; (b) cross section of nanofiber core-spun yarn; (c, d) nanofiber arrangement on the surface of nanofiber core-spun yarn under magnifications of 2000 and 25,000.

where R_a is abrasion growth rate, %; N_0 is the abrasion cycles of core yarn, cycle; N_1 is the abrasion cycles of nanofiber core-spun yarn, cycle.

Wicking property: Wicking effect (H), defined that when textile is infiltrated in liquid, some liquid can rise along capillaries due to the surface tension, was tested by a wicking property tester (YG(B)871, China). Wicking effect can be expressed as follows:

$$H = \frac{\sum_{i=1}^{n} h_i}{n} \tag{3}$$

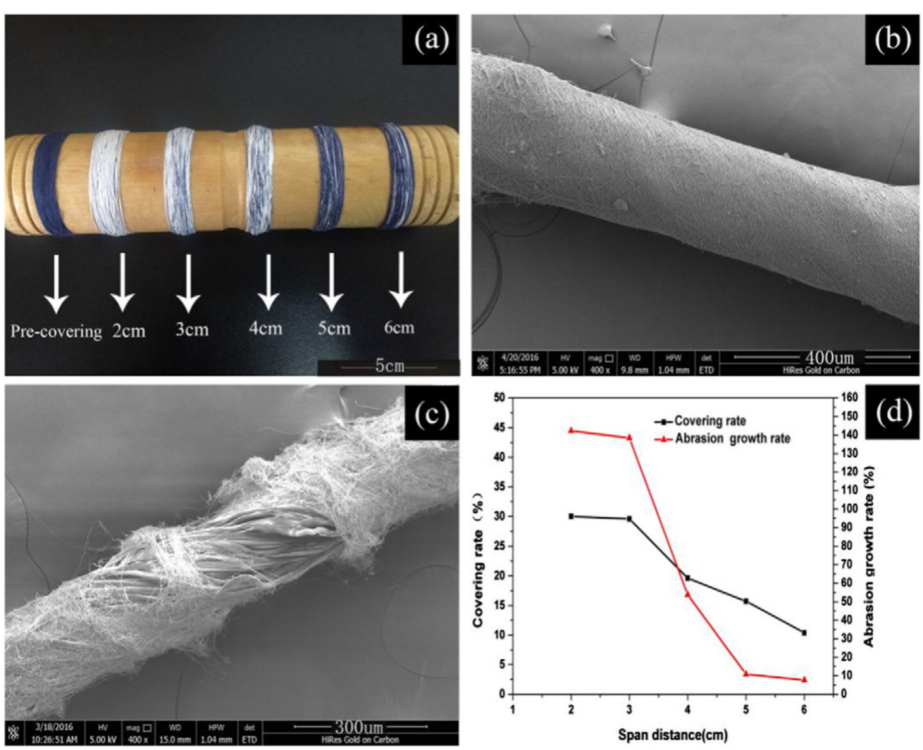

Fig. 3. (a) nanofiber core-spun yarn fabricated under different span distances (2 cm, 3 cm, 4 cm, 5 cm, 6 cm); (b, c) nanofiber core-spun yarn with a complete and incomplete covering; (d) effect of span distance on covering rate and abrasion growth rate of nanofiber core-spun yarn.

