Electron Microscopy 1998
Paper presented at ICEM14, Cancun, Mexico, 31 August to 4 September 1998
Symposium CC, Volume III

In-situ Bending Deformation of Carbon Nanotubes in a HVEM

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Carbon nanotubes, discovered by Iijima in 1991 [1], hold a great promise for novel materials applications ranging from nano-scale electronic components to high strength fibers in structural composites. For applications in composites, it is important to understand their mechanical behavior, especially large elastic deformation and fracture strength. The Young's modulus of such nanotubes has been measured by electron microscopy as an average value of 1.8 TPa [2], one of the highest of any material. This material was also shown to be extraordinarily resilient [3]. However, most other mechanical properties still elude measurement, in part to the difficulty of handling nanotubes because of their small size. It is envisaged that this challenge can be addressed by a combination of microfabrication and transmission electron microscopy (TEM). The former provides ways to construct devices for manipulating nanotubes, and the latter provides a visual means with sufficient resolution to locate and observe them during manipulation. Progress has been made by using a special TEM specimen stage with a piezoelectrically driven manipulator to deform carbon nanotubes during *in-situ* observation. It is the purpose of this note to report on a set of preliminary experiments in a high-voltage microscope (HVEM) to demonstrate that transmission electron microscopy is a viable technique for studying the deformation of nanotubes.

We have modified a special specimen stage originally designed for indentation experiments [4] for the bending deformation experiments (Fig. 1). It consists of a central rod that can move independently along the rod axis and two perpendicular lateral directions. At the end of the rod, a diamond tip is mounted if it is to be used for indentation. For the present experiments, the diamond indenter is replaced by a thin metal wire with a sharp tip, to which an aggregate of carbon soot is attached by glue. These carbon soots usually have an elongated texture and it is not uncommon that a number of nanotubes stick out from the edge at the end. These protruding nanotubes can be used as the test sample. Opposite to the central rod is a clean silicon chip with cantilever beams intended to give a qualitative estimate of the force involved in the deformation by measuring the degree of their deflection.

Typical mechanical behavior of carbon nanotubes, such as their exceptional flexibility and resilience, is demonstrated in a series of deformation sequences recorded during a bending experiment conducted in the Kratos EM1500, a 1.5 MeV high voltage microscope at the National Center for Electron Microscopy. The specimen was a bundle of single-walled tubes forming a so-called carbon nanorope (Fig. 2). As the rope touched against the silicon chip at the opposite side, it started to deform. In the linear small deformation limit (Figs. 2a and 2b), the bending deformation was homogeneous; the sample formed a smooth arc along its length. However, as deformation proceeded further, the deformation mode bifurcated from the homogenous mode to kinking where finite strain was now concentrated locally (Fig. 2c). Further deformation only increased the degree of kinking, and did not reach the stage of fracture failure which would be typical for other materials at this point. After the nanorope was pulled back, the kink disappeared and the nanorope recovered from most of the strain. This behavior was reproducible through several cycles. Further work will focus on obtaining quantitative information with aim to shed light on the mechanical behavior of carbon nanotubes, specifically the elastic modulus and bending strength, in the regime of both small and large deformations.

References

1. Iijima, S., *Nature*, 354 (1991) 56.
2. Treacy, M. M. J., et al., *Nature*, 381 (1996) 678.
3. Falvo, M. R., et al., *Nature*, 389 (1997) 582.
4. Wall, M. A. and Dahmen, U., *Proc. Ann. MSA Meeting*, 3 (1997) 593.

5. The authors wish to thank M. A. Wall at LLNL for the technical support. This work is supported by the Director, Office of Energy Research, Office of Basic Energy Sciences, Materials Science Division of the U.S. Department of Energy under Contract No. DE-AC03-76SF00098.

