Chemical Engineering Journal 325 (2017) 396–403

Contents lists available at ScienceDirect

Chemical Engineering Journal

journal homepage: www.elsevier.com/locate/cej

Flexible and wearable strain sensing fabrics

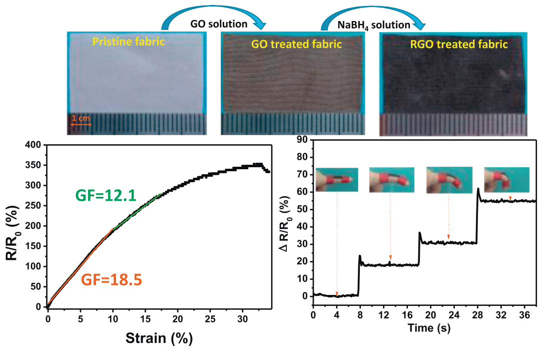
Guangming Cai[a], Mengyun Yang[a], Zhenglin Xu[a], Jiangang Liu[c], Bin Tang[a,b,*], Xungai Wang[b,a]

[a] Wuhan Textile University, Key Laboratory of Textile Fiber & Product, Ministry of Education, Wuhan 430073, China
[b] Deakin University, Institute for Frontier Materials, Geelong, Australia
[c] Changchun Institute of Applied Chemistry, Chinese Academy of Sciences, Changchun, China

HIGHLIGHTS

- Flexible strain sensor is fabricated using elastic fabric and reduced graphene oxide.
- Reduced graphene oxide endows elastic fabric with electrical conductivity.
- Mechanical properties of fabrics change slightly after surface modification.
- Strain sensing fabric exhibits a large workable strain range and great stability.
- Real-time monitoring of human motions is achieved by the obtained strain sensor.

GRAPHICAL ABSTRACT



ARTICLE INFO

Article history:
Received 16 March 2017
Received in revised form 5 May 2017
Accepted 14 May 2017
Available online 15 May 2017

Keywords:
Reduced graphene oxide
Strain monitoring
Flexible and wearable sensor
Nylon/PU fabric
Electromechanical performance

ABSTRACT

Flexible electronic devices have attracted considerable attention in recent years. Textile fabrics have been widely used to fabricate flexible strain sensors owing to their high flexibility. However, the elasticity of ordinary textile fabrics is low, which limits their strain sensing range. In this article, we used a simple method to fabricate flexible strain sensing fabrics (FSSFs) through the coating of graphene oxide (GO) nanosheets on elastic nylon/polyurethane (nylon/PU) fabric, followed by reduction of GO with sodium borohydride. The reduced graphene oxide (RGO) nanosheets were adsorbed on the elastic fabrics to impart electrical conductivity to the fabrics. The coated fabrics were characterized with scanning electron microscopy (SEM), X-ray photoelectron spectroscopy (XPS) and Raman scattering spectroscopy. The electromechanical performance and strain sensing properties of the FSSF were investigated. The fabricated strain sensor exhibited high sensitivity, a large workable strain range (0–30%), fast response and great stability. The mechanical property of fabrics did not change remarkably after the treatment with RGO. The surface resistance of the RGO/nylon/PU only increased from ~112 KΩ/m^2 to ~154 KΩ/m^2 after 8 washing cycles, exhibiting good washability. Furthermore, real-time monitoring of human motions, such as bending of finger and rotation of wrist, was achieved by the as-prepared FSSF. The RGO/nylon/PU fabrics as flexible strain sensors have potential applications in wearable electronic devices.

1. Introduction

Flexible and wearable electronic devices have attracted considerable attention because of their great potential applications, in areas such as wearable displays, smart clothing, human motion

---

* Corresponding author at: Wuhan Textile University, Key Laboratory of Textile Fiber & Product, Ministry of Education, Wuhan 430073, China.
E-mail address: bin.tang@deakin.edu.au (B. Tang).

http://dx.doi.org/10.1016/j.cej.2017.05.091

and health monitor [1–3]. Compared to traditional electronics, flexible electronic devices possess many particular features, including good flexibility, light weight, high sensitivity and large deformation ability [4–11]. Most of the flexible sensors are made of electrically conductive metal nanoparticles or nanowires, metal thin films, carbon nanotube and graphene [12–15]. Although these sensors are electrically conductive and have high sensitivity, the workable strain range of such sensors is still small, which limits their applications. It remains a challenge to develop strain sensors with a large workable strain range and high sensitivity.

Textile materials, as flexible materials produced from fibers, possess many particular features, such as porous structure, high surface area, light weight, good flexibility and recoverable deformation [16–18]. Moreover, the textile materials exhibit high strength, good tear resistance, and excellent bending and stretching recovery. By virtue of these properties, textile materials have been utilized to prepare flexible strain and pressure sensors, recently [19–32]. It has been reported that the strain sensors were prepared by carbonization of textile fabrics [33–35]. The sensors have excellent sensitivity and large strain sensing range, but the carbonization process destroys the structure of fabrics, which lose their original mechanical properties. Therefore, the carbonized fabrics cannot be used alone as a strain sensor. Graphene, carbon nanotubes, silver nanowires and polyaniline have been coated on fabrics for preparation of flexible strain sensors. However, the sensors from ordinary textile fabrics have a relatively small strain range and low long-term stability due to the small deformation ability and poor elasticity recovery, which limit their applications.

