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Towards the development of carbon nanotube based wires

Agnieszka Lekawa-Raus, Lukasz Kurzepa, Xiaoyu Peng, Krzysztof Koziol *

University of Cambridge, Department of Materials Science and Metallurgy, 27 Charles Babbage Road, Cambridge CB3 0FS, United Kingdom

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A B S T R A C T

The excellent electrical and mechanical performance of individual carbon nanotubes combined with their extremely low weight make these structures highly interesting materials for electrical wiring applications. The recent manufacture of macroscopic wire-like assemblies made purely of carbon nanotubes – carbon nanotube fibres – has opened up new prospects in this area. The extensive research on the optimization of the morphology of the fibres indicates that it will be soon possible to produce carbon nanotube fibres exceeding both the electrical and mechanical performance of conductive metals currently used in electrical engineering. To enable the application carbon nanotube fibres as wires in everyday electrical circuits it is necessary to provide them with electrical insulation. This paper proposes, for the first time, a method of insulation of the fibres and analyses the parameters which control the successful development of insulating coating on the surface of these highly porous carbon materials. It is shown that the applied insulation does not compromise either the electrical or mechanical performance of the fibres. The proposed insulation method is inexpensive, easy to integrate into a production process for the carbon nanotube fibres and it can be scaled up.

1. Introduction

The rapidly increasing demand for electrical energy observed all over the world entails a constant expansion and modernization of electrical wiring systems. There are several problems with current materials like copper and aluminium, mainly involving poor mechanical performance, weight, creep, resistive losses, electromigration and limitations in current carrying capacity. Moreover, there are possible future limitations in terms of materials availability and related cost. Such reasons have stimulated a search for new materials based on elements which are abundant in nature and can outperform conventional conductors both in electrical and mechanical terms, being lightweight simultaneously. Carbon nanotubes (CNTs) are very promising candidates for this type of applications.

Carbon nanotubes (CNTs) are tubules with the walls made of a single layer of sp^2 bonded carbon atoms arranged in a hexagonal lattice, i.e. graphene [1]. Depending on the exact structure (diameter and orientation of the hexagonal lattice) the nanotubes can be either semi-metals (often referred to as simply metals) or semiconductors of varying widths of bandgaps. As the CNTs are long (reaching even centimetres) but are extremely narrow, with conductor diameters in the range of several atomic distances, they are a type of quantum wires [1]. The electron wavevectors are quantized along the circumferences of the nanotubes and the charge carriers are free to travel only along the axial directions. Similarly to other quantum wires, the CNTs may show ballistic electron transport i.e. without scattering, which has been confirmed experimentally [2,3]. According to theoretical calculations, electrons in CNTs should travel over micrometre range

* *Corresponding author:* Tel.: +44 1223 334356.
E-mail address: kk292@cam.ac.uk (K. Koziol).
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distances without experiencing scattering at room temperature [2]. The maximum mean free path measured experimentally amounted to 1 μm at room temperature [3]. For comparison, electrons in copper at room temperature have mean free paths of only 40 nm [4]. The maximum current density measured experimentally in individual CNTs (at room temperature) was extremely high and amounted to 10^9-10^{10} A/cm^2 [5]. These numbers exceed the critical current densities of superconductors (10^8–10^9 A/cm^2) [6] not to mention any standard copper or aluminium wires [7]. Other benefits of carbon nanotubes include high thermal conductivity of 3000-3500 W/m K in axial direction [8,9] and superior mechanical properties with experimentally measured tensile strength of up to 100 GPa and tensile moduli up to 0.95 TPa and tensile strains up to 12% [10–12]. Simultaneously, carbon nanotubes are characterized by low weight. The volumetric density of individual CNTs amounts to approximately 1.3 g/cm^3 for single-wall nanotubes (SWNTs – which are made of a single layer of rolled-up graphene) [13] and 2.1 gcm^3 for multi-wall nanotubes (MWNT – made of several concentric SWNTs) [14]. The commercially available powders of SWNTs vary in density from 0.1 g/cm^3 [1] to 0.14 g/cm^3 [2] and MWNTs from 0.15 to 0.28 g/cm^3.[2] Finally, the CNTs are synthesized out of widely available compounds such as methane and their production can be inexpensive.