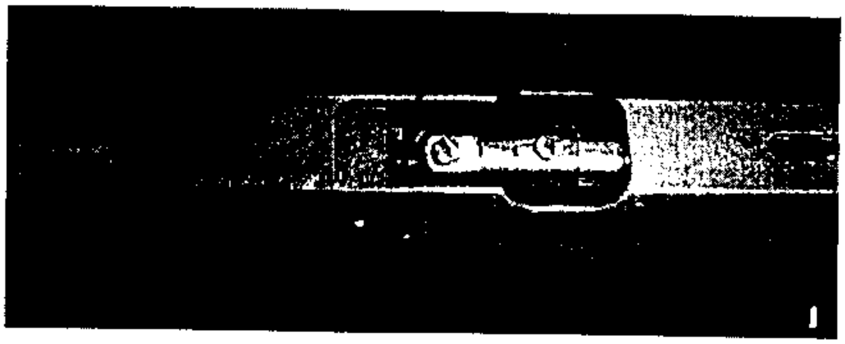

FIG. 1. The specimen stage modified for the *in-situ* bending experiment. Carbon soot (arrow) is mounted at the tip of a thin metal wire fastened to the central rod of the holder.

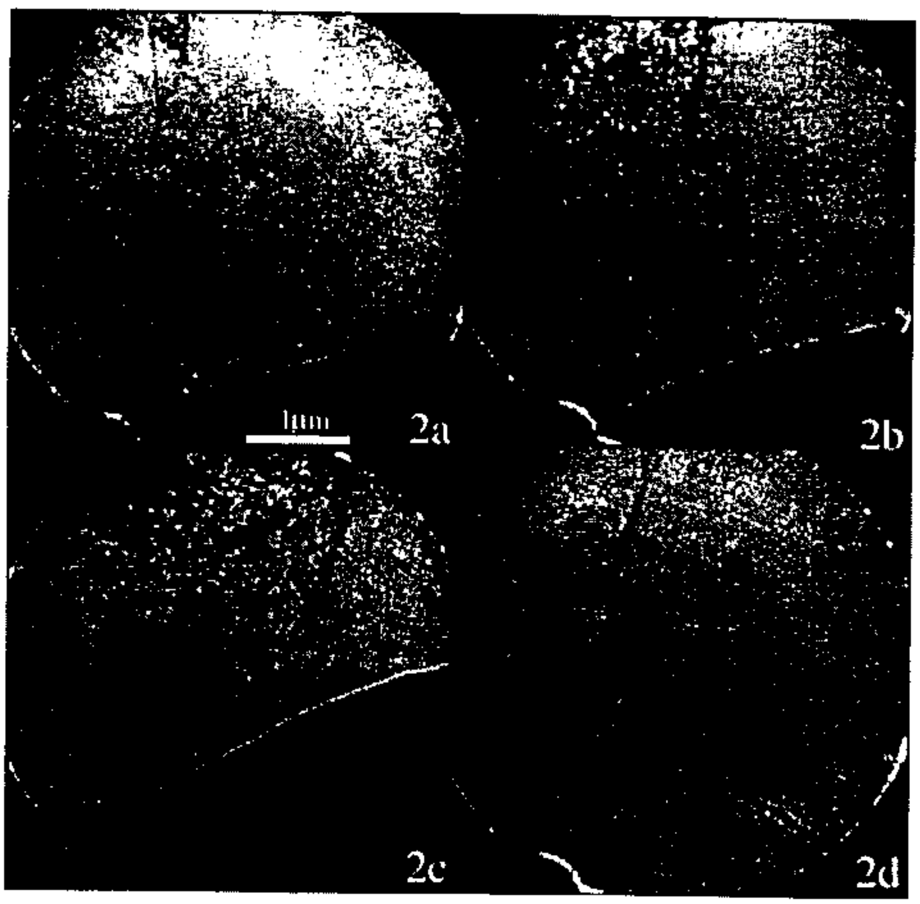

FIG. 2. *In-situ* bending experiment showing the switch of deformation modes from homogeneous deformation (2a and 2b) to kinking (2c) at large deformation. Exceptional resilience of the carbon nanotube is also demonstrated by the recovery of most of the deformation (2d).