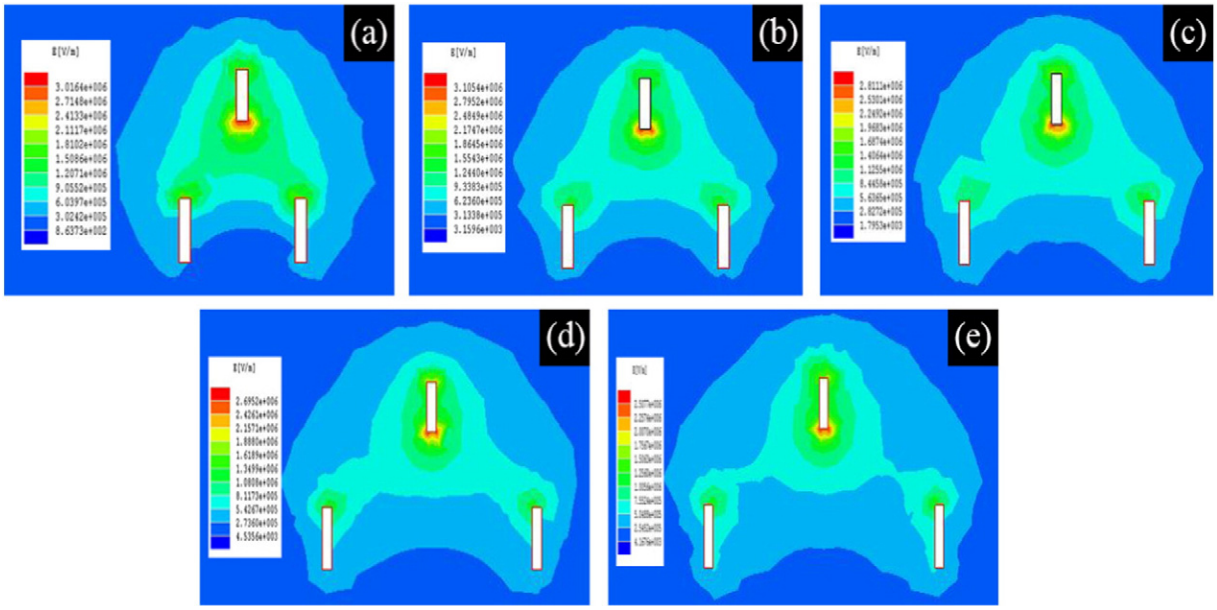

Fig. 4. Distribution of electric field intensity for different span distances: (a) 2 cm, (b) 3 cm, (c) 4 cm, (d) 5 cm, (e) 6 cm.

where H is the mean of wicking effect, cm; h_i is the wicking effect of every nanofiber core-spun yarn, cm; n is the number of nanofiber core-spun yarn.

Mechanical property: Breaking strength was measured by a strength tester (5565, Instron, America).

3. Results and discussion

3.1. Apparatus and mechanism of preparing nanofiber core-spun yarn

The schematic and image of the self-made electrospinning set-up are shown in Fig. 1, which consists of four major systems: the electrospinning system (a syringe and a spinneret with the inner diameter of 1.65 mm), the applied voltage system (a DC high-voltage generator), the grounded collecting system (two parallel aluminum flakes), the covering system (two rotating disks with two winding rollers).

During electrospinning, solution was pushed into spinneret and a Taylor cone was formed on the spinneret tip. Applied voltage was increased until the jets ejected from Taylor cone, and nanofibers with a certain degree of orientation would suspend over the edges of two parallel aluminum flakes. Meanwhile, two disks began to rotate in the same direction to make aligned nanofibers cover around the surface of the core yarn, and two winding rollers also rotated to obtain the resultant nanofiber core-spun yarn.

