

## Structural Characterization and Investigation of Selected Properties of Hybrid Yarn Coated with Carbon Nanotube Composite Nanofibers

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**ABSTRACT**: The current research discusses the efforts to achieve yarns coated with composite nanofibers and investigates some of their properties. Polyacrylonitrile/dimethyl formamide solutions containing various mass concentrations of single-wall and multiwall carbon nanotubes (SWCNTs and MWCNTs) and also functionalized SWCNTs were electrospun onto an acrylic staple yarn to produce hybrid yarns. The effect of the CNT addition on the final morphologies of the nanofibers was evaluated using SEM. The fibers prepared with higher CNT concentrations had larger diameters than those of fibers obtained by lower concentrations. The SEM, the optical microscope, and the microtome were used to investigate the structural morphology of the hybrid yarns. The conductivity and the viscosity of the solutions at different SWCNT concentrations were measured. The surface electrical resistance and the mechanical properties of the hybrid yarns composed of the nanofibers as sheath were analyzed. © 2012 Wiley Periodicals, Inc. J. Appl. Polym. Sci. 000: 000–000, 2012

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#### **INTRODUCTION**

Electrospinning is an effective fabrication technique that utilizes an external electrostatic field to generate fibers with diameters ranging from several nanometers to micrometers. This method has gained much attention in recent years. In electrospinning, a polymer solution is charged with a high voltage. The charged solution is conducted to a grounded collector and as solvent vaporizes on the way toward the collector; dry fibers are formed on the collector.<sup>1</sup> For some applications such as electronic, optoelectronic, photonic, sensors, etc., it is more desirable to obtain nanofiber assemblies which are oriented along the same axis.<sup>2</sup> Therefore, producing the yarn from nanofibers is considered as one of the great potentials in electrospinning. It should be noted that current nanofiber yarns have poor mechanical properties.3 Various types of nanosized fillers have been embedded recently in nanofibers through electrospinning to modify the properties of electrospun fibers.<sup>4</sup> Among them, carbon nanotubes (CNTs) have attracted researchers,<sup>4</sup> because of their unique structure and strong physical properties.<sup>5</sup> CNTs which consist of cylindrical graphite sheets with nanometer diameter,<sup>6</sup> exhibit excellent mechanical properties and great electrical and thermal conductivity. These properties make them ideal candidates for reinforcing polymer materials.<sup>7</sup> Typically, they serve as a reinforcement component in polymer fibers, but they are also used to improve the electrical properties of fibers.<sup>8</sup>

To fully explore their reinforcing properties, both exfoliation and uniform dispersion of CNTs are important. CNTs are normally curled and twisted in the form of bundles and ropes due to their small size and also strong van der Waals forces between nanotubes. Therefore, CNTs embedded in a polymer matrix only exhibit part of their potential.<sup>6</sup> Any aggregation of CNTs in polymeric composites can cause unwanted properties. In views of the preceding, there has been an immense attempt to establish the most appropriate conditions for transferring mechanical load and electrical charge between individual CNTs in a polymeric composite. A prerequisite for such effort is the efficient dispersion of individual nanotubes and the creation of a strong chemical affinity (covalent or non-covalent) with the surrounding polymer matrix.9 The preparation based on simple polymer-CNTs mixtures, even by using high-shear mixing and ultrasonication process, typically results in composites of partly poor dispersion of the CNTs, which decrease the predicted or expected performance.<sup>10</sup>

Electrospinning is a new and operative tool for generating CNTs-polymer composites.<sup>11</sup> CNTs composite nanofibers have been prepared by various researchers. For example, Hou et al. and Ge et al. produced MWCNT/PAN nanofibers via electrospinning technique. In their study, they introduced carboxylic acid (-COOH) functional groups onto MWCNT by acid treatment.<sup>7</sup> Ko et al. also produced continuous CNTs-filled nanofiber yarns made by electrospinning.<sup>12</sup>

