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Properties of Carbon Nanotubes and their applications in Nanotechnology – A Review

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Abstract

One of the most distinctive inventions in the world of nanotechnology is the carbon nanotube (CNT). Many scholars around the world have been studying carbon nanotubes (CNTs) over the past two decades due to their enormous potential in a variety of sectors. Single-wall CNTs with dimensions in the nanometer range are commonly referred to as carbon nanotubes. Carbon nanotubes are also known as multi-wall CNTs, which are made up of nested single-wall CNTs that are weakly bonded together in a tree ring-like structure by van der Waals interactions. Tubes having an unknown carbon wall structure and diameters smaller than 100 nanometers are also referred to as carbon nanotubes. A carbon nanotube's length is often substantially longer than its diameter, according to standard manufacturing methods. Carbon nanotubes are capable of exhibiting a variety of remarkable properties. CNTs have distinct electrical, mechanical and optical properties that have all been thoroughly investigated. The properties and applications of carbon nanotubes are the focus of this review.

Keywords: Carbon nanotubes, properties, nanotechnology, applications

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1. Introduction

Nanotechnology and nanocomposites have received a lot of attention in recent years. Everyday life is being transformed by nanotechnology. Nanotechnology, which has become a well-known field in the last three decades [1], is derived from the Greek word "nano," which means "dwarf (little)." Scientific treatment at the nano level (atomic level) with the aid of unique scientific instruments is known as nanotechnology. Nanotechnology is a broad field that investigates many aspects of material structures and behaviours. Carbon nanotubes (CNTs), also known as buckytubes, are cylindrical carbon molecules with unusual properties that could be beneficial in a range of applications. Nanoelectronics, optics, and materials applications are only a few examples. CNTs are extremely strong and have unusual electrical, mechanical, and thermal properties. The fullerene family includes carbon nanotubes. Buckyballs are spherical fullerenes, whereas CNTs are cylindrical fullerenes having a buckyball structure at least on one end. The name CNT comes from the nanotube's size, which is measured in nanometers.

1.1. Types of Carbon nanotubes

CNTs are classified into three groups based on the number of tubes they include. These are explained as follows.

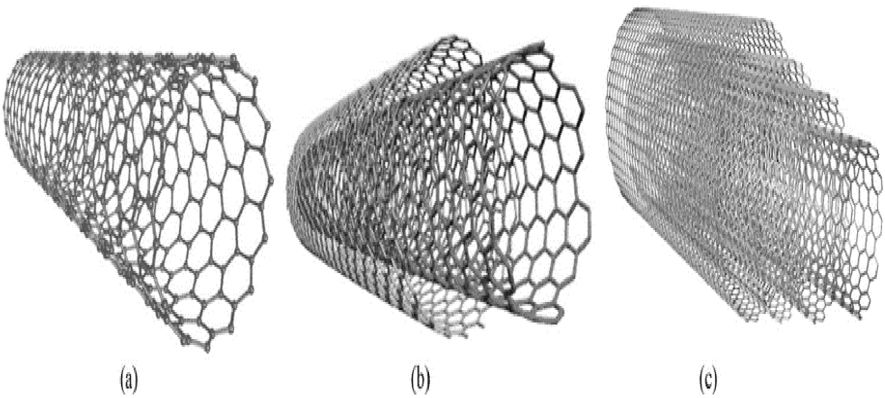

Figure 1: a) Single-walled carbon nanotube, b) Double-walled carbon nanotube and c) Multiwalled carbon nanotube

Single-walled CNTs: Single-walled CNTs (SWCNTs) are made of a single graphene sheet rolled upon itself with a diameter of 1–2 nm (Fig. 1a). The length can vary depending on the preparation methods.

Double-walled CNTs: These nanotubes are made of two concentric carbon nanotubes in which the outer tube encloses the inner tube, as shown in Fig. 1b.

Multi-walled CNTs: MWNTs consist of multiple layers of graphene rolled upon itself (Fig 1c) with diameters ranging from 2 to 50 nm depending on the number of graphene tubes. These tubes have an approximate inter-layer distance of 0.34 nm [2].

2. Properties of carbon nanotubes

CNTs are said to have a lot of surface area, a lot of aspect ratios, and a lot of mechanical strength. CNTs have a tensile strength 100 times that of steel, and their thermal and electrical conductivities are comparable to copper [27,28]. Because of their unique properties [29,30], CNTs are strong contenders as fillers in various polymers and ceramics to generate desirable consumer products. CNT-based FETs are expected to supplant their silicon-based analog counterparts in the near future [31]. Because of their unique electrical, mechanical, and thermal capabilities, carbon nanotubes are excellent at incorporating agents.

Some of the important studies to be conducted to aware of the mechanical properties of CNTs are discussed in this para. CNTs are now thought to be the strongest materials in nature, especially in the axial direction [47]. Young's modulus is in the range of 270 to 950 GPa, while the tensile strength is in the range of 11–63 GPa. CNTs are soft in the radial direction, according to several studies [48]. Vander Waal's forces deform two nearby nanotubes, according to the first TEM measurement of radial elasticity [49]. Later, various groups of researchers used an atomic force microscope (AFM) to generate nano-indentations in MWNTs to quantitatively evaluate their radial elasticity, and tapping/contact mode AFM was recently used to investigate SWNTs [50-52]. The radial direction elasticity of CNTs is crucial when a load is applied to a composite structure, notably for the fabrication of CNT nanocomposites and their mechanical properties, in which embedded tubes are subjected to significant deformation in the transverse direction. CNