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Carbon nanotube fiber–silver hybrid electrical conductors

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ABSTRACT

Carbon nanotubes are very promising materials for many electrical and electronic application. Particularly, it is expected that macroscopic assemblies made purely of carbon nanotubes may form highly efficient and reliable electrical conductors for the next generation of electrical wires. It has already been demonstrated that wire-like nanotube assemblies—carbon nanotube fibres can successfully work as electrical wires, however, their performance needs further research and development. This paper presents the possible method of enhancement of electrical conductivity and current-carrying capacity of the carbon nanotube fibres via incorporation of silver nanoparticles into the nanotube network and formation of a hybrid carbon nanotube fibre–silver conductor.

1. Introduction

The need for electrical energy is increasing dramatically. Simultaneously, the performance of conventional conductors currently used in electrical wires and devices cannot be improved any more. This introduces a demand for new materials able to outperform the traditional conductors, being both cost-effective and environmentally sustainable.

Due to their exceptional physical properties, carbon nanotubes (CNTs) have recently gained widespread attention. CNTs are very light-weight nanoscopic tubules of stunning electrical and mechanical performance [1,2]. These features, together with the fact that carbon is a widely available element and that CNTs may be produced cost-effectively on an industrial scale, make carbon nanotubes extremely interesting materials for electrical wiring applications [3–6]. Particularly, the recent manufacture of macroscopic wire-like assemblies made purely of CNTs – CNT fibres – opened up new prospects in this area [6–9].

It has been shown that CNT fibres can be spun continuously via cost-effective and very easy to upscale processes [6–9]. The fibres are already much more light-weight and mechanically stronger than any conventional metallic conductor [6,10,11]. Further, it has been demonstrated that the fibres may be successfully used as simple electrical wires or parts of electrical machines [3-5,12]. However, the electrical performance of CNT fibres is still inferior to conventional conductors which is due to the insufficient control over the fibres morphology. Although extensive research is conducted in this area, up to now the issue has remained challenging. The possible temporary solution is the doping of fibres with strong acids and iodine [5,6]. However, this approach may not be ideal for all applications. Therefore, in this study we explore another way of improving the conductivity of the fibres i.e. the incorporation of nanoparticles of the most conductive of metals- silver into the CNT fibre network and thus formation of a hybrid CNT—silver conductors.

2. Methods

Materials: The base CNT fibres used in this study were produced via floating catalyst chemical vapour deposition method described earlier [3,7,9,10]. The hybrid material was prepared by the infiltration of CNT fibres with a commercial dispersion of silver nanoparticles in organic solvents (1-ethoxypropan-2-ol, acetone, ethanol, ethyl acetate) [13].

Sample preparation: The samples were prepared by placing 1–5 cm long fibres on holders with lifted up contacts so that the full length of the tested fibre was suspended to ensure even heat removal from the fibre at high current flow and facilitate the incorporation of silver and production of hybrid material. To produce the hybrid conductor the suspended samples was immersed in a droplet of the acetone-diluted silver dispersion produced on tweezers. The droplet was moved along the fibre several times to deposit the desired amount of particles. At least 10 min drying time was allowed to ensure the evaporation of the solvent and proper adherence of the silver to the CNT network.

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Testing: The conductivity and current-carrying capacity measurements were performed with the use of Keithley 2000 multimetres and TTi QL564P DC power supply. The response of a fibre resistance to low temperatures was measured using a cryostat VarioxAC (Oxford Instruments). To calculate the specific conductivity the samples were weighed using ME36S Sartorius microbalance (1 μg resolution).

3. Results and discussion

The compositing of conductive metals with CNTs is not a straightforward task as metals in liquid state have extremely high surface tension and cannot wet the nanotubes [4]. Here, this problem was solved by the use of a suspension of silver nanoparticles in organic solvents which have extremely low surface tensions and viscosity, and therefore easily enter the CNT fibre carrying the nanoparticles along with them [4,14]. Upon evaporation of the solvent, nanosilver clusters adhere to CNT bundles, and form an evenly distributed silver phase inside of the fibre (Fig. 1).

The incorporation of silver increases conductance of the fibres. Fig. 2 presents changes of the conductance vs. an amount of silver infiltrated into five samples. The amount of silver was controlled by the number of applications of suspension and further monitored by the measurement of samples weight.

