Powering up nanoparticles: versatile carbon materials for engineering and medicine

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Nanocomposites synthesized from different combinations of nanoparticles and matrix materials demonstrate notably increased strength, thermal stability, and electrical conductivity.

Given carbon’s unique properties and versatility, carbon nanomaterials are being used in an increasing number of engineering and medical applications. For example, when carbon nanoparticles are dispersed in matrix materials like epoxy, polyurethane, rubber, cement, or ice, they confer unique electrical and magnetic properties, unlocking a number of new and exciting applications. When such materials are placed under strain, changes in electrical resistance (piezoresistive) and magnetic properties (piezomagnetic) emerge. In an electrolyte, the materials can expand due to an applied voltage.

An interdisciplinary research team is developing carbon materials for commercialization in products such as spray-on continuous sensors for structural health monitoring (SHM), smart nanocomposites that are self-sensing, nanoreinforced laminated composites (NRLCs) that are tough in shear, and carbon nanotube (CNT) electrical fibers. This article provides a summary of how these composites are being developed at our facility to form different prototypes for diverse applications.

Carbon nanofibers (CNFs) are multiwall, highly graphitic, low-cost fibers with diameters ranging from 70 to 200 nm and lengths up to a few hundred microns: see Figure 1(a). The fiber walls sit at an angle of about 20 degrees to the fiber axis and terminate along the surface of the fiber in a zigzag form. Remarkably, a relatively small loading of CNFs in a polymer matrix material can improve its mechanical properties and affect its electrical conductivity, piezoresistive, electromagnetic shielding, and heat dissipation characteristics. As such, promising CNF water-based nanofluids are currently being evaluated for heat-exchange applications. The cost of high-grade PR-25 CNF material is low, at about $125/lb. Furthermore, the material is well characterized and produced in tons per year, making it ideal for use in an array of applications.

Carbon nanosphere chains (CNSCs) are a novel nanostructured material with a spherical morphology and a high electrical conductivity that can be postprocessed to have magnetic properties. CNSCs are unique because they are the only documented carbon nanoparticle that has high electrical conductivity and weak magnetic properties. Postprocessing can tailor these properties for applications in smart polymeric nanocomposites and magnetic materials. Different materials built using CNSCs are shown in Figure 2, including a magnetic pellet formed using high-pressure fabrication methods and structural nanoskins that are electrically conductive on one side and insulating on the other. CNSCs can be produced in large volume, and their cost is expected to be moderate.

CNTs produced by chemical vapor deposition can be synthesized in arrays to form structures that are nanometers in

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Figure 2. Smart CNSC nanocomposites: (a) magnetic pellet, (b) CNSC-polyvinyl alcohol structural nanoskin, and (c) CNSC-epoxy nanoskin.

Figure 3. CNT spray-on continuous sensors.

diameter and that range from a few microns long to 1.8 cm: see Figure 1(c). CNTs grown in an array or forest are called Black Cotton™. This material holds promise for developing unique and revolutionary strain sensors, actuators, biosensors, and nanocomposites for multifunctional applications. When fabricated as a long film, CNTs can function as long continuous sensors (see Figure 3). A structural neural system (SNS) can be fabricated using a dispersed nanoparticle solution applied with an airbrush on a patterned surface to form a grid pattern. The electrochemical impedance (resistance and capacitance) of the SNS changes due to deterioration of the structure where the neuron is located. As such, SNSs can be used to detect cracking of bridge supports early enough to prevent collapse of the structure. CNT arrays presently have a high cost, thereby limiting their application, but the cost will decline as production increases.

Other unique applications also take advantage of the structure and properties of CNT arrays. For example, interlaminar materials are subject to stress cracks propagated along the interlaminar planes. To address this problem, a prototype NRLC is being developed (see Figure 4). The NRLC is composed of layered microfiber textile cloth in a polymeric matrix with nanoscale reinforcements in the form of multiwalled CNT cores that pass transversely between each set of plies. Besides shear reinforcement, the CNT cores also alter the electrical conductivity through the thickness of the laminated composites. Therefore, electrodes can be sputtered on the surface of the laminate, and the electrical impedance through the thickness of the laminate can be monitored to detect cracking or delamination. The NRLC is thus a responsive multifunctional material with improved shear strength and stiffness that also self-senses damage.

The versatility of nanoscale materials is rapidly expanding, and engineers are only now realizing their full potential. Other multifunctional materials in development are CNT threads and sheets (see Figure 5). These CNT forms may be used to make smart fabrics with several unique properties, including reinforced fabric composites (for use in garments for soldiers, firefighters, and first responders), electromagnetic radiation shielding, or SHM sensors. Furthermore, because of their inherent strength and inert nature, there are several medical applications for CNTs currently under development, including small nanotube electrodes that can penetrate an individual living cell, which might be used as tiny biosensors, and nanotube scaffolds that can be used to culture neurons in hopes of repairing damage to the central nervous system. As we further explore the unique properties of different nanocomposites, their potential may further inspire other unique applications.

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