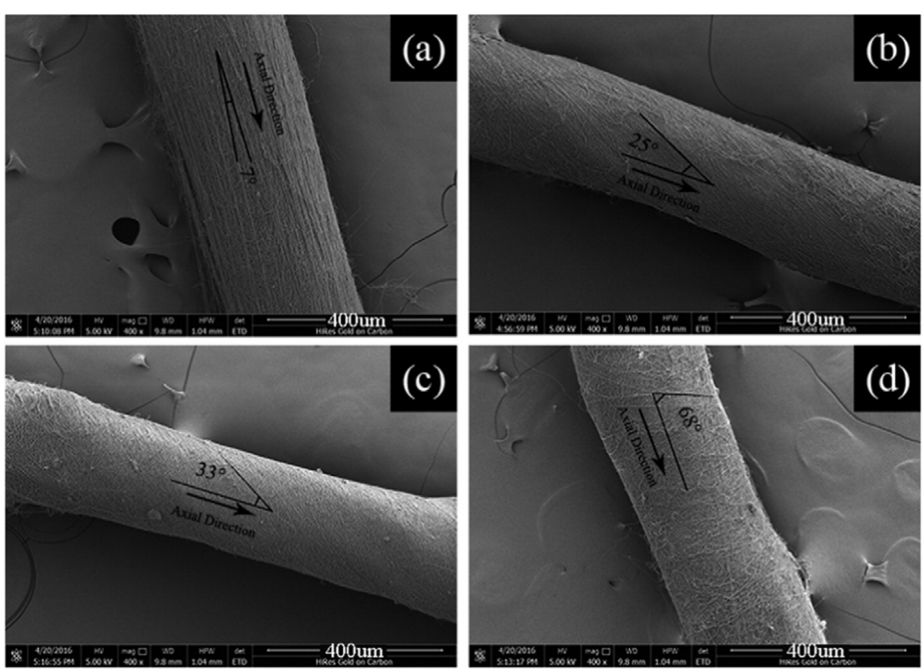

Fig. 5. Alignment direction of nanofibers on the surface of core-pun yarn for different rotation speeds: (a) 200 rpm, (b) 350 rpm, (c) 500 rpm, (d) 700 rpm.

Table 1
Wicking property of nanofiber core-spun yarn for different rotation speeds.

Rotation speed of disks/rpm	Wicking effect (H)/cm			
	1	2	3	Mean
Core yarn (without covering)	6.1	5.7	5.3	5.7
200	8.8	7.4	6.6	7.6
350	7.8	7.6	6.7	7.4
500	7.4	7.3	6.9	7.2
700	7.4	7.0	7.0	7.1

3.2. Morphology of the nanofiber core-spun yarn

Although some random fibers could be observed on the surface of nanofiber core-spun yarn as shown in Fig. 2a, most nanofibers with relatively uniform diameter had a large extent of alignment along a certain direction (Fig. 2(c, d)). The layered structure could also be observed through the cross section of nanofiber core-spun yarn shown in Fig. 2b.

3.3. Effect of span distance on covering effect and abrasion resistance of nanofiber core-spun yarn

Nanofiber core-spun yarns prepared under different span distances (2 cm, 3 cm, 4 cm, 5 cm, 6 cm) are shown in Fig. 3. Fig. 3a shows that the covering effect of nanofiber core-spun yarn gradually becomes poor with the increase of span distance. When the span distance was 2 cm, it could be found that core yarn were covered very well by electrospun nanofibers. While the covering effect began to deteriorate when the span distance was more than 5 cm, and only there were few nanofibers on the surface of core yarn. Fig. 3b and c show the SEM images of core-spun yarn with a complete and incomplete covering.

From Fig. 3d, it could be discovered that covering rate decreased from 30.0% to 10.4% when the span distance increased from 2 cm to 6 cm, which is in agreement with the result of Fig. 3a. The reasons can be attributed as follows: When the span distance becomes larger, the color between the flake electrodes is becoming from green to blue shown in Fig. 4, which indicates that electric field intensity of the horizontal component between the two parallel collectors is turning small and difficult to guide nanofibers span over the gap. Furthermore, the greater gap also leads to larger gravity of nanofibers. Therefore, nanofibers cannot deposit across the gap smoothly with the increase of span distance. The maximum covering rate from a single needle was up to 30.0%, while that from 4 needles reported by He [12] was only 70.4%. In addition, covering effect is the main driving factor for abrasion resistance, so the abrasion growth rate dependent on the covering rate also became deteriorated with the increase of span distance. The maximum value of the abrasion growth rate was 142.3% at the span distance of 2 cm.

