Strain Sensing Elastic Core-Spun Yarns Based on Long Silver Nanowires

Liping Jia\textsuperscript{1}, Qi Zeng\textsuperscript{1}, Quanquan Zhu\textsuperscript{1}, Runxuan Cai\textsuperscript{2}, Wei Guo\textsuperscript{3}, Jianhua Ran\textsuperscript{1}, Shuguang Bi\textsuperscript{1,}\textsuperscript{a} and Shiwei Li\textsuperscript{1,}\textsuperscript{b}\textsuperscript{*}

\textsuperscript{1}Hubei Key Laboratory of Biomass Fibers and Eco-Dyeing & Finishing, State Key Laboratory of New Textile Materials and Advanced Processing Technologies, College of Chemistry and Chemical Engineering, Wuhan Textile University, Wuhan 430200, China.
\textsuperscript{2}Department of Biochemistry & Molecular & Cellular Biology, Georgetown University, Washington DC 20057, United States
\textsuperscript{3}College of Physical Education, Jianghan University, Wuhan 430056, China
\textsuperscript{\dagger}These authors contributed equally to this work.
Email: \textsuperscript{a}sgbi@wtu.edu.cn, \textsuperscript{b}lishiwei1988@126.com

Abstract. Strain sensing is one of the important functions of intelligent fabric, which can transform the external stress (or strain) into visible electrical signals and monitor the characteristics of human physiology and motion. At present, the flexible strain sensor has low sensitivity, small strain range and unstable performance after repeated stretching. In this work, core-spun yarns with polyurethane (PU) filament as core and long silver nanowires (AgNWs) loaded cotton fiber as shell was fabricated by spinning technology. The results showed that when the loading of AgNWs was 10 wt\%, the strain range of the PU/cotton@AgNWs core-spun yarn was 0-60\%, the gauge factor of 12.6 was linear, and the strain sensing and mechanical properties were stable after repeated stretching. This strain sensing elastic core-spun yarns constructed by spinning technology could be used as one of the important materials for intelligent wearable devices.

Keywords. Silver Nanowires (AgNWs), Elastic Core-spun Yarns, Flexible Strain Sensor, Polyurethane (PU) Filament, Cotton Fiber.

1. Introduction

The strain sensors with high flexibility and sensing characteristics have broad application prospects in wearable devices, robots, human movement and physiological monitoring, etc. [1]. Compared with the strain sensors based on thin film and foam materials, the fiber-based strain sensors have the advantages of light weight, good flexibility, strong deformation recovery ability and good knittability, so they are one of the most promising next-generation electronic devices [2-3]. The earliest fiber-based strain sensors are usually fabricated by blend spinning using metal wires and textile fibers, resulting in low sensitivity, small strain range and unstable circulation due to rigidity [4-5]. Subsequently, the conductive polymer fibers made of polymers and conductive fillers are used as the strain sensors, which have good conductivity, elasticity and recoverability, and are considered to be the ideal material to solve above problems [6-9]. However, in order to obtain low drive voltage, a large number of conductive fillers are necessarily added to achieve adequate conductivity. In this work, a core-spun yarn strain sensor was designed and fabricated by spinning process with polyurethane (PU)
filament as core and long silver nanowires (AgNWs) loaded cotton fiber as shell, and its strain sensing and mechanical properties were discussed and analyzed.

2. Experimental

2.1. Materials
Polyethylene pyrrolidone (PVP, molecular weight of 1.3 million) was obtained from Shanghai Aladdin Biochemical Technology Co., Ltd. Silver nitrate (AgNO₃), sodium chloride (NaCl), ethylene glycol, acetone, and anhydrous ethanol were procured from Sinopharm Chemical Reagents Co., Ltd. Anionic waterborne polyurethane with solid content of 30 wt% (WPU) was provided by Suzhou YuanTaiRun Co., Ltd.

2.2. Synthesis of Silver Nanowires (AgNWs)
The synthesis scheme of long AgNWs was upgraded on the basis of the published literature [4], and the specific steps were as follows: 0.2 g of AgNO₃ and 0.3 g of PVP were mixed in 50 mL of ethylene glycol, then 12.5 μm of sodium chloride was added and stirred well. The mixture was transferred to the hydrothermal reactor and heated to 130 °C for 8 h. Finally, the AgNWs aqueous solution was obtained by centrifugation and purification.

2.3. Preparation of PU/Cotton@AgNWs Core-Spun Yarn by Friction Spinning
The cotton fibers were impregnated in acetone and swelled by ultrasound for 2 h. Then, an appropriate amount of 4 mg/mL of AgNWs and 10 mg/mL of WPU aqueous solution were added and infiltrated on the surface of cotton fibers in a shaker for 1 h at room temperature. AgNWs coated cotton fibers (cotton@AgNWs) were prepared after drying. The core-spun yarn was blended with elastic polyurethane (PU) filaments by friction spinning machine.

