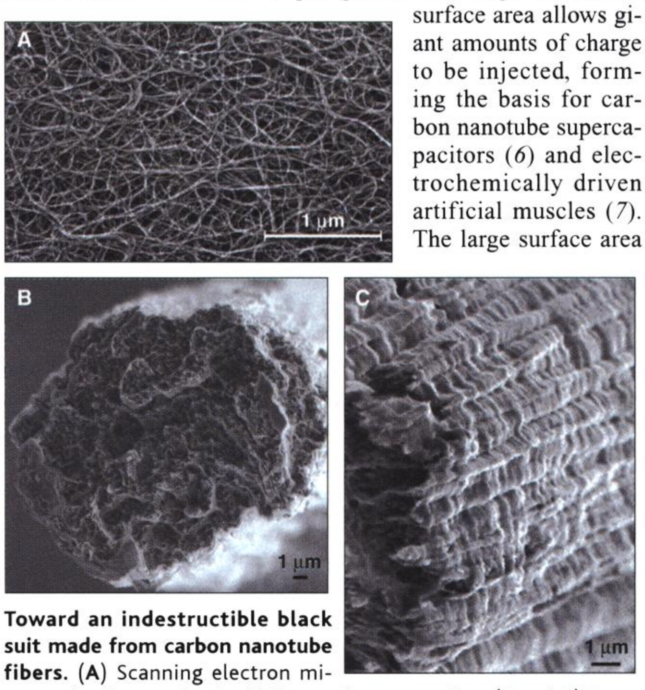
PERSPECTIVES: MATERIALS SCIENCE

Putting a New Spin on Carbon Nanotubes

Ray H. Baughman

The Man in the White Suit (played by Alec Guinness in the 1951 British comedy) invented a textile fiber that was nearly indestructible (*1*). With some important new twists, a black version of this suit is coming closer to reality, thanks to the pioneering carbon nanotube spinning process described by Vigolo *et al.* on page 1331 of this issue (*2*). Their single-wall carbon nanotubes each consist of a graphite sheet seamlessly wound into a ~14 Å diameter, hollow cylinder. The Young's modulus (a measure of stiffness) of these individual nanotubes is very high in the tube direction (*3*), but more importantly, they are spectacularly strong and damage resistant. It has been shown that small-diameter nanotube bundles can sustain strains of about 6% without breaking (*4*), corresponding to a failure strength of more than 36 gigapascals (GPa). Normalized to density, this failure strength is much higher than for any other known material. For applications outside the realm of nanotechnology, however, individual tubes or small bundles are too small to exploit their remarkable mechanical properties. The challenge is thus to self-assemble trillions of these nanotubes into long fibers that preserve the mechanical properties of the individual tubes.

Nanotechnologists have suggested many uses for continuous, ultrastrong carbon nanotube fibers. [One of the more extreme suggestions was Yakobson and Smalley's futuristic vision of tethering satellites to Earth with such fibers (*5*).] In contrast to Alec Guinness' white suit, which does not get dirty because nothing adheres to or wets the fibers, carbon nanofibers can be easily wet and have an extremely high surface area of more than 300 m^2 per gram. This huge accessible surface area allows giant amounts of charge to be injected, forming the basis for carbon nanotube supercapacitors (*6*) and electrochemically driven artificial muscles (*7*). The large surface area might also be used for hydrogen storage (*8*) and electrical energy harvesting (*9*).



Toward an indestructible black suit made from carbon nanotube fibers. (**A**) Scanning electron micrograph of as-synthesized HiPco carbon nanotubes. (**B** and **C**) Scanning electron micrographs of spun HiPco nanotube fibers. The as-synthesized HiPco nanotubes contain few carbonaceous impurities, explaining the absence of the impurity sheath seen by Vigolo *et al.* (*2*). The striations parallel to the fiber length in the side-wall view (C) are consistent with nanotube alignment in this direction.

Not all of these applications intrinsically require high mechanical strengths. Production of carbon nanotube fibers therefore does not necessarily have to optimize mechanical properties. However, cost and weight savings could result from the use of strong nanotube fibers for nonstructural and structural functions simultaneously. These and other "synthetic multifunctional materials" are being explored by U.S. Defense Advanced Projects Agency (DARPA) for applications ranging from protective vests that store energy for the "energy sufficient" soldier, to structural shells that provide actuation, energy storage, energy conversion, and/or sensing functions for bird- or insect-like micro air vehicles (*10*).

