Torsion fracture of carbon nanocoils

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We fix a carbon nanocoil (CNC) on a substrate in a focused ion beam instrument and then fracture the CNC with a tensile load. Using the CNC spring index, we estimate the maximum to average stress ratio on the fractured surface to range from 1.3 to 1.7, indicating stress concentration on the coil wire inner edge. Scanning electron microscopy confirms a hollow region on the inner edge of all fractured surfaces. © *2012 American Institute of Physics*. [http://dx.doi.org/10.1063/1.4758921]

I. INTRODUCTION

Motojima and Chen originally synthesized helical-shaped carbon microcoils (CMCs) on a graphite substrate (coated with Ni powder catalyst) using catalytic thermal chemical vapor deposition (CVD) with ($C_2H_2 + H_2 + N_2 + C_4H_4S$) source gases.[1] Presently, one can synthesize much smaller helical carbon nanofibers (HCNFs), with typical carbon nanocoil (CNC) fiber diameters and coil radii ranging from 100 to 200 nm and 300 to 900 nm, respectively. Several groups have studied the physical properties and electrical characteristics of tiny helical-shaped elements, such as nano-springs,[8,9,11–14,17] as well as carbon micro-coils[1,3,6,18] and nano-coils.[2,4,5,7,10,15,16] Using cantilever atomic force microscopy (AFM) and subjecting CNC to a tensile load, Chen *et al.*[2] determined the CNC spring constant to be 0.1 N/m^2. Potential CNC applications (at nanometer scales) include resonant elements, mechanical springs, nano-solenoids,[6] and field emitters.[4]

Presently, there are no data regarding the cause of CNC fracturing under tensile loads. In this paper, we study the CNC fracturing properties of 8 CNCs using a focused ion beam (FIB) technique for applying uniaxial loads. We use scanning electron microscopy (SEM) to establish the CNC fracture mechanism and employ CVD for CNC synthesis.

II. EXPERIMENTAL

A. Preparation of CNC

After vacuum-evaporation deposition of 40 nm thick Sn on a Si substrate, we pour 10-μl Fe_2O_3 solution onto the Sn-coated Si substrate and anneal the Fe-Sn catalysts at 400 °C for 5 min. We introduce the source [C_2H_2 (50 ml/min)] and dilute [N_2 (1000 ml/min)] gasses into a CVD reactor in which 10×10 mm^2 catalytic substrate deposition occurs at 700 °C for 10 min.[19,20] After synthesis, we cool the reactor to below 100 °C and recover the substrate.

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B. Tensile test

We perform CNC tensile tests using a FIB apparatus (FEI Quanta 200 3D) with a tungsten (W) probe of 500 nm tip diameter. With the Pt ion beam, the W probe approaches and then adheres to CNC, whereas the Si ion beam cuts the CNC bottom. The CNC-adhered W probe approaches a Si substrate surface then the Pt ion beam irradiates the CNC bottom so that it adheres to the Si substrate. We fix the CNC almost perpendicularly to the Si substrate and perform tensile tests for 8 CNCs by gradually changing the distance between the Si substrate and the W probe.

III. RESULTS AND DISCUSSIONS

A. Fracture of CNCs

Fig. 1 shows CNC tensile test micrographs. We carefully maintain constant tensile speeds for all tensile tests. We observe the elongation behavior of CNCs in the FIB instrument using scanning ion microscopy (SIM). Fig. 1(c) shows that the CNC coil pitch returns to its original length after fracturing, thus confirming that CNC is a spring. We measure CNC stretch ratios from SIM image pixels and observe the following parameter ranges for the 8 fractured CNCs: coil radius (0.7–0.9 μm), coil pitch (1.0–2.3 μm), fiber diameter (0.3–0.6 μm). The average stretch ratio of the 8 CNCs on the verge of fracture is 150% as shown in Table I.

B. Mechanism for CNC fracture

We use the above data, together with the compression mechanism of springs in automobiles,[21] to formulate a mechanism for CNC fracture. When we apply a uniaxial tensile load F to a coil spring with a radius of R, the torsion moment, PR [Nm], and direct shear force, P [N], act on the coil wire[21,22] as shown in Fig. 2(a). The force and moment act parallel to the cross section of the coil wire (aa′), generating stress only on the aa′ surface. It is known that the stresses generated by the displacements of dAs in the tiny element