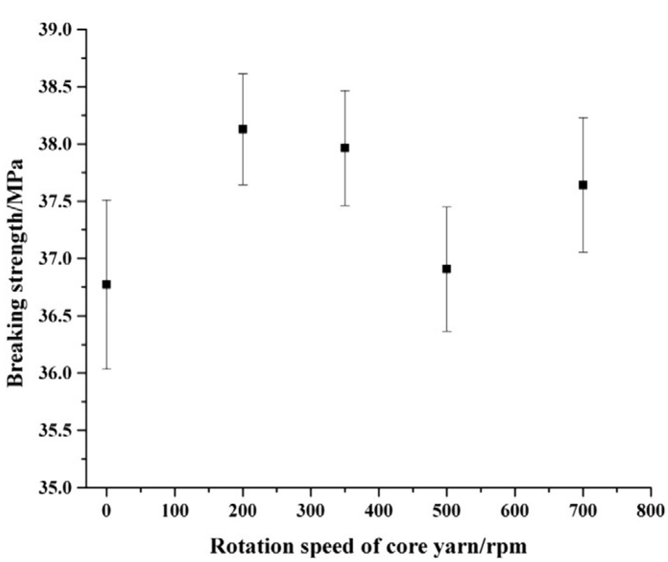

Fig. 6. Breaking strength of nanofiber core-spun yarn for different rotation speeds.

3.4. Effect of rotation speed of disks on alignment direction of nanofibers on the surface of nanofiber core-spun yarn

Rotation speed of disks is also the rotation speed of core yarn, different rotation speeds will lead to different covering cycles of nanofibers in a unit of length. So alignment direction of nanofibers on the surface of core-spun yarn is dependent on rotation speed of disks. SEM images of nanofiber core-spun yarn for different rotation speeds are shown in Fig. 5. When rotation speed of disks was 200 rpm, the alignment angle between direction of nanofibers and axial direction of core yarn was only 7°, and increased with the increase of rotation speed of disks. In addition, it was observed that nanofibers on surface of core yarn were relatively random when rotation speed was 700 rpm.

3.5. Effect of rotation speed of disks on wicking property of nanofiber core-spun yarn

Table 1 represents the wicking property of nanofiber core-spun yarn for different rotation speeds. As shown in the table, wicking property of nanofiber core-spun yarn for different rotation speeds was better than that of core yarn. The maximum wicking property of nanofiber core-spun yarn was 7.6 cm for the rotation speed of 200 rpm, which was enhanced by 33% when compared to core yarn. Although the wicking property for different rotation speeds has a small difference, it still presents a slight decrease with the increase of rotation speed of disks. The reasons leading to this result can be explained from the following aspects: Firstly, more capillaries formed between nanofibers due to the nano-sized diameter are beneficial to diffusion of liquid. Secondly, the alignment angle between direction of nanofibers and axial direction of core yarn increases with the increase of rotation speed, which will result in the inclining of route and bring resistance for diffusion of liquid.

3.6. Effect of rotation speed of disks on mechanical property of nanofiber core-spun yarn

Fig. 6 gives the breaking strength of the nanofiber core-spun yarn for different rotation speeds. Breaking strength of the nanofiber core-spun yarn presented a slight increase compared with the core yarn. With the increase of rotation speed, breaking strength was decreased first and then increased. The reasons might be given as follows: At a relatively low speed, more aligned nanofibers will be oriented along the axial of the core yarn, which is beneficial to the increase of breaking strength of nanofiber core-spun yarn. With the increase of rotation speed, angle between direction of aligned nanofibers and the axial of core yarn starts to become smaller and smaller, resulting in a decrease of component force along the stretching direction. While at a relatively high speed, large friction and cohesive force between fibers due to the high twist level can make the nanofiber core-spun yarn withstand larger tension at break.

4. Conclusion

A novel covering method for preparation of continuous nanofiber core-spun yarn through electrospinning has been developed. Nanofibers were firstly aligned between the gap of collectors, and then wound on the surface of core yarn. So more aligned nanofibers deposited on the surface of core yarn could be obtained through the method. Effect of span distance on morphology, covering rate, and abrasion resistance were analyzed. Wicking property and mechanical property of nanofiber core-spun yarn for different rotation speeds of disks were also studied. Covering rate and abrasion growth rate both decreased when the span distance increased from 2 cm to 6 cm. Wicking property of nanofiber core-spun yarn became deteriorated with the increase of rotation speed of disks. Breaking strength was decreased first and then increased with the increase of rotation speed. Nanofiber core-spun yarn prepared by this method can be hoped to prepare many kinds of functional textiles by use of the properties of nanofiber.

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