Unlike for chemical doping, the increase in conductance is accompanied by a decrease in specific conductivity (Fig. 2b) which is not advantageous for applications where the weight factor is important [3,5]. However, the conductance increase is also correlated with an improvement in current-carrying capacity of the fibres, which is not observed upon application of liquid chemicals [3]. The results of the tests performed on CNT fibres infiltrated with formic acids and insulating polymeric compounds (Table 1) show that independent of the conductivity improvement observed at low current the current-carrying capacity and power dissipated at burning are not influenced by the treatments. These observations indicate that current induced heating simply removes the liquids from the fibre.

On the other hand, while testing many samples infiltrated with silver (example in Table 1) we observed that the current-carrying

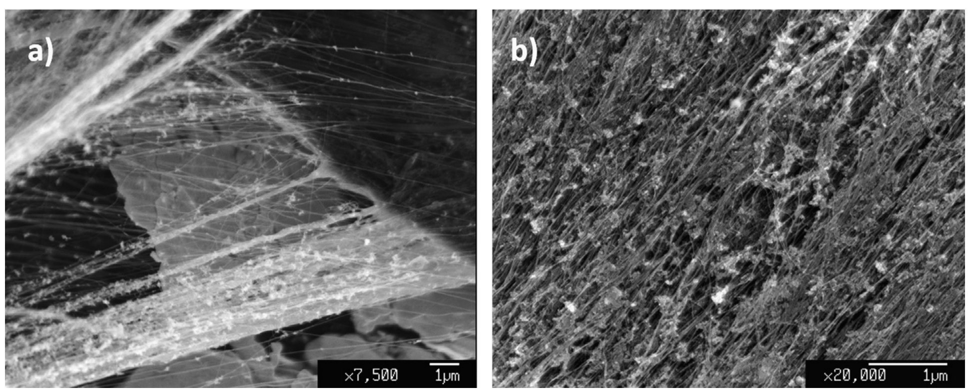

Fig. 1. Scanning Electron Microscope images showing (a) silver clusters attached to individual CNT bundles and (b) the distribution of silver on the lateral surface of the fibre.

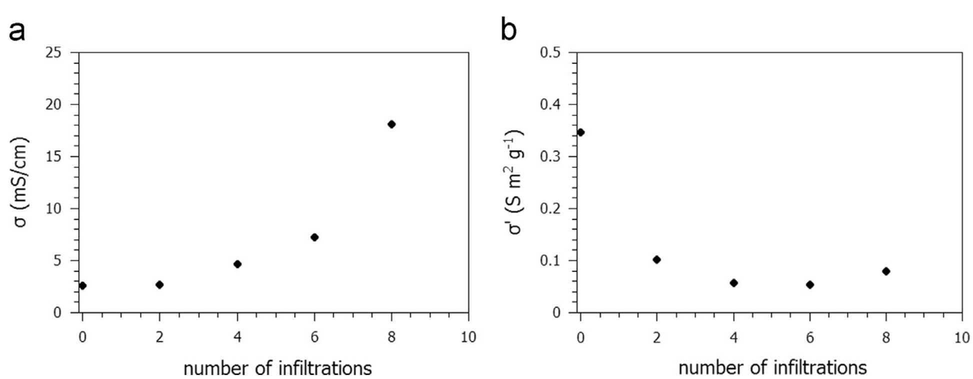

Fig. 2. The correlation of (a) conductance and (b) specific conductivity of the CNT fibre samples with an amount of silver incorporated into them.

Table 1
Maximum current passed through the fibre before burning and maximum power obtained at burning point for as-made and treated CNT fibre samples.

Sample name	R before experiment (Ω/cm)	ΔR after treatment (%)	I_{max} at burning (mA)	ΔI_{max} at burning (%)	P_{max} at burning (mW/cm)	ΔP_{max} at burning (%)
As-made fiber	496	–	14.4	–	259	–
Formic acid doped	315	−36	14.5	+0.7	269	+4
Treated with PEG	583	+18	14.4	0	265	+2
Silver infiltrated 1	391	−12	16	+10	182	−34
Silver infiltrated 2	280	−27	18.3	+26	151	−45
Silver infiltrated 3	245	−54	22	+52	141	−49
Silver infiltrated 4	99	−80	17.7	+23	36	−86