Polyurethane (PU) fiber is known for its high elasticity and elastic recovery, which has been widely used to manufacture elastic yarns and textiles. Recently, some researchers have proposed combining carbon materials such as carbon nanotubes (CNTs) onto PU/cotton yarns to develop lightweight, stretchable and flexible electronic devices [18,36,37]. However, the low strength, poor fatigue and chemical corrosion resistance of cotton fiber may limit their applications. Additionally, it is difficult to use a yarn alone as a wearable sensor, and combination of the yarn with other elastic materials is often needed. Nylon as a type of synthetic fiber, has high strength, elongation and good resistance to fatigue and chemical corrosion, and is widely used in textile industry [38]. Graphene has received tremendous attention owing to its outstanding mechanical, thermal, optical and electronic properties [39,40]. As one of carbon materials, graphene possesses high electrical conductivity. As such, modification of textile substrate with graphene can impart conductivity to the substrate materials [41–45].

In this study, we developed a simple method to fabricate flexible strain sensors by reducing graphene oxide in the presence of elastic nylon/PU fabrics, which serve as the skeleton for the reduced graphene oxide conductive layer. The reduction process of the GO on fabric was analyzed. The morphology and component of the RGO/nylon/PU fabric were characterized. The electromechanical performance and strain sensing properties of the FSSF were also investigated. These results show the RGO/nylon/PU fabrics have good application potential as strain sensors for wearable electronic devices.

2. Materials and methods

2.1. Materials

White knitted nylon/PU fabrics (138 g·m^{-2}), 97% nylon and 3% PU, were used in this study. The nylon/PU core spun composite yarn were used to knit fabric, the liner density of composite yarn is 80 D. The wale density and course density of knitted nylon/PU fabric are 280/5 cm and 140/5 cm, respectively. Graphene oxide (GO) nanosheets with a thickness of 0.8–1.2 nm and a two-dimensional length of 0.5–5 μm were provided by Nanjing Xianfeng Nano Science and Technology Ltd, China. Sodium borohydride (NaBH$_4$, >98%) was purchased from Aladdin Reagent Company (Shanghai, China). All chemicals were of analytical grade and used without further purification.

2.2. Preparation of sensing fabric

The sensing fabric for strain monitoring was prepared by dip-coating of GO nanosheets and subsequent reduction of GO by NaBH$_4$, which is illustrated in Fig. 1. A stable GO suspension was obtained through the dispersion of GO nanosheets in water and 30 min of sonication at room temperature. Nylon/PU fabrics were soaked in ethanol for 30 min and then washed thoroughly with deionized water. The fabric was dried for 24 h in vacuum. Fabric samples (4 × 4 cm) were dipped into GO suspensions with different concentrations (0.5, 1.0, 1.5 and 2.0 mg·L^{-1}) and kept in solution for 2 h at 40 °C under sonication. The fabrics were dried at room temperature. The fabrics changed to brownish yellow from white due to adsorption of GO nanosheets. Six cycles of "dip and dry" were performed to obtain the GO treated fabrics. And then the fabrics with GO were immersed in 200 mL of 0.5 mol L^{-1} NaBH$_4$ aqueous solution. The mixtures were kept for 2 h at 40 °C under stirring. The color of fabrics turned to black from brownish yellow during treatment. The GO nanosheets on fabrics were reduced by NaBH$_4$. Finally, the fabrics were rinsed with deionized water and dried in an oven at 40 °C.

2.3. Instruments

Scanning electron microscopy (SEM) measurements were performed with a Supra 55 VP field emission SEM. X-ray photoelectron spectroscopy (XPS) measurements were carried out on a Kratos XSAM800 XPS system with Kα source and a charge neutralizer. Raman analysis was performed on a Renishaw inVia Raman microscope system (Renishaw plc, Wotton-under-Edge, UK). A 50×/N.A. 0.75 objective and a 785-nm near-IR diode laser excitation source (500 mW, 10%) were used in all measurements. Raman spectra were recorded using a mounted CCD camera with integration time of 10 s by single scan. The mechanical properties were measured using an Instron Model 5566 Materials Testing System. The changes in electric resistance of fabric samples at different strain levels were recorded by using a self-built fabric dynamic resistance tester.

2.4. Durability test to washing

In this study, water washing durability test of the obtained RGO/nylon/PU fabric was carried out according to AATCC Test Method 61-2006. A standard color-fastness to washing laundering machine (Model SW-12AII, Wenzhou Darong Textile Instrument Co., Ltd., China) was used in a washing procedure. The RGO/nylon/PU fabric (5 × 10 cm) was washed in a rotating closed canister containing 200 mL of detergent aqueous solution (0.37 wt%)

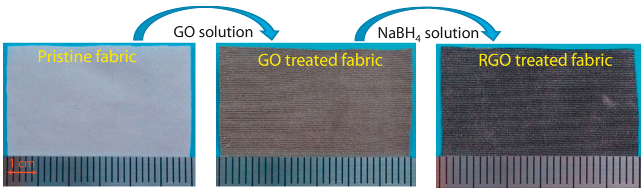


Fig. 1. Preparation process of strain sensing fabrics (FSSF).