Study on the characteristics and applications of functional continuous conductive fibers in energy-harvesting textiles

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ABSTRACT

Characteristics and application of functional continuous conductive fibers (CCF) are studied. CCF was fabricated using a spinning coating strategy, in which the conductive fiber in the core layer was tightly encapsulated by triboelectric materials with the help of staple fibers to effectively address interfacial compatibility issues. Importantly, the CCFs have the potential to act as self-powered wearable sensors for wearable sensing applications, including tracking hand movements or functioning as a compact textile keyboard. They could be made into CCF-TENG energy fabric for harvesting energy from human motions based on their flexible and weavable characteristics, which provides a new sight for further wearable e-textiles.

Keywords: Conductive fibers, Energy harvesting, Triboelectric nanogenerators.

1. INTRODUCTION

Fiber-based triboelectric nanogenerators (TENGs) composed of one-dimensional (1D) fiber-based materials can realize the application of TENG in flexible electronic textiles[1-4]. They are wearable and can harvest mechanical energy into electricity via the electrostatic coupling effect caused by contact separation between friction materials[5-7]. However, the fabrication of fiber-based TENG faces challenges, especially the interface compatibility problems between the conductive layer and triboelectric layer, which will affect the performance of wearable TENG and its applications as flexible electronic textiles.

The strategy combining core-spun yarn and dip coating method would be adopted to solve the above problem. A filament in the core layer is surrounded by staple fibers in the outer layer, resulting in the formation of core-spun yarn. Cotton materials are usually used as staple fibers owing to their excellent adsorption capacity, while conductive fiber materials in the core layer are applied as filaments. By utilizing the unique structure of core-spun yarn, the solutions of triboelectric materials could be applied to the filament with the help of staple fibers based on the capillary action of stable fibers[8-10], and the conductive fiber could thus be tightly wrapped by the triboelectric materials, resolving the structural and performance problems caused by interfacial failure.

Herein, a functional continuous conductive fiber (CCF) was prepared using a core-spun yarn coating strategy. It is composed of a conductive fiber core and short fibers wrapped outside. The sort fibers can tightly adsorb triboelectric materials through capillary action, thus enhancing the compatibility of the interface. The fabricated CCF could be prepared as a TENG (CCF-TENG) when the conductive fiber was coated with different friction materials, including polydimethylsiloxane (PDMS) and thermoplastic polyurethane (TPU). It was further integrated into a two-dimensional energy-harvesting textile, which can be utilized as a wearable sensor to detect the gesture or as a wearable mini keyboard.

2. EXPERIMENTAL SECTION

2.1 Materials

PDMS and TPU as triboelectric materials were purchased from Dow Corning Co., Ltd. and BASF, respectively. N,N-Dimethylformamide (DMF) was purchased from Dieckmann. Ag-coated nylon yarn was acquired from Tianyin Technology Co., Ltd. Cotton staple fibers were obtained from Huzhou Luke New Material Co., Ltd.

2.2 The fabrication of CCF and CCF-TENG energy fabrics

Firstly, the cotton fibers were wrapped around the conductive fibers to form a core-spun yarn using the core-yarn spinning equipment. Subsequently, the PDMS was dip-coated on the core-spun yarn with a ratio of 10 to 1 and was cured at 100℃

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for 5 mins. This prepared CCF was labeled as CCF@PDMS. Similarly, using the dip-coating method, TPU solution with DMF solvent was coated on the core-spun yarn to fabricate CCF@TPU. These two fibers, CCF-coated PDMS and TPU, acted as electronegative and electropositive parts, respectively, and thus were integrated into a 2D energy fabric by weaving approaches like commercial fibers or yarns.

2.3 Characterization and measurements

The morphologies of the functional continuous conductive fibers were observed by using a scanning electron microscope (SEM, TESCAN VEGA3) with 20 kV accelerating voltage. The voltage was tested using the Keithley 6514 system electrometer and Keithley DAQ6510 Data Acquisition/multimeter system.