2.4. Characterization
X-ray diffractometer (XRD) (D/Max 2500, Rigaku, Japan) was used to detect the crystal structure of AgNWs in the range of 10-80° with Cu Kα radiation. The morphology of AgNWs and PU/Cotton@AgNWs core-spun yarn were observed by SEM (JSM-5600LV, JEOL, Japan). Electrochemical workstations (CHI604E Instruments, Shanghai, China) were used to record the resistance per cm for all three samples. The mechanical properties of the core-spun yarns with length of 6 cm were determined by Instron at the tensile rate of 60 mm min⁻¹ and the average values of three samples were obtained.

3. Results and Discussion

3.1. Characterization of Long AgNWs
As shown in figure 1(a), the XRD pattern peaks of AgNWs at 2θ = 38.2°, 44.38°, 64.54° and 77.5° correspond to (111), (200), (220) and (311) crystal planes, respectively. The length of AgNWs synthesized in this experiment shown in figure 1(b) can reach 160 μm and the diameter is only 158 nm, so the aspect ratio is as high as 1000.
3.2. Micromorphology of PU/Cotton@AgNWs Core-Spun Yarn
SEM images of PU/cotton@AgNWs core-spun yarn are shown in figure 2. A very obvious core-spun yarn structure with PU multifilament as core and AgNWs loaded cotton fibers as core was prepared by friction spinning process. Through local magnification, it can be seen that AgNWs are attached to cotton fibers through WPU to form a uniform conductive network. Cotton fibers loaded with AgNWs are wound on the PU filament to obtain conductive core-spun yarn. When the load of AgNWs is 10%, the resistance value is 56 Ω. Low initial resistance is conducive to the large resistance changes during the strain process.

3.3. Strain Sensing Performance
As shown in figure 3(a), when the static stretching range is 1%-60%, the resistance value of the PU/cotton@AgNWs core-spun yarn increases continuously owing to the decrease of the number of joints in AgNWs conductive networks during the stretching deformation. The linear variation of U/I relationship indicates that the core-spun yarns have good ohmic properties under static tension, presenting a stable conductive network structure.
Figure 3. Static resistance-strain curve with an insert U/I curves at different tensile strains (a) and dynamic resistance rate-strain curve (b) of PU/cotton@AgNWs core-spun yarn.

Gauge factor (GF= ($\Delta R/R_0$)/$\varepsilon$) represents the sensitivity of strain sensor, where $\Delta R = R - R_0$, $R$ is the tensile resistance, $R_0$ is the initial resistance, $\varepsilon = \Delta L/L_0$ is the strain, $L_0$ is the initial length, $\Delta L = L - L_0$, $L$ is the tensile length. The dynamic strain sensing performance of PU/cotton@AgNWs core-spun yarn is shown in figure 3(b). The resistance change rate of the core-spun yarn is proportional to the elongation in the strain range of 0-60%, that is, the GF value remains unchanged, indicating that the AgNWs in the core-spun yarn prepared have strong adhesion to the cotton fibers. During the stretching process, the conductive network formed by AgNWs deforms together, so that PU/cotton@AgNWs core-spun yarn shows the high and stable GF value of 12.6 in the wide strain range of 0-60%.

3.4. Mechanical Property

The tensile mechanical property of PU/cotton@AgNWs core-spun yarn is shown in figure 4(a). The force gradually increases with the deformation when the core-spun yarn is drawn. At the stretching length of 60 mm, i.e., the elongation of 100%, the PU inner core of the core-spun yarn breaks. The cyclic tensile mechanical properties of core-spun yarn at 60% strain are further tested, as shown in figure 4(b). After at least 10 times of repeated stretching, the deformation of the core-spun yarn can be quickly recovered, showing good mechanical stability.

Figure 4. Tensile mechanical property and cyclic tensile stability of PU/cotton@AgNWs core-spun yarn.

4. Conclusion

In this work, a flexible strain sensor with high linear sensitivity, wide strain range and good cycle stability was prepared by using the core-spun yarn with AgNWs loaded cotton fibers as the conductive layer, WPU as the dispersant and adhesive, and PU as the elastic substrate. When the loading of AgNWs on cotton fibers is 10 wt%, the strain response range can be reached up to 0-60%, the
sensitivity GF is 12.6, and the performance is stable after repeated stretching. This preparation method by spinning technology would be favorite to the mass production of wearable intelligent devices.

Acknowledgments
Authors would like to acknowledge the financial support of Science and Technology Research Projects of Department of Education Hubei Province (B2020073); Hubei Biomass Fibers and Eco-dyeing & Finishing Key Laboratory (STRZ201901, STRZ2019001, STRZ2019002).

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