Telescoping Nanotubes Demonstrated as Nanoscale, Linear, Low Wear "Bearings" and "Springs"

A research team led by Alex Zettl in the Berkeley "sp^2 Materials" program has demonstrated that individual concentric carbon nanotubes in a multiwall nanotube can "telescope" with minimal resistance, much like a greased radio antenna. These results suggest that these tubes could possibly be used as nanoscale linear bearings with very little friction. A report of this work appeared recently in *Science*.

Graphite has a low coefficient of friction because its sp^2-bonded "graphene" planes have little mutual attraction and thus can slide over one another easily. It might therefore be expected that neighboring tubes in multiwall carbon nanotubes would have a similarly low friction coefficient. This might allow one set of tubes to freely "extend" relative to the others, thus performing the mechanical motion of a linear bearing (see figure). Until now, however, the extremely small size of carbon nanotubes has precluded demonstration of these effects

The mechanical properties of these tubes were successfully studied by the Zettl group using an *in-situ* nanomanipulation stage recently constructed at the National Center for Electron Microscopy (NCEM). It enables the investigator to manipulate nanosized objects under continuous transmission electron microscope (TEM) observation. In the first experiment, the group attached one end of an outer tube in a multiwalled tube to a rigid mount and the protruding inner tubes at the other end to a movable manipulator. The manipulator was then retracted, pulling the inner nanotubes out of the outer sheath of nanotubes (see figure). The sliding motion was observed to be reversible, and the inner tubes could be pulled out and pushed back repeatedly without any observable damage. These observations are highly suggestive that nanotube linear bearings could have near-zero fatigue and wear.

In a second experiment, the team observed that if they released the extended nanotube, it experienced an atomic-scale attractive force that pulled it back inside the nanotube sheath. This force results from the greater van der Waals attraction energy achieved by increasing the tube-tube contact area. Evidently, this small force is sufficient to overcome whatever friction exists between the nanotube sections. The researchers were able to estimate the magnitude of this restoring force and thus conclude that the frictional coefficient for the nanotube "linear bearing" motion is either non-existent or exceedingly small. They calculate that the static friction is less than 2.3×10^{-14} Newtons/atom (6.6×10^{-15} N/Å^2) and the dynamic friction is less than 1.5×10^{-14} Newtons/atom (4.6×10^{-15} N/Å^2). These frictional force upper limits are already approximately 1000 times smaller than the analogous (small scale) frictional forces associated with conventional MEMS technology materials. Further, the nature of these forces suggests that the tubes are acting as a constant force spring.

The low friction, low wear, apparently fatigue-free and robust character of these nanosize bearings and springs makes them attractive candidates for nanotechnology device components. In fact, it is expected that a related frictionless motion, not yet studied, where one tube rotates with respect to the other, could constitute a rotational bearing.

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Cumings, John, and Alex Zettl, "Low-Friction Nanoscale Linear Bearing Realized from Multiwall Carbon Nanotubes," Science, Volume 289, Page 602, July 28, 2000.