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Conducting textiles from single-walled carbon nanotubes

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Abstract

In this paper we present a simple and straightforward route to prepare conducting textiles by incorporating carbon nanotubes through a dyeing approach. This process consists of immersing textiles in an aqueous sulfonated polyaniline-carbon nanotube dispersion acting as a dye. Incorporating carbon nanotubes into textiles increased the conductivity by four orders of magnitude and doubled the capacitance compared to textiles dyed with sulfonated polyaniline. Textile durability and their applicability as strain gauges were also demonstrated.
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Keywords: Carbon nanotubes; Conducting polymers; Conducting textiles; Electronic textiles; Polyaniline

1. Introduction

Adding functionality to textiles is an area of great interest. In particular, wearable electronics would allow the use of textiles as a communication platform with wide ranging applications in sportswear, healthcare, military and work wear. Current electronic textiles (e-textiles) are either ‘deconstructed’ devices [1] connected by conventional wiring technology or based on weaving conductive threads into the fabric [2]. Woven and knitted metal electrodes have been used in a textile-monitoring suit [3,4], but have the distinctive disadvantage of increasing stiffness and reducing elasticity. In addition the durability of these materials is an issue as routine bending and stretching that cause normal fibres to fray and tear over time could break wires. An ideal e-textile should still “stretch and recover, drape and handle”, i.e. retain conventional textile behaviour [1]. As a result of this constraint conducting polymers are being considered as they can be integrated into a traditional fabric structure [5–10]. Electrically conducting textiles can be prepared by *in situ* polymerisation of conducting polymers such as polypyrrole [5] and polyaniline [6], so-called “intelligent materials” [11]. These coated textiles have been utilised as wearable strain gauges as they can conform to the shape of the human body [7,8].

The limitations of these polymers include low mechanical strength and more important for e-textiles lower conductivity and current carrying capacity compared to metals. This can be addressed by combining the process-ability of polymers with the exceptional properties of carbon nanotubes, which has lead to significant advances in the mechanical and electronic properties of composite materials [12–15]. Moreover single-walled carbon nanotubes (SWNT) offer the distinctive advantages of: (a) being highly electrically conductive, up to at least 10^6 S/cm several orders of magnitude higher to conducting polymers [15] and (b) possessing a current carrying capacity of up to 10^9 A/cm^2, almost four orders of magnitude higher than most metals [16]. Therefore it is obvious that incorporation of carbon nanotubes into textiles could lead to enhanced properties. The challenge remains how to incorporate carbon nanotubes into textiles without losing functionality.

However, for thousands of years humans have been decorating clothing through immersion of fabrics in liquid dyes [17]. This well-established process provides a useful pathway for incorporating carbon nanotubes into textile materials. The process involves bringing textile and dyes into contact through a suitable medium. The key point is using a dye which can also disperse carbon nanotubes. It is well-established that nanotubes can

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be ‘easily’ dispersed in common solvents using chemical modification of the nanotubes’ surface [18]. Recently we demonstrated that SWNT can be stabilised in water soluble fully sulfonated polyaniline, poly (2-methoxy aniline-5-sulfonic acid) PMAS [19]. The use of an aniline based dispersant is highly advantageous as it is readily taken up by textiles; in fact some of the first synthetic organic dyes were based on aniline derivatives [20].

In this paper we investigate the incorporation of carbon nanotubes into textiles prepared through conventional dying, *i.e.* immersion into an aqueous polyaniline-SWNT dispersion acting as a liquid dye. We found that this dyeing process provides a simple way to fabricate conducting textiles. Textile materials were characterized using spectroscopic, microscopic, electrical and electrochemical techniques.

2. Experimental

Single-walled carbon nanotubes produced by the method of high pressure decomposition of carbon monoxide [21] (HiPco method) were purchased from Carbon Nanotechnologies Inc., lot #HPR-86. The fully sulfonated polyaniline, poly(2-methoxyaniline-5-sulfonic acid), average molecular weight range 8000–10,000 g/mol was produced in-house [22]. Textile material, wool nylon Lycra 7010 replacement fabric consisting of 95% wool, 4.5% nylon and 0.5% Lycra was kindly provided by CSIRO Textile and Fibre Technology, Australia.

Carbon nanotube dispersions were prepared by sonicating 40 mg SWNT in 0.1% weight per volume aqueous solutions of PMAS at pH 2.9 until a dense black dispersion had formed. Textile materials were dyed by immersion in either a PMAS polymer solution or a PMAS-SWNT dispersion for up to 4 h at 90 °C. All textile materials were washed with water and dried at room temperature. These samples were labeled as T1 (PMAS dyed textile) and T2 (PMAS-SWNT dyed textile).

