Thermal properties of continuously spun carbon nanotube fibres

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ABSTRACT

As indicated by theory and experimental measurements individual carbon nanotubes (CNTs) have very high values of thermal conductivity. One of the challenges is to achieve high thermal conductivity in macroscopic assemblies of CNTs such as fibres, films and composites, paving the way to a wide range of applications. CNT fibres have tremendous potential in succeeding as the future materials for a variety of applications when properties at the nanoscale are translated to their macroscopic assemblies. In this paper we report the measurements of thermal conductivity of continuously spun CNT fibres and its dependence on temperature.

1. Introduction

Exceptional thermal properties of carbon based materials are very attractive due to the benefits associated with the material low density. The best in the family are graphene (with thermal conductivity measured between 1500 and 2000 W/mK [1–3]), diamond (with thermal conductivity up to 2200 W/mK [4]) and special carbon fibre T1300 (with thermal conductivity up to 1300 W/mK [5]). However these materials are expensive due to their multistage and time consuming production. It has been demonstrated experimentally that individual single-wall CNTs, which also belong to the carbon family, reach extremely high thermal conductivity of around 3500 W/mK [6]. Due to their high performance and the relative ease of formation of CNT macroscopic assemblies such as fibres and films they naturally attracted massive interest of the community and industry.

Thermal conductivity depends on many properties of a material, particularly its microstructure and composition. For instance, pure crystalline substances exhibit very different thermal conductivities along different crystal axes, due to differences in phonon coupling along a given crystal axis. Moreover, thermal conductivity value of a particular material should be reported along with the temperature, at which it was measured because it has a non-linear dependence on temperature.

There are various possibilities to measure thermal conductivity, each of them suitable for a limited range of materials, depending on the thermal properties and the medium temperature. Also most of the methods are suitable for bulk materials (like the steady-state and transient techniques). It is however challenging to measure thermal properties of fibres made of different materials. In this paper a Veeco explorer AFM thermal probe setup adapted for work in high vacuum was built in-house and used for the thermal conductivity measurements. It has been calibrated with different fibres of common materials before applied to the measurements of CNTs.

2. Experimental

2.1. Materials

CNT fibres used in this work were directly spun from the CVD reactor according to already published procedure [7]. The synthesis temperature was 1300 °C and the feedstock was ethanol/ferrocene/thiophene. A typical scanning electron microscope (SEM) image of the macroscopic fibre is shown in Fig. 1.

2.2. Methods

The CNT fibre was wedged mechanically (using a micromanipulator) between the arms of a Veeco Thermal Probe, shown in Fig. 2A, which consists of an Ag Wollaston wire (75 mm in diameter) etched at the tip to expose the 90Pt/10Rh core (5 mm in diameter). The complete setup is shown in Fig. 2B.

The Pt/Rh core is the thermal element of the probe and is heated, using Joule heating, to a temperature T set by R₂, A feedback system of the AFM probe (diagram shown in Fig. 3) adjusts Vout so as to keep the...
heated probe tip at a constant temperature. From $V_{out}$, the heat lost by the probe, $Q$, can be determined (Eq. (1)).

$$Q = \frac{R_p}{(R_0 + R_p)^2} V_{out}^2$$  

(1)

$R_1=20 \, \Omega$ and $R_p$ is the probe’s resistance

$$R_p = R_0 [(T - T_0) \alpha + 1]$$  

(2)

$R_0$ is the probe’s resistance at room temperature, $\alpha$ is the temperature coefficient of resistance for 90Pt/10Rh ($0.00165 \, K^{-1}$), $T_0$ is room temperature.

The operating temperature of the thermal probe can be changed by modifying the resistance $R_C$ in the Wheatstone bridge according to the Eq. (3)

$$T = \frac{[R_C - R_L]S R_0}{\alpha} - \frac{1}{T_0}$$  

(3)

$R_L$ is the leads resistance.

The thermal probe with mounted fibre is lowered onto a gold foil substrate (the cold stage) using the piezo element of the AFM. The temperature of the cold stage is controlled with a thermocouple. The heat flux and electrical resistance can be simultaneously recorded using two independent circuits (DC and AC respectively).

The fibre was brought in and out of contact with the substrate (the withdraw/approach speed was typically 500 nm/s) for several times and the heat lost by the thermal probe when the fibre was in/out of contact with the substrate was recorded.

In order to calculate the thermal conductivity the effective length of the fibre (from the end of thermal probe to the tip of the fibre) protruding from the thermal probe and its active contact (area of the fibre in contact with the cold stage surface) were measured using SEM. Thermal conductivity is finally calculated based on Eq. (4).

$$\kappa = \gamma \left( \frac{\Delta Q}{A} \frac{\Delta x}{\Delta T} \right)$$  

(4)

where $\Delta Q$ is the heat lost through the fibre, $A$ is the contact area between the fibre and the substrate, $\Delta x$ is the length of the fibre, $\Delta T$ the temperature gradient along the fibre and $\gamma$ is a correction factor dependent on fibre type.

There are two main uncertainties in the technique: the size of the contact area between the wire and the substrate (active surface of the fibre but this can be measured using SEM) and the real temperature at the fibre-probe contact which depends on the morphology of the fibre used and how well it was wedged to the probe. In order to calibrate the
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