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Carbon Nanotubes: Bearing Stress Like Never Before

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Carbon, element number six, is often considered the backbone of life on Earth. With four valence electrons and many different bonding geometries, carbon is present in all biological macromolecules and plays an integral role in fundamental biological processes, making it truly deserving of its own field, organic chemistry. While carbon is usually anecdotally known for its abundance in biological systems, carbon's many bonding geometries and versatile electronic configurations make it an exceptional material for synthetic molecules for physical applications, such as building materials or semiconductors. Serious investigation into carbon for physical applications began in 1985, when a group of researchers at Rice university designed a "buckyball," a molecule known as buckminsterfullerene with the chemical formula C60 arranged in a structure akin to a soccer ball, with six and five-membered rings positioned adjacent to each other. In fact, buckminsterfullerene, named after the American architect R. Buckminster Fuller, who built geodesic domes resembling the molecule's shape, was only one molecule in a class of many fullerenes, molecules made entirely out of carbon, arranged in the shape of a hollow sphere or tube. After the 1996 Nobel Prize in Chemistry was awarded to a team for the discovery of fullerenes, research into the fullerenes was taken up in earnest by much of the scientific community.

During this time of high interest in the fullerene molecules, a Japanese team of scientists led by Dr. Sumio Ijima designed a tubular fullerene designed entirely out of six-membered carbon rings; forming a large cylindrical structure they termed the "carbon nanotube" (Popov, 2004). Since this fortuitous discovery in 1991, research into carbon nanotubes increased rapidly, spanning from the original field of chemistry into related disciplines such as physics, materials science, and biology. Research into the properties of carbon nanotubes continues in full force even today, and new applications for carbon nanotubes are currently being studied at the forefront of scientific research.

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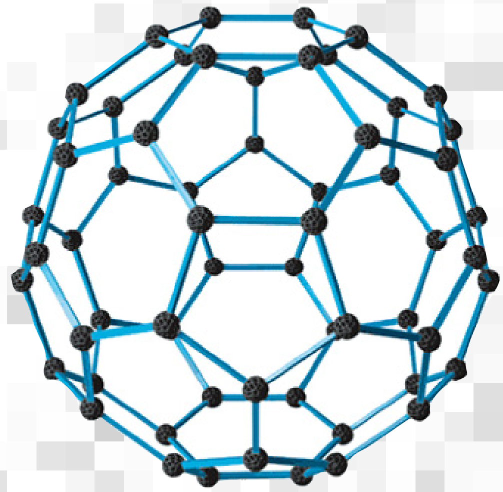
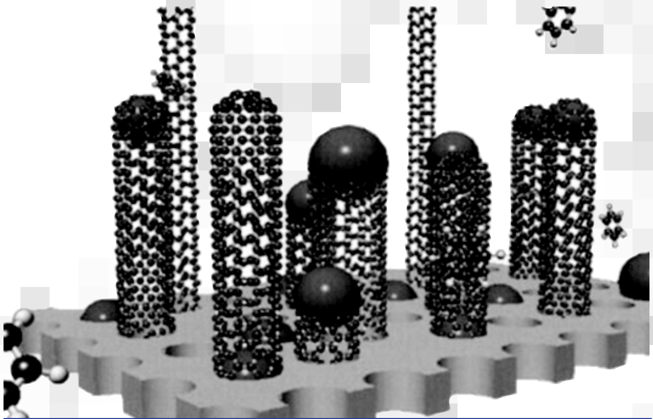
One of the most important properties of the carbon nanotube is its incredible ability to withstand applied tensile forces. When choosing the appropriate material for structural applications, materials engineers often need to consider the way in which a material responds to outside stresses, such as the tensile forces applied in cabling for bridges or the compressive forces applied against reinforcement beams in buildings. In these cases, it is important to select a material that can withstand an appreciable amount of stress without fracturing, and the carbon nanotube presents quite an enticing choice. The stress response of materials is often quantified using the Young's modulus or elastic modulus, which is the ratio of the stress applied to a material to the subsequent strain, either compressive or expansive, that the applied stress causes. Materials with high elastic moduli, such as a steel beam, are stiff, while materials with low elastic moduli, such as rubber bands, are flexible. For most building applications, a delicate balance must be struck between stiffness and flexibility, since very stiff materials such as ceramics can break very easily, while very flexible materials support little weight. Based on these constraints, the carbon nanotube presents a very good choice for a structural material, with an elastic modulus five to ten times greater than high-strength steel, but an ability to flex under certain stress conditions. Based on these properties, carbon nanotubes have been studied in many different stress-bearing applications, with the goal of exploiting the molecular structure and mechanical properties of the carbon



Buckminsterfullerene Ball



Carbon Nanotube Synthesis

nanotube to design strong materials for myriad applications.

While carbon nanotubes present extraordinary properties useful for a wide range of physical applications, the properties of any material are inherently limited by its ability to be synthesized properly, and carbon nanotubes are no exception. Since carbon nanotubes derive their unique mechanical properties from their carefully arranged hexagonal bonding structure, even small deviations, such as a void or a similar defect at one point along the nanotube can cause a severe degradation in the mechanical properties of the nanotube (Popov, 2004), making it important to use a highly precise synthesis process. Carbon nanotubes were originally discovered through arc-discharge synthesis, which runs a current through two carbon electrodes spaced 1 millimeter apart, stripping the carbon atoms from the electrode and forming a nanotube structure on the opposite electrode (Popov, 2004). Unfortunately, this synthesis also leads to the creation of other fullerenes and amorphous carbon by-products, such as soot and ash, which lower both the purity and quality of the final product, making it unsuitable for industrial-scale generation (Popov, 2004). In order to improve the nanotube product yield, new methods such as chemical vapor deposition (CVD) were developed in order to create long nanotubes with very few imperfections. This process involves using small organic molecules such as acetylene or ethylene in the vapor phase, stripping away the carbon from them and "growing" the nanotube by depositing the carbon atoms stripped from the vapor phase onto a metal catalyst, creating a large, tubular assembly of carbon atoms. The CVD process shows much promise for industrial production of carbon nanotubes, and can be used to produce very high-purity products with very few defects or voids.