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The current study employs a new innovative method where manipulated electrospinning is used to coat a traditional yarn with nanofibers. The system designed by Hosseini et al.<sup>13</sup> was successfully used to fabricate hybrid yarn containing carbon nanotubes/polyacrylonitrile (PAN) composite nanofibers as the sheath, while an acrylic staple yarn was used as the core yarn. PAN polymer was chosen because of special properties of PAN nanofibers as a precursor of carbon nanofibers.<sup>14</sup> In addition, PAN nanofiber mats can be directly utilized for electrode materials after stabilization and carbonization.<sup>15</sup> CNTs used in the present experiment can be utilized in precursor fibers since CNTs can drastically resist heat shrinkage in composite fibers during the carbonization process.<sup>8</sup> In this study, both types of CNTs, namely, multi wall carbon nanotubes (MWCNTs) and single wall carbon nanotubes (SWCNTs), were used. Because of the fact that existence of strong van der Waals forces between CNTs and their small size cause the non-uniform dispersion, ultra-sonication process has been used to disperse the CNTs in solution in this study. Also, nonionic surfactant (polyethylene glycol, PEG) was added to decrease the agglomeration and improve the dispersion, as suggested by Ko et al.<sup>12</sup> In order to achieve interfacial bonding, SWCNTs modified with carboxylic groups were used.

This work, generally, describes the manufacturing of continuous hybrid yarns containing the composite nanofibers as the sheath component. In addition, some physical, mechanical, and morphological properties of the hybrid yarns are discussed.

#### EXPERIMENTAL

#### Materials

Dimethyl formamide (DMF) was purchased from Merck Company. The PAN powder (containing methyl methacrylate (4%) and Methacrylic acid (2%)) with average molecular weight  $(M_w)$  100,000 g mol<sup>-1</sup> were bought from Iran Polyacryl Company. The MWCNTs and SWCNTs with purity of 90% were supplied by Research Institute of Petroleum Industry (RIPI), Iran, and were used without further purification. They were manufactured by CVD. The average length and diameter of the MWCNTs were about 10 microns and 10-30 nm, respectively. The average length of the SWCNTs was 10  $\mu$ m and their average external and internal diameters were 1-2 nm and 0.8-1.1 nm, respectively. The functionalized SWCNTs with -COOH groups (purity of 90%) produced by CVD were obtained from Times, China. The average length of the SWCNTs-COOH was about 5–30 $\mu$ m and their average external and internal diameters were about 1–2 nm and 0.8–1.6 nm, respectively. PEG ( $M_w$ : 4000 g mol<sup>-1</sup>) was obtained from Sigma-Aldrich, Germany. Staple acrylic yarn was also supplied by Iran Polyacryl Company.

#### Preparation of the Solutions

The steadiest electrospinning jets and uniform pure PAN nanofibers without beads (observed by using optical microscope) were obtained from 13% (w/w) concentration of PAN in DMF. Thus, in all subsequent experiments, PAN concentration was fixed at 13%. All measurements were done as weight by weight (w/w). Suspensions were prepared with CNT concentrations of 5, 10, 15, and 20% of the mass of the dissolved PAN. The composite solutions were prepared in three steps. The procedure for

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Figure 1. A schematic diagram of the modified electrospinning setup.

making the PAN/CNT composite solutions can be explained as: (1) firstly, a small and certain amount of PAN powder was suspended in DMF solvent and was stirred on a magnetic stirrer for 15 min to dissolve, because this can act as a dispersing agent as said by Heikkilä et al.8; (2) secondly, 1 wt % of nonionic surfactant (polyethylene glycol, PEG) related to solution weight was added to decrease the agglomeration and improve the dispersion of the CNTs.<sup>12</sup> Afterward, CNTs were added and suspended in the diluted polymer solution by ultrasonic homogenizing for 15 min; (3) Finally, the rest of the polymer was added to achieve the desired polymer concentration(13 wt %).After being stirred, it was sonicated at any level for 15 min. The resulting solutions were used for electrospinning. It should be noted that hereafter we use these abbreviations: M, S, SC, and 0%N instead of multiwalled carbon nanotube, single-walled carbon nanotube, single-walled nanotube containing carboxylic acid groups, and pure PAN, respectively.