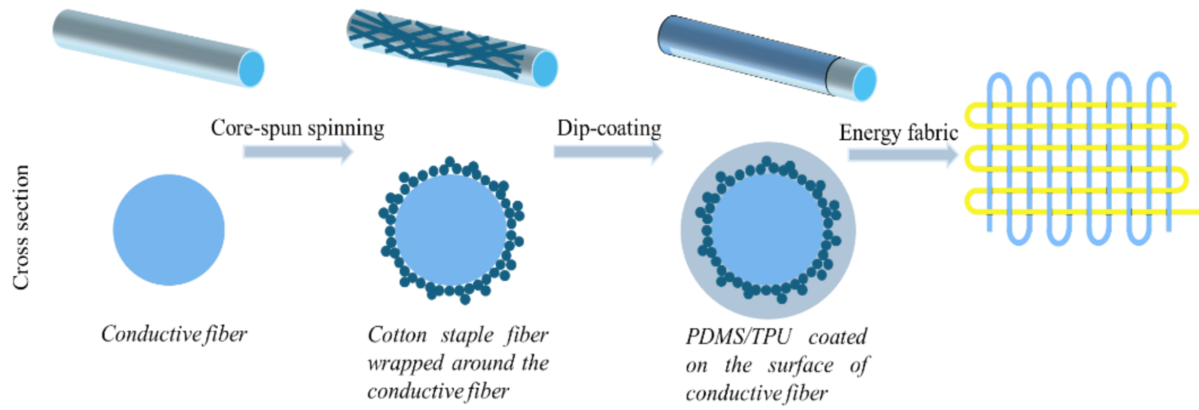

Figure 1. The fabrication strategy of CCF using a core-spun coating method.

3. RESULTS AND DISCUSSION

3.1 Fabrication and characteristics of CCFs

The method for making CCFs involves spinning a conductive fiber with short fibers to create a core-spun yarn, and subsequently enveloped with triboelectric substances. Within this structure, the conductive fiber serves as a flexible core electrode, tightly wrapped by the short fibers. The coating process utilizes materials such as PDMS and TPU, which bond effectively with the core-spun yarn due to the extensive surface area and high adhesive properties of the staple fibers such as cotton. This results in a CCF with enhanced interfacial compatibility, as illustrated in Figure 1. To further explore the structure, the CCFs were observed via optical microscope and SEM, as presented in Figure 2. Figures 2a and 2b show the optical microscope images of CCF coated by PDMF and TPU respectively, indicating that the CCFs have a uniform and continuous surface coating and a total diameter of about 0.66 mm. SEM images of the cross-section of CCFs are shown in Figure 2c-f. It is clearly displayed that there was no interfacial failure between the conductive layer and organic triboelectric materials, illustrating that the conductive fiber in the core layer was encapsulated by triboelectric materials (PDMS/TPU) with the help of short fiber. With the unique structure of core-spun yarn, the solutions of triboelectric materials could be applied to the filament with the help of staple fibers based on the capillary action of stable fibers, and the conductive fiber could thus be tightly wrapped by the triboelectric materials, resolving the structural and performance failure caused by interfacial problems.

3.2 Application of CCF-TENG energy fabrics

Owing to the flexibility and softness, CCF coated with PDMS and TPU could be prepared and made into a 2D energy-harvesting fabric like commercial yarn for acting as self-generating wearable sensors. The 2D energy fabric possesses the properties of flexibility and wearability, as well as the ability to be attached to the human body. When it acts on the joint of the human body, the bending of the joint causes the contact-separation of the friction materials to generate an electrical signal. As illustrated in Figure 3, the energy fabrics could attach to the fingers to monitor the gesture changes. There are four channels corresponding to four fingers. When a finger moved, the channel corresponding to the finger would respond with signals. For example, when the index finger is bent, channel 1 has a voltage signal output, while other channels have no signal. According to the signals output by different channels, it can be known which finger is moving so that the changes in gestures can be identified.