UV–vis spectra were recorded using a Shimadzu UV1601 spectrophotometer. Solution samples were recorded after dilution with water, while spectra for dyed textile samples were recorded in *o*-dichlorobenzene. SWNT and PMAS-SWNT dispersions were drop cast onto glass substrates for Raman investigations. Raman spectra of these samples and textile materials were collected using a Jobin Yvon Horiba high-resolution LabRam Raman spectroscopic microscope under ambient conditions in a backscattering configuration, using a 632.8 nm excitation line. Scanning electron microscopy (SEM) images were recorded using a Leica Model Stereoscan 440 SEM. The current–voltage characteristics across textile materials were determined using an Agilent 33220A waveform generator and a Thurlby Thandar Instruments 1906 digital multimeter. Straining data was obtained by monitoring the current at constant voltage. All experiments were conducted under ambient conditions, e.g. room temperature and relative humidity 40%. The capacitance was evaluated from cyclic voltammetry at different scan rates, using a Princeton Applied Research Model 363 potentiostat/galvanostat coupled to an ADInstruments PowerLab 4/20. Samples of textile materials measuring 2 cm × 1 cm were wrapped around reticulated vitreous carbon as working electrode, with Ag/AgCl (3 M NaCl) as the reference electrode.

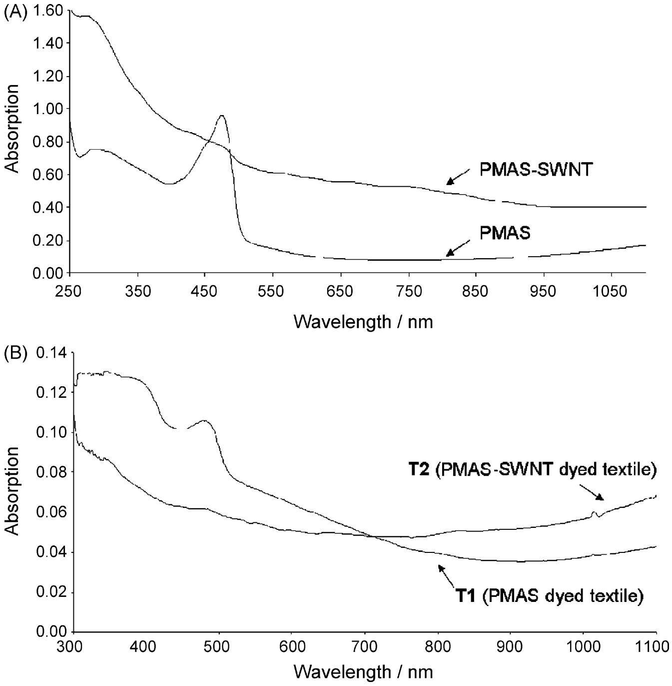

Fig. 1. UV–vis absorption spectra for (A) PMAS solution and PMAS-SWNT dispersion and (B) dyed textiles T1 and T2 in *o*-dichlorobenzene.

3. Results and discussion

3.1. Textile dyeing

Fig. 1A shows the UV–vis spectra of the PMAS solution and the PMAS-SWNT dispersion to be employed in the dying process. PMAS solution exhibited two characteristic UV–vis absorption bands at 290 and 473 nm associated with π–π^* and polaron band transitions in excellent agreement with our previous observations [19,23]. While the UV–vis spectrum for the PMAS-SWNT dispersion exhibited in the following changes in to the PMAS spectrum: a blue-shift for the polymer π–π^* band, a significant reduction in the polaron band intensity and broad features indicating the presence of carbon nanotubes aggregates, as observed previously [19,24]. The Raman spectrum of an evaporated PMAS-SWNT dispersion was up-shifted compared to that of SWNT. Similar changes to UV–vis and Raman spectroscopy have been observed previously and were attributed to the effect polymer interactions with the nanotube surface [19,25].

The UV–vis spectra (Fig. 1B) of dyed textiles T1 and T2 are similar to their respective dyes, *i.e.* either PMAS solution or PMAS-SWNT dispersion. In particular, the characteristic PMAS band at 473 nm is clearly visible in the UV–vis spectrum for dyed textile T1. Similarly, the spectrum for dyed textile T2 has retained the UV–vis absorption characteristics observed for the PMAS-SWNT dispersion.

Upon dying with PMAS or PMAS-SWNT the textile changes colour from white to brown, as shown in Fig. 2. The UV–vis spectra and photographs provide an indication that PMAS

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