#### **Electrospinning Setup**

A modified electrospinning set-up for producing hybrid yarns containing nanofibers as the sheath component was used. The schematic diagram of the modified setup is shown in Figure 1. This system includes three main sections: (1) Feeder unit for feeding core varn, (2) Middle unit for producing nanofibers, (3) Take up unit for collecting the hybrid yarns. Core yarn is transferred to the middle unit. Middle unit equipment consists of four basic components containing a high voltage DC power supply (0-22 kV), two syringe pumps (STC-527,TERUMO, Japan), two nozzles, and a rotating conductive half-sphere. The high voltage power supply was employed to generate a potential difference between two needle tips. The potential difference between two needle tips was adjusted to 11 kV. The feeding rate of the polymer solution was selected 1.8 mLh<sup>-1</sup> using the syringe pumps reported earlier. The rotating speed of the halfsphere was 32 rpm. The polymer solution was introduced into the electric field. Once ejected out of the nozzles, the charged solution jets were evaporated to become fibers. The electrospun nanofibers were formed from the solution, between two nozzles on the rotating half-sphere bearing electrical charges of the opposite polarity. Core yarn emerged from inside of the hole at the center of the half-sphere. The nanofibers collected on the half-sphere were pulled out onto the core yarn, forming a conical geometry which we named it "spinning cone." Spinning



Figure 2. Viscosity of polymer solution versus the CNT content. [Color figure can be viewed in the online issue, which is available at wileyonlinelibrary.com.]

cone was rotated by the half-sphere and thus, nanofibers were twisted on the core yarn. Finally, the nanofiber-coated staple yarn was wound onto a low-speed rotating drum. Electrospinning of solutions was conducted at ambient humidity and temperature of 26°C. Electrospinning process of solutions was optimized to fabricate nanofibers with desired morphology.

#### Solution Characterization

The final morphologies and diameters of the fibers are dependent on two main characteristics of initial solutions: viscosity and conductivity. Therefore, in this study, their effect was assessed through changing concentrations of SWCNTs. The effect of CNT on the viscosity of electrospinning solutions was studied by using a rotating viscometer (DV-II+Pro-Brookfield model) with spindle rotation speed of 1.5 rpm, and at room temperature ( $26^{\circ}$ C). The effect of CNTs on the conductivity of the solutions was studied by using a conductivity meter (CG855 model). All measurements were performed after mixing and before electrospinning.

#### Morphological Characterization

The morphology of the electrospun fibers was first characterized by optical microscope (Motic, B3) and then by scanning electron microscopy (SEM, XL-30 model). Moreover, the optical microscopy and SEM were employed to check and analyze the morphological characteristics of hybrid yarns. SEM was used on gold-coated samples. The electrospun samples were coated with Au to reduce charging and produce a conductive surface. The average diameter and morphology of the electrospun fibers as well as degree of alignment of nanofibers as sheath of yarn can be estimated from SEM images. For fiber diameter measurements, SEM images from the electrospun fibers were obtained and then, these images were analyzed by using microstructure distance measurement software. One hundred measurements were made at each trial and then, by using statistic software SPSS 15, mean diameter (nm) and also standard deviation of fiber diameters (nm) were calculated. Surveys on the measurements of coating degree of the nanofibers onto the core yarn were done. Thus, by using microtome (SLEE cut 4055), some cross-sections of hybrid yarns were obtained and then, by using the optical microscopy, their images were obtained. Finally, coating degree of the nanofibers onto the core yarn was measured using a formula presented below and through an image processing program in Matlab (R2008a):

Coatingpercent (%) = (sheatharea/cross - sectionarea)  $\times$  100 (1)

# Characterization of Mechanical Properties of Composite Nanofibers

The tensile properties of the hybrid yarns were measured using a Zwick (1446-60Model). The tests were carried at a standard condition (humidity 65%, temperature  $20^{\circ}$ C)with a 5-cm gauge length and a 50 mmmin<sup>-1</sup> crosshead speed with a 50 cN preload. The tensile tests were carried out to evaluate the mechanical properties of the hybrid yarns as well as the core yarn.