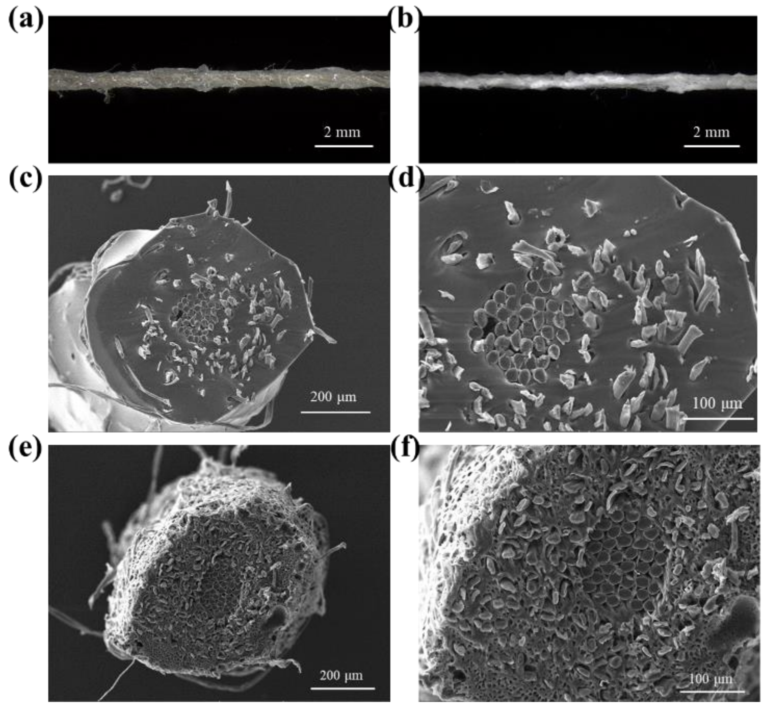

Figure 2. Optical microscope images of (a) CCF@PDMS and (b) CCF@TPU. SEM images of the cross-section of (c-d) CCF@PDMS and (e-f) CCF@TPU.

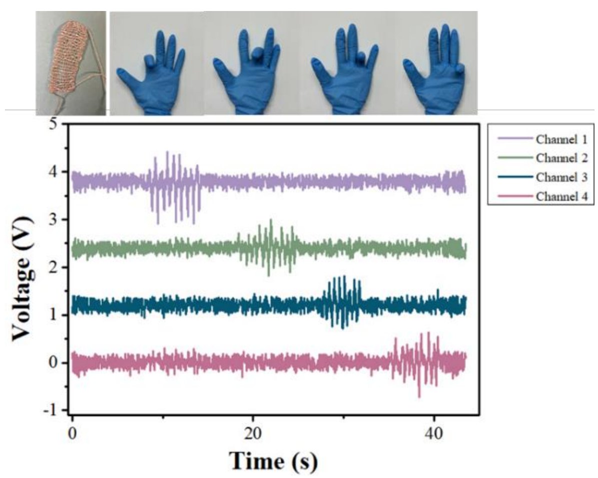

Figure 3. The gesture monitoring application and the output voltage signal with different gestures in different channels.

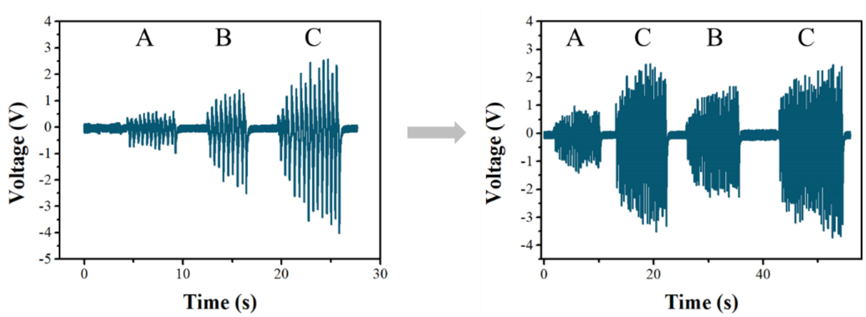

Figure 4. Application as a mini keyboard to output letters according to different voltage signals.

In addition, the energy fabric could also be used as a mini keyboard. Different sizes of energy fabrics could produce different output voltages that correspond to different letters. As shown in Figure 4, three fabrics with different sizes generated voltage signals with different three levels, about 0.6V and 1.4V, as well as 2.6V, which could be labeled as “A,” “B,” and “C,” respectively. When different fabrics are pressed randomly, the corresponding letters could be output and determined based on different voltage signals, as illustrated in the right graph of Figure 4. This application can provide feasibility for energy fabrics to be subsequently used as wearable and flexible mini keyboards.

4. CONCLUSION

To summarize, our study introduces a novel functional continuous conductive fiber (CCF) made from the integration of spinning and coating methods. By utilizing the unique structure of core-spun yarn, the solutions of triboelectric materials could be applied to the filament with the help of staple fibers based on the capillary action of stable fibers, and the conductive fiber could thus be tightly wrapped by the triboelectric materials, resolving the structural and performance failures. Characteristics and application of functional continuous conductive fibers (CCF) are also studied. Importantly, this fiber could be made into an energy-harvesting textile suitable for wearable sensing applications, including tracking hand movements or functioning as a compact textile keyboard. The proposed CCF could provide potential feasibility for further wearable electric textiles.

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