Polymer fibers are often made by melt spinning. The polymer is melted and pumped through a spinneret with numerous holes. The molten fibers are cooled, solidified, and collected on a take-up wheel. Nanotube-containing fibers have been made by melt spinning polymer-nanotube composites (*11*) and also by electrophoretic assembly (*12*). Both of these methods have their drawbacks, however: The nanotube concentration is low for the melt spinning process, and the electrophoretic assembly method seems too slow for economical fiber production.

The spinning process of Vigolo *et al.* (*2*) is based on their fundamental understanding of the phase behavior of a nanotube/surfactant/water system. It is exciting because it likely can be scaled up for the simultaneous spinning of hundreds or thousands of high strength fibers to make nanotube yarns. Ribbons made of low-density nanotube meshes are first formed by spinning structurally uniform nanotube dispersions into a flowing stream of an aqueous poly(vinyl alcohol) solution in a coagulation bath (*2*). Slowly pulling the nanotube mesh from the coagulation bath causes the mesh to collapse into a high-density fiber. Forces due to surface tension, which are enhanced by the huge surface area of the nanotube bundles, cause this densification. Despite the use of unpurified nanotubes containing ~50% carbonaceous impurities, the as-produced carbon nanotube fibers have an elastic modulus of up to 15 GPa (*2*). This is much lower than the ~600 GPa modulus of the individual carbon nanotubes (*3*), but over an order of magnitude higher than for sheets of single-wall carbon nanotubes made by the usual paper-making process (*13*). Dramatic further improvements in mechanical properties are likely to result from increased fiber alignment and interbundle binding.

We have attempted to improve the Vigolo *et al.* (*2*) spinning process by replacing the unpurified nanotube soot with purified nanotubes prepared through traditional methods (*14*). This effort was so unsuccessful that we thought that impurities in the nanotubes might serve as binding agents at the junctions between nanotubes. The whole picture changed, however, when we used high-purity nanotubes produced directly by the Rice high-pressure carbon monoxide process (HiPco) (*15*). These nanotubes, which have narrow individual diameters (~8 Å) and long bundle lengths, spin over a much broader concentration range of nanotubes and surfactant than the arc-produced nanotube soot and produce mechanically robust ribbons that are easily pulled

The author is at Honeywell International, Materials Research, Morristown, NJ 07962, USA. E-mail: ray.baughman@honeywell.com

from the coagulation bath (see the figure).

Our efforts to use the carbon nanotube fibers as artificial muscles provided another surprise (*14*). All fibers made by the Vigolo *et al.* (*2*) process swell in diameter by up to ~200% when immersed in water or an aqueous electrolyte, resulting in markedly decreased modulus and strength. Interbundle stress transfer within the fiber is apparently facilitated by residual poly(vinyl alcohol) from the spinning bath. Immersion in an aqueous solution transforms the poly(vinyl alcohol) into a gel with little binding capability, causing the fibers to partially expand. The fiber swelling remains above 50% even if the precursor ribbon-shaped nanotube mesh is washed in water for several days, apparently because the poly(vinyl alcohol) is strongly bound to the nanotubes. Fortunately, the swelling and degradation in aqueous liquids can be avoided by simply annealing the as-spun fibers at temperatures as low as 400°C for 1 hour while maintaining a vacuum (*14*). Thereafter, the carbon nanotube fibers provided actuator performance exceeding that reported for carbon nanotube sheets (*7*).

The brilliant work of Vigolo *et al.* (*2*) provides the first spinning process that can be modified to provide fibers comprising mostly single-wall carbon nanotubes. I am confident that by building upon their discoveries, it will be possible to devise an economically viable process for spinning strong nanotube fibers. However, at the current price of purified single-wall carbon nanotubes (~$1000/g), single-wall carbon nanotube fibers are only attractive for devices requiring little material. The HiPco nanotubes, which will become commercially available in small quantities this fall, may eventually remove this cost barrier. These tubes perform particularly well in the Vigolo *et al.* process (*2*), require no purification, and are believed to be scalable to economic volume production at a much lower price than present methods.