# Characterization of Electrical Properties of Composite Nanofibers

The main objective of this study is to investigate the electrical transport properties of the CNTs in the composite nanofibers. The electrical properties of the surface of the hybrid yarns were investigated using resistance measurement with a Static-Volt-meter (RothschildR-4021). This instrument can determine electrical resistance of the samples through charging the surface of the yarns, and then measuring the time of the electrical discharge. The prepared samples, in suitable dimensions (10 cm length), were clamped between the two yarn electrodes. The insulated input terminal was charged to 150 V. The discharge time was recorded with a stopwatch until the drop of the tension to half its initial value. We have used the following formula offered by instrument catalogue to calculate the electrical resistance.

Surface electrical resistance ( $\Omega$ ) = discharge time (s) × 10<sup>11</sup>

It is obvious that with increasing the surface electrical resistance, discharge time increases.

We have studied the surface electrical resistance of the hybrid yarns for various concentrations and types of CNTs. All experiments were conducted at a standard condition (humidity 65%, temperature  $20^{\circ}$ C) on 10 cm length of yarns.

 Table I. Values of the Electrical Conductivity of the Solutions Containing

 Different Types and Concentrations of CNT

Solution type	Electrical conductivity ( $\mu$ S cm <sup>-1</sup> )
5%M	94
10%M	97.3
15%M	98.8
20%M	100.5
5%S	124
10%S	129
15%S	135
20%S	143
5%SC	148
10%SC	286
15%SC	317
20%SC	330





Figure 3. SEM images of electrospun nanofibers containing different SWCNT concentrations; (a) 0%, (b) 5%, (c) 10%, (d) 15%, (e) 20%. [Color figure can be viewed in the online issue, which is available at wileyonlinelibrary.com.]

#### **Statistical Analysis**

Results of all measurement were subjected to statistical analysis using SPSS 15. *P* values lower than 0.05 were considered statistically significant. The one-way analysis of variance (ANOVA) was used to test the difference between the groups.

#### **RESULTS AND DISCUSSION**

#### **Characterization of Initial Solutions**

The measurement of the viscosity was performed at different SWCNT concentrations. The obtained results show that the viscosity increases with increasing SWCNTs content (Figure 2).



Figure 3. (Continued)

Even increasing the SWCNTs content up to 5% increases the viscosity of SWCNT/PAN solution as compared to pure PAN solution. This is because of poor dispersion of CNTs that increases the viscosity of their solutions via increasing agglomerates in the solution.<sup>4</sup> Upon addition of more SWCNTs, it becomes more difficult to disperse the nanotubes and therefore, larger and more agglomerates are formed and the viscosity gradually increases.

Electrospinning utilizes electrical forces, so the electrical properties of the solutions can affect the process. Therefore, we investigated solution conductivity for solutions containing MWCNTs, SWCNTs, and COOH-SWCNTs. Conductivity increases with the increase of the CNTs mass fraction.

Moreover, the solutions containing COOH-SWCNT are more conductive than the solutions containing SWCNT, and the latter are more conductive than the solutions containing MWCNT (Table I). The improvement of the electrical transport in the solutions containing COOH-SWCNT compared to others can be attributed to one factor: the presence of carboxylic groups on the SWCNT improves the interactions between SWCNTs and the solvent DMF, thus their dispersion in the solution improves too. Solutions containing SWCNT have more conductivity than solutions containing MWCNT because the size of SWCNTs is smaller than that of MWCNTs. Indeed, the number of SWCNTs is larger than that of MWCNTs in a certain weight; therefore, this can cause the enhancement in the conductivity of solution containing SWCNTs.

#### Morphological Study of the Nanofibers

Figure 3 shows several samples of SEM images of electrospun nanofibers of the PAN and PAN/SWCNT composites containing different SWCNT concentrations. It illustrates the effect of adding SWCNT at different concentrations on final fiber's morphologies. PAN/SWCNT composite nanofibers showed more obvious surface irregularity [see Figure 3(b), red circle] and larger fiber diameters than the pure PAN nanofibers. The results extracted from SEM images of samples containing different amounts of SWCNT have been summarized in Table II. The fiber diameters varied between 200 and 600 nm, depending on CNT concentration. The surface irregularity is an observed characteristic at the CNT composite nanofibers, and the increase of fiber diameter can be explained by increasing the viscosity. Conductive filler particles have an effect on the solution conductivity and may develop two phenomena with opposite results on the fiber diameter: (1) Firstly, it's possible to raise flow rate which causes

