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Electromechanical properties of a yarn strain sensor with graphene-sheath/polyurethane-core

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ABSTRACT

This paper reports on the fabrication of a new yarn strain sensor based on commonly used polyurethane yarn which is easily incorporated into textile structures by using textile technologies for wearable applications. By integrating graphene/poly(vinyl alcohol) composites as the conductive sheath around yarn, and polyurethane yarn as the elastic core by using a layer-by-layer assembly method that is simple, scalable and low in cost, the merits of both types of materials are incorporated to fabricate sensors with enhanced performance. The combined effects of graphene concentration and number of coatings on sensor properties are elucidated, and on that basis, the electromechanical properties can be modified by adjusting the parameters. The sensors are characterized in terms of sensitivity, resistivity, linearity, repeatability, hysteresis and thermal stability. There are two sensors (graphene concentration of 0.8 wt% and 1.0 wt%, and 12 and 9 cycles of coating respectively) with high sensitivity (gauge factor of 28.48 and 86.86, respectively), good linearity between the change in relative resistance and applied strain (correlation coefficient of 0.95 and 0.97, respectively), good repeatability (repeatability error of 2.03% and 1.81%, respectively), low hysteresis (hysteresis error of 7.03% and 9.08%, respectively) and excellent thermal stability (within the range of 25 °C–310 °C).

1. Introduction

There is a rapidly growing demand for wearable electronics, especially flexible, wearable and stretchable sensing devices that have the ability to monitor human physiological conditions. Material interfaces between the human body and the environment have become increasingly more prevalent in the last decade [1]. One of these devices are strain sensors (or strain gauges), which measure strain by converting physical deformation into electrical signals [2–4]. Compared to traditional metallic-, semiconducting- and thin-film-based electronic devices, textile-based strain sensors that are made of fiber, yarn or fabric have many exceptional properties, such as good wearability, conformability, comfort and washability, so that they are appropriate for various applications on the human body, such as for health care reasons, rehabilitation purposes, and sports and occupational wear for monitoring purposes [5–10].

In comparison to other types of textile-based strain sensors, yarn strain sensors have several advantages, as follows: (1) it is easy to incorporate sensing yarns into textile structures by using knitting, weaving or braiding technologies to impart a variety of sensing functions; (2) the measurement of the distributed strain and pressure can be easily carried out; (3) there can be increased flexibility in the textile design to target the positions of measurement; and (4) it is noninvasive and causes less irritation to the skin. Recently, the fabrication of yarn strain sensors has been realized by using conductive-material-filled polymer composites produced through fiber spinning [11,12] or by applying a piezoresistive coating on staple fibers or filament yarn substrates with various coating techniques [13–16]. For instance, Bilotti et al. reported the fabrication of multi-walled carbon nanotubes that contain thermoplastic polyurethane fibres with strain sensing ability by using an extrusion process [17]. Granero et al. provided a solvent/non-solvent wet-spinning method for producing Poly(styrene-β-isobutylene-β-styrene)-poly(3-hexylthiophene) conducting composite fibers. These composite fibers showed reversible mechanical and electrical characteristics, thus demonstrating their applicability as strain gauges [18]. Regueira et al. proposed a novel inverse emulsion polymerization technique for fabricating polyaniline (PANI)/graphene nanocomposites. The nanocomposites showed

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consistent, direct and reproducible connection to resistivity, which means they show promising potential applications as electromechanical sensing materials [19]. Seyedin et al. developed highly stretchable polyurethane/poly(3,4-ethylenedioxythiophene):poly(styrenesulfonate) (PEDOT:PSS) elastomeric composite fibers by using a fiber wet-spinning method. The resultant sensors were capable of sensing a large range of strains [20]. These fiber spinning methods can fabricate yarn sensors with very good fatigue properties and high stretchability, but the fabrication process is relatively complicated and incurs a high cost compared to the use of coating. On the other hand, the coating methods that are often used to endow textiles with different functionalities have many advantages including easy formation of continuously coated layers, simple and low-cost fabrication, as well as ease of scalability [13]. Zhang et al. developed a yarn-based sensor by coating Spandex multifilament yarn with a thermoplastic polyurethane/carbon nanotube (TPU/CNT) composite with a simple coating process [21]. The strain sensor showed partial recovery of resistance with good reversibility in a number of cycles. Wu et al. proposed a layer-by-layer (LBL) assembly method for coating a carbon black (CB) cellulose nanocrystals (CNC)/natural rubber (NR) nanohybrid onto polyurethane yarn [22]. The sensor exhibited excellent sensitivity for the monitoring of small motions as well as good reproducibility of over 10,000 cycles under a strain of 1.0%. Zhang et al. developed graphite/silk (sheath/core) fibers for strain sensors which were fabricated by using a dry-Meyer-rod-coating process. The resultant sensor showed high sensitivity with a gauge factor of 14.5 and outstanding stability (up to 3000 cycles) under an applied strain of 15% [23].