An electrical wire produced from a material with the properties of individual CNTs would be considerably superior to conventional wires, not only in terms of pure electrical, thermal and mechanical performance but also due to its low weight. The highly important latter characteristic of potential CNT wires is expected to revolutionise many areas of technology. As an example, one of the crucial arguments for the use of aluminium instead of copper in overhead power lines is its low density. Aluminium has twice higher conductivity to weight ratio than copper and 30% better strength to weight ratio than copper, which is further improved by addition of a supporting steel wire into the whole overhead conductor. The low weight of aluminium ensures less strain on the supporting pylons and in the wires themselves, while keeping the sufficient electrical conductivity. The whole construction reinforced with steel guarantees low probability of mechanical failures of the grid. The use of highly conductive, strong and lightweight CNT wires would simplify the construction of the overhead conductors. The advantage of low production costs and maintenance of CNT wires would make them even more attractive for such applications. Yet another example to mention is from aerospace and automotive industry. Here, the decrease in weight of the large machines is an absolutely crucial issue. Every kilogram less, reduces the amount of fuel needed to propel the machines, making them much more economical and safer for environment. Also in these applications CNT wires could be highly beneficial and make a global impact.

However, in order to produce electrical wires from CNTs several challenges need to be overcome. These include, the assembly of CNTs into macroscopic structures and the precise control of the morphology of the structures such that they produce a highly conducting and mechanically stable material. For majority of applications it is also necessary to provide electrical insulation so that these new CNT wires may be used in conventional electrical circuits.

There are different ways to continuously produce macroscopic CNT assemblies, however particularly relevant to the electrical wiring application are CNT fibres, also referred to as threads or yarns.

Fibre production methods include wet spinning, e.g. extrusion from surfactant-stabilised suspensions [15] or from liquid crystalline phase [16,17], and dry methods such as drawing from the CNT carpets [18], cotton [19] or direct spinning from chemical vapour deposition (CVD) synthesis zone, used to produce the fibres studied in this paper [20].

CNT fibres have diametres ranging from a few to several tens of micrometres and may be kilometres-long. They are, made of axially aligned bundles of SWNTs and MWNTs or a mixture of both, holding together due to van der Waals forces, friction forces and local entanglement.

There has already been a lot of progress in the optimisation of the morphology of the fibres so as to obtain the best mechanical or electrical performance, while keeping low weight of the material.

Fig. 1(a) shows the comparison of strength and stiffness of these fibres with the properties of several materials crucial for electrical wiring applications as well as the strongest and stiffest examples of carbon fibres. Due to the fact that the most interesting applications for CNT fibres involve the weight issue described above, therefore, strength and stiffness of the materials are presented as specific values i.e. are divided by density factor. This approach allows also a much more reliable comparison of the fibres to other materials as it allows the avoidance the measurement of a cross-sectional area of the wires which is often highly uneven by using linear density [20]. Linear density (LD), i.e. the weight of the fibre per unit of its length, is widely used in textile industry giving an exact measure of density of thin fibres where the precise measurement of the cross-sectional area may be unreliable. For CNT fibres the specific strength and stiffness are represented by force divided by linear density and are measured in units of N/tex where tex is a unit of LD and equals g/km. For other materials the specific strength and stiffness are represented by GPa/SG. SG – specific gravity is a ratio of the weight of a given material to the weight of water for the same volumes considered (dimensionless parameter). As the SG of CNT fibre after densification is about 1 the specific values in GPa/SG are numerically equal to values in N/tex. It is visible that the specific mechanical properties of the CNT fibres, presented in this paper, are better than of any conducting metal or metal alloy used in electrical engineering.

Electrical properties of the same materials are compared in Fig. 1(b) using values of specific conductivity plotted against volumetric density [21,22]. The use of specific conductivity allows, analogously to specific strength and stiffness, the reliable comparison of various materials via incorporation

[1] NanoIntegris, data provided by the manufacturer on http://www.nanointegris.com/en/hipco, (accessed April, 2012).
[2] CreativeNano, data provided by the manufacturer on http://www.creativenanotech.com/carbon_nanotubes.html, (accessed April, 2012).