Once economic production of inexpensive high-quality single-wall nanotubes can be realized, large devices and strong composites may become commercially viable. Until then, the universe of nanotube applications will be largely restricted to the smaller (but no less interesting) world of nanoscale devices and nanothickness coatings.

References and Notes

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16. I thank the authors of (*2*) for describing their spinning process to me; A. A. Zakhidov and R. E. Smalley for useful comments; and R. E. Smalley, M. Bronikowski, P. Willis, D. Colbert, and K. Smith for the gift of HiPco nanotubes used in collaborative research. Supported by DARPA grant MDA972-00-C-0032.

PERSPECTIVES: MICROBIOLOGY

Turning Up the Heat on *Histoplasma capsulatum*

Bruce S. Klein

At least 70,000 fungal species inhabit our planet, yet remarkably few of them cause disease in humans. This happy coexistence may be set to change, however, as opportunistic fungal species (such as *Candida albicans* and *Aspergillus fumigatus*) and pathogenic fungi (such as *Histoplasma capsulatum*) take advantage of patients who are immunosuppressed either because of treatment with toxic cancer drugs or because of a primary infection with, for example, human immunodeficiency virus. The AIDS epidemic itself has changed the epidemiology of fungal diseases (*1*) with a dramatic increase in the number of opportunistic fungal infections—for example, the incidence of cryptococcal meningitis caused by the fungus *Cryptococcus neoformans* has increased 1000-fold in New York City alone.

Dimorphic fungi—the silent majority of pathogenic fungal species—exist as either a free-living mycelial (mold) form in soil or as a parasitic yeast form that inhabits its cells such as macrophages within a mammalian host. The mold forms are saprophytes that absorb nutrients from dead organic matter in the soil and produce infectious spores. When inhaled by mammals, these spores are induced to undergo a morphogenetic transformation into the yeast form by the warmer temperature of the mammalian respiratory tract. Although this morphogenetic switch is essential for the dimorphic fungus to become parasitic, relatively little is known about the identity and regulation of the virulence genes that direct this transition (*2, 3*). With a cunning combination of molecular genetics techniques, Sebghati *et al.* (*4*) identify a crucial virulence gene encoding a calcium binding protein (CBP1) in the systemic dimorphic fungus *H. capsulatum*. As they report on page 1368 of this issue, disruption of the *CBP1* gene resulted in decreased survival of *H. capsulatum* yeast in cultured macrophages (the host cells that they normally parasitize) and in a mouse model of respiratory infection.

Histoplasmosis, the respiratory disease caused by *H. capsulatum*, is found worldwide and is endemic in the Ohio and Mississippi River Valley of the United States where most people are infected by age 20. The majority of infections are mild, but the illness progresses further in up to 10% of infected individuals producing life-threatening symptoms, such as inflammation of the membranes covering the heart (pericarditis) and fibrosis of major blood vessels. The seriousness of histoplasmosis grabbed public attention when noted songwriter and performer Bob Dylan was hospitalized with *H. capsulatum*–induced pericarditis several years ago. This systemic dimorphic fungus establishes a latent (silent) infection that can be reactivated (as happens in up to 40% of AIDS patients), necessitating long-term treatment.

In addition to its clinical importance, several other features make *H. capsulatum* an appealing target for basic investigation. The fact that the yeast form is haploid (it has a single set of chromosomes) permits recessive traits to be readily unearthed because only one copy (not two) of a target gene needs to be inactivated to see an effect. The life-style of *H. capsulatum* yeast parasites inside macrophages offers clues to secrets about the life-styles of other intracellular parasites. Upon infecting a mammalian host, *H. capsulatum* spores become transformed into yeast and are phagocytosed (engulfed) by macrophages and other cells of the reticuloendothelial system (see the figure). The yeast forms reside within the macrophage cytoplasm in phagosomes (phagocytic vesicles surrounded by host cell membranes) or in phagolysosomes (organelles formed by the fusion of phagosomes with lysosomes). Infection of macrophages by *H. capsulatum*

The author is in the Department of Pediatrics, University of Wisconsin–Madison, Madison, WI 53792, USA. E-mail: bsklein@facstaff.wisc.edu