Table II.	The Average	Fiber Diameters	of Samples	Containing	Different
SWCNT	Concentration	ns			

Sample	Average diameter (nm)	CV%ª
0%N	256.74	11.48
5%S	358.70	14.83
10%S	375.73	11.86
15%S	395.53	18.37
20%S	436.85	10.66

<sup>a</sup>Coefficient of variance = (standard deviation/mean)  $\times$  100.

larger fiber diameters. (2) And second, it's possible to increase net charge density which represses the Rayleigh instability and increases the whipping instability, which causes smaller fiber diameters. In fact, salts and other conductive additives can reduce and also increase fiber diameter.<sup>8</sup> Therefore, the difference in viscosity is one reason for the difference in the fiber diameter of PAN/CNTs and pure PAN solutions. In addition, higher conductivity leads to increase mass flow and thus larger fiber diameters. Our findings are consistent with those of Heikkilä et al.<sup>8</sup>

Bead-like structure or surface irregularity was observed in PAN/ SWCNT composite nanofibers when the amount of SWCNT was increased. It's probably due to the less dispersion and agglomeration of the CNTs. When CNTs are not well dispersed, charge aggregation is localized along fiber axis due to the inhomogeneity of polymer solution conductivity, and the charge density is not dispersed uniformly along nanofiber; therefore, electrical field is not homogenous along fiber. The inhomogeneity of charges and electrical field causes the bead formation along fiber axis.<sup>4</sup> It was reported that electrical force varied capillary breaking of electrospinning jet by the surface tension, which causes the formation of the beaded nanofibers.<sup>6</sup> It was also reported that the CNT large aggregations are located inside the beads along the nanofibers. Thus, at higher CNT concentrations, the number of beads increases, and they are filled with CNTs. In fact, the beads are CNT aggregation sites.<sup>4</sup> Therefore, the presence of aggregated CNTs leads to the bead formation and the surface roughness. Thus, both fiber diameter and surface morphology could be controlled by the CNT dispersion. So the dispersion condition could be presented as a controlling factor of the fiber morphology.

#### Morphological Study of the Hybrid Yarns

Figure 4 shows the SEM images from the surface layer of an acrylic staple yarn coated with the electrospun PAN/15%SWCNT composite nanofibers. SEM observation showed that the nanofibers were oriented along the axes of the yarn. Figure 5 shows some microtome images of the cross-sections of the hybrid yarns. In Figure 6, the SEM images show the edge of an acrylic staple yarn coated with the electrospun PAN/15%SWCNT composite



Figure 4. The image of surface of an acrylic staple yarn coated with the electrospun PAN/15%SWCNT composite nanofibers at different magnifications.



Figure 5. The specimens of microtome images of the cross-sections of the hybrid yarns at different SWCNT concentrations; (a) 0%, (b) 5%, (c) 10%, (d) 15%, (e) 20%. [Color figure can be viewed in the online issue, which is available at wileyonlinelibrary.com.]

nanofibers. From Figures 5 and 6, it is clearly observed that the surface of the core yarn has been well coated by the nanofibers. Table III presents the average coating percent of the yarns containing different SWCNT concentrations. This experiment was performed on five samples of each yarn.

#### Mechanical Characterization of Hybrid Yarns

The detailed mechanical properties data listed in Table IV, show that each data point was obtained by averaging the results of 10 test samples. Results related to the values of tensile strength of the hybrid yarns did not show any statistical significant difference in comparison with the core yarn and also with each other. Thus, the tensile strength of the hybrid yarns is affected more by the tensile strength of the core yarn, and the contribution of the sheath to the tensile strength of the hybrid yarns is poor. It has been found that there is a significant difference between elongation of the core yarn and the hybrid yarn coated with pure PAN nanofibers. The hybrid yarn containing pure PAN nanofibers has significantly high elongation compared to the core yarn. All hybrid yarns have no significant difference in their elongation; also there is no significant difference in elongation of hybrid yarns coated with composite nanofibers and the core yarn.