While carbon nanotubes can now be synthesized nearly perfectly, nanotubes by themselves, due to their small size, are not well suited for structural and stress-bearing applications. Instead, these nanotubes must be embedded into a different material to enhance its mechanical properties. Currently, this is accomplished by using carbon fiber, a carbon-based material drawn or woven into fibers 5-10 micrometers in diameter and embedded into a host matrix, or surrounding material. At the moment, carbon fiber represents a $13 billion market worldwide, with an annual growth rate of over 7% and expanding applications in areas such as aerospace, wind energy, and automobiles. Most of these applications use carbon fiber oriented in one direction embedded into a host matrix such as a metal airframe in the aerospace industry or a structural polymer in the automotive industry.

While current carbon fiber composites show promise for building materials, carbon nanotube nanocomposites offer an opportunity for much greater property enhancement due to their small size. Industrial focus on these polymer-nanoscale filler nanocomposites began when industrial researchers at Toyota demonstrated they could create a five-fold increase in the strength of nylon composites by embedding nanoscale mica sheets into the material instead (Balazs et al., 2006). While these mechanical property improvements are certainly enticing, the advent of carbon nanotubes as composite fillers presents even greater opportunity for structural polymer nanocomposites to replace the current carbon-fiber market. Not only does the carbon nanotube independently have superior elastic properties as compared to woven carbon fiber, but the nano-scale size of the carbon nanotube unlocks a much larger range of interactions with the polymer that strengthen the structural properties of the overall composite. When materials are embedded into a composite, the total surface area of interaction between the polymer and the filler often determines the property changes it effects. Since the carbon nanotube is so small, it can span a much larger surface area of interaction while maintaining the same weight fraction in the material as a regular carbon fiber composite. Due to their size, many more nanotubes can be inserted into the material at the same weight fraction, leading to a stronger composite overall.

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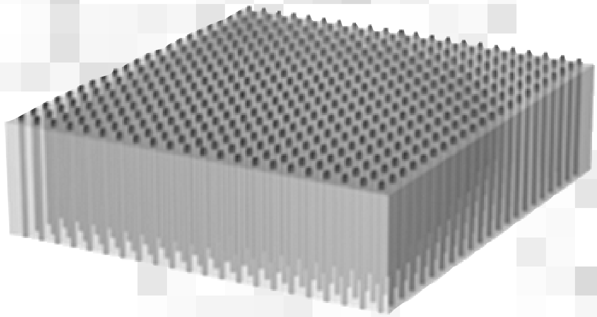
Due to this surface area effect, carbon nanotube-polymer composites have been created that confer a 23% increase in the stiffness of an epoxy resin at a paltry 1 wt% loading (de Volder et al., 2013), meaning that even at such sparse dispersion, the nanotubes can change the stiffness of a composite by an appreciable amount. Another team of researchers was able to combine Kevlar, an incredibly stiff polymer, with carbon nanotubes to form a nanocomposite with an elastic modulus of 1

TPa (Endo et al., 2008). For comparison, the elastic modulus of steel is only 200 GPa, five times lower than the modulus of this composite. Given these dramatic mechanical property improvements, the carbon nanotube appears to be poised to take over the carbon fiber composite market share as a structural material, as they perform nearly all of the same functions that polymer-carbon fiber composite materials do, but to a greater extent.

While most applications for carbon nanotubes show significant amounts of promise, some barriers, both economic and scientific, exist that currently block the widespread use of carbon nanotubes. One major obstacle for carbon nanotubes in the polymer nanocomposite market is the tendency of carbon nanotubes to aggregate when placed into a larger polymer matrix. Since carbon nanotubes are usually grown to large lengths that span a significant fraction of the composite's length, they can entangle very easily, especially



Aligned Composite Image

due to the favorable interactions between adjacent carbon nanotubes. Not only does this aggregation effect lower the overall mechanical properties of the composite, but it also confounds any process to predictably align the carbon nanotubes within the composite, one of the main reasons why carbon fiber composites achieve such a high elastic modulus to begin with (Coleman et al., 2006). While this does present a pressing problem for industrial adoption of polymer-carbon nanotube composites, current research is making leaps and bounds in finding a solution, from computationally modeling the energy effects that cause aggregation in the first place to attaching molecules to the outside of carbon nanotubes in order to discourage, at a molecular level, the observed aggregation behavior.

Based on the current trajectory of carbon nanotube research and the extraordinary properties this unique molecular arrangement brings to the table, it is clear that carbon nanotubes will undoubtedly play a large role in the future of structural materials, especially polymer-nanotube composites in the aerospace, automotive, and renewable energy sectors. If the past is any indicator of the future trajectory of carbon nanotubes, it appears that new applications and interesting properties will be discovered in the future, paving the way for new and exciting structural, stress-bearing applications of carbon nanotubes.

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