However, as mentioned above, the majority of these yarn strain sensors in which coating is applied as a technique to impart different functions, are fabricated by using CB, CNT or some other conductive composites as the coating on polyurethane yarn or coating silk, rubber or wool yarn with graphite and graphene composites. To date, there has been a lack of reported work on the coating of graphene layers onto a polyurethane multifilament substrate to fabricate yarn strain sensors, and in doing so, utilizes the merits of both types of materials. Compared to CB and CNT, graphene possesses higher aspect ratios, superior electrical and mechanical properties as well as thermodynamic stability [24–29] while polyurethane yarn has extremely high stretchability and elasticity as well as good textile processability in comparison to substrates with low extendable staple fiber yarns and other elastic materials such as rubber [30–35]. Moreover, to the best of our knowledge, there are no studies that examine the combined effects of graphene concentration and number of graphene coatings on sensor properties and very few studies have reported on the linearity, repeatability, hysteresis and thermal property of yarn sensors, which are critical for sensor optimization and practical wearable applications.

In this study, we develop yarn strain sensors with a bi-coaxial structure that can be easily incorporated into textile structures by using advanced textile technologies such as weaving, knitting and braiding for various wearable sensing applications. The performance of the sensors will be enhanced by utilizing the merits of both the graphene/poly(vinyl alcohol) (PVA) composite as a conductive sheath around the yarn, and polyurethane yarn as the elastic core with the LBL method. Moreover, by investigating the combined effects of the concentration of graphene dispersion and the number of graphene coatings, optimal material and structural parameters can be identified for fabricating sensors with the desired sensing properties. To fully characterize the sensor performance, and not just sensitivity as the majority of relevant past studies have done so, the morphological structure, mechanical and electromechanical properties as well as thermal properties of the sensors are studied, including not only stretchability and sensitivity but also linearity, repeatability, hysteresis as well as thermal stability for facilitating practical applications.

2. Experimental

2.1. Sensor structure and material system

The electromechanical properties of a yarn strain sensor are closely related to its structure, fabrication, and the mechanical and electromechanical properties of its components. In order to obtain good sensing performance, the yarn strain sensors were fabricated with a bi-coaxial structure with an elastic core and an electrically conductive layer, as illustrated in Fig. 1. The elastic component endows the sensors with high stretchability and repeatability while the conductive layer is wrapped around the elastic core as a yarn sheath, and provides electrical conductivity as well as variation of electrical conductivity when the yarn is extended. When longitudinal deformation is applied onto the sensors, the yarn will transform from its original state to an extended state. Consequently, micro-cracks could form on the conductive layer due to the reduced elasticity of the conductive layer as opposed to that of the elastic core, which results in an increase of the electrical resistance of the conductive yarn [36]. After unloading, the sensor can almost return to its original length due to the elastic core of the yarn. As shown in Fig. 1, elastic polyurethane yarn is used as the core of the yarn sensors in this study due to its excellent elasticity and elastic recovery. A commercially available Spandex yarn (polyurethane yarn) with a linear density of 140D was purchased from Notion Merit Limited, an Invista authorized distributor (HK). Commonly, it is a block copolymer with rigid aromatic segments connected by urethane linkages to polyester segments. The 140 D Spandex (polyurethane) core is a multifilament yarn comprising of ten monofilaments wherein the diameter of the monofilament is 40 μm. The ten monofilaments of polyurethane yarn are twisted together to limit failure under lateral pressure and to increase elasticity on a yarn (Fig. S1, Support Information). Multilayer graphene (TNPRGO, purity: > 98%, scale: 2–10 μm, thickness = 1–3 nm, layers: < 3) which was purchased from TIMESNANO, formed the conductive sheath of the sensors due to its outstanding electrical conductivity and good mechanical and thermal properties. Sodium lauryl sulfate (SLS) and polyvinyl alcohol (PVA) (Mw ≈ 89000–98000) were purchased from Sigma-Aldrich. They were used as a dispersing agent to facilitate the stable dispersion of the graphene in deionized (DI) water, and as adhesion to bind the graphene and polyurethane yarn, respectively. PVA is a water-soluble synthetic polymer with the idealized formula $[CH_2CH(OH)]_n$.

2.2. Fabrication of sensors

2.2.1. Preparation of graphene dispersion and PVA solution

PVA is a water-soluble synthetic polymer that contains many alcohol groups, and demonstrates excellent adhesive, stabilizing and dispersing properties. In this work, the PVA is put into DI water for 10 min at 80 °C and stirred to obtain a PVA solution. Then the PVA solution was further agitated through ultrasonication for 30 min. The PVA layer coated onto the polyurethane core yarn plays a significant role in adhering the graphene nanosheets. Specifically, the PVA was coated onto the surface of the polyurethane yarn through non-covalent interactions, including hydrogen bonding, van der Waals forces and hydrophobic attraction. Then, the PVA-coated polyurethane yarn was subsequently dipped into the graphene dispersion solution wherein the combination of graphene nanosheets and PVA contributed to the interaction between the