These could be due to the solidification of CNT composite nanofibers which occurred faster than pure polymer nanofibers due to intensive bending instabilities. While, pure polymer nanofibers were deposited on the core yarn before the solvent can be completely evaporated. The remaining solvent gradually evaporated, and PAN nanofibers were adhered to the core yarn.

Further, mechanical tests showed that tensile modulus of the hybrid yarns containing the pure PAN nanofibers was significantly



Figure 6. SEM images of the cross-section of hybrid yarn containing 15% SWCNT at different magnifications.



 Table III. The Average Coating Percent for the Yarns Containing Different

 SWCNT Concentrations

Yarn type	Average coating percent	CV%
0%N	27.44	4
5%S	25.13	5.69
10%S	26.71	5.42
15%S	27.32	6.37
20%S	25.39	4.35

higher than that of the other hybrid yarns and the core yarn. In addition, the hybrid yarns had significantly high average work at the break, as compared to the core yarn. In general, mechanical properties of hybrid yarns are close to those of the core yarn. Of course, by increasing the portion of the sheath in the yarn, the contribution of the core yarn to the mechanical properties of the hybrid yarn can be affected.

#### Electrical Characterization of Hybrid Yarns

Because CNTs have excellent electrical properties, we expect a better electrical conductivity in the PAN/CNTs nanofibers.

The electrical properties were examined as a function of the CNT concentration (0, 5, 10, 15, and 20%), the CNT type (MWCNT or SWCNT), and also, functionalized and non-functionalized CNTs (COOH-SWCNT and SWCNT). The surface electrical resistance of the hybrid yarns with two different types of carbon nanotubes (MWCNT and SWCNT) and also the functionalized carbon nanotubes (COOH-SWCNTs) for different concentrations of CNT have been tabulated at Table V. As can be seen, each data point was obtained by averaging the results of ten test samples.

The ANOVA analysis indicated that increasing the MWCNT content from 0 to 15% did not lead to any significant difference in the surface electrical resistance of yarns, while a significant decrease of the electrical resistance was obtained by further increasing MWCNT content up to 20%.

It was demonstrated that increasing the SWCNT content from 0 to 10% had no significant difference in the surface resistance of yarns, while a significant decrease of the electrical resistance was observed by further increasing SWCNT content up to15 and 20%.

There was a significant decrease in the electrical resistance by increasing the SWCNT-COOH content from 0 to 15%.

Generally, a decrease of the electrical resistance was obtained by the addition of the CNT. Further, the SWCNT composites showed more improvement in the electrical conductivity than MWCNT for a given loading. Thus, the type of the CNT (SWCNT or MWCNT) plays an important role in the enhancement of the electrical conductivity of the CNT composites. It can be attributed to the smaller size of SWCNTs compared to MWCNTs. Because the number of the SWCNTs is more than that of the MWCNTs in a given weight, and in a percolation dependent conductivity, this larger number will certainly contribute to an increase in the conductivity. Furthermore, the functionalized SWCNT composites showed better improvement in the electrical conductivity than nonfunctionalized SWCNT for a given loading. This is mainly due to the fact that the functionalization improves the dispersion. In 15% content of COOH-SWCNT, the composites showed the lowest resistance as expected. Basal problem associated with providing conducting composite nanofibers by using the CNTs is the task of dispersing the nanotubes in the host polymer matrix.<sup>5</sup> It has been widely accepted that the chemical functionalization reduces the electrical conductivity of isolated nanotubes.<sup>16</sup> However, several researchers have reported that functionalization can enhance the electrical conductivity of the CNT composites by increasing dispersion.<sup>17</sup> Addition of surfactants also improves the dispersion and subsequently the electrical conductivity, unless the dispersant remains among the CNTs and enhances the interfacial resistance.18

The electrical resistance of the composite nanofiber can be expressed by  $R_{\text{Total}} = R_{\text{PAN}} + R_{\text{CNT}}^{15} R_{\text{CNT}}$  is related to the intrinsic properties of the CNT used. First, it is notable that all known preparations of CNT create mixtures of variant chirality, diameters, and lengths along with different amounts of impurities and structural defects. CNTs, depending on their structural parameters can be conductors or semiconductors.<sup>6,17</sup> CNTs obtained from the regular method are usually a blend of conducting and semiconducting materials.<sup>19</sup> These parameters change significantly both within a sample and between samples from different batches and labs. Thus, it is too difficult to perform reproducible controlled experiments with these dissimilar nanofillers. In fact, it is impossible to compare the results

Table IV. The Mech	nanical Properties	Data for the F	lybrid Yarns	Containing	Different SWCNT	Concentrations

	Average of ya	count arn	Average te strengt	nsile h	Average elo at brea	ngation ak	Average v at brea	work ak	Elastio modulus	c (E)
Sample	den <sup>a</sup>	CV%	cN/tex <sup>b</sup>	CV%	%	CV%	N (mm)	CV%	cN/tex	CV%
Core yarn	232	4.32	17.3	8.49	19.615	10.18	28.583	16.88	187	6.75
0%N	267	3.68	18.037	9.46	21.647	7.16	36.605	15.74	223	3.63
5%S	276	2.45	17.303	5.26	20.578	5.76	34.975	9.67	188	8.19
10%S	276	3.17	17.92	6.02	21.379	4.52	36.901	9.66	178	5.69
15%S	276	2.97	16.849	8.45	20.309	7	33.381	7.22	184	7.06
20%S	276	3.35	18.433	8.93	21.307	4.8	38.219	11.39	200	5.52

<sup>a</sup>Denier count (den): Den = g/9000 m, <sup>b</sup>Tex count (Tex): Tex = g/1000 m.

Table V. The Average Surface Electrical Resistance of the Hybrid Yarns

Sample	Discharge time (s)	Electrical resistance (Ω)	CV%
0%N	8.03	$8.03 \times 10^{11}$	15.88
5%M	8.47	$8.47 \times 10^{11}$	16.68
10%M	8.71	$8.71 \times 10^{11}$	16.83
15%M	7.28	$7.28 \times 10^{11}$	12.14
20%M	4.25	$4.25 \times 10^{11}$	24.18
5%S	8.15	$8.15 \times 10^{11}$	22.80
10%S	8.44	$8.44 \times 10^{11}$	19.08
15%S	3.76	$3.76 \times 10^{11}$	22.43
20%S	3.02	$3.02 \times 10^{11}$	41.50
5%SC	6.07	$6.07 \times 10^{11}$	19.67
10%SC	4.23	$4.23 \times 10^{11}$	18.10
15%SC	3.18	$3.18 \times 10^{11}$	18.23

obtained by different researchers. Therefore, the property of the composite fiber could be affected by the intrinsic properties of the CNTs used as well as the factors that can affect the electron transportation along the fiber axis.<sup>19</sup>

It has to be said that electrospinning of PAN/20%COOH-SWCNT solution encounters the process problems and thereby, we were not successful in producing the uniform yarns containing nanofibers of PAN/20%COOH-SWCNT solution. It should be noted that the optimization of the process parameters for the systems with more solution conductivity can be more challenging than for typical polymer systems as a result of the interactions between the conductive fillers and additives with solvent, polymer, or both of them.

#### CONCLUSION

This work employed a system to produce hybrid yarns composed of nanofibers as the sheath component to shift the nanofiber properties to higher order structures. In the work reported here, PAN/CNT composite nanofibers containing different loading percentages (0–20 wt %) of MWCNT and SWCNT and the functionalized SWCNT were prepared by electrospinning, and an acrylic staple yarn was coated with electrospun nanofibers. The surface chemical modification strategy was used to improve the CNT dispersion into the composite. As expected, the CNTs facilitated electron transportation and increased the electrical conductivity of the nanofibers. The effect of functional group on improved compatibility was proved through the comparison of the electrical properties test results in PAN/SWCNT and PAN/COOH-SWCNT systems. This proved the important effect of dispersion on final fiber morphologies and properties. Therefore, the degree of the dispersion of the CNTs in the polymer matrix is a key issue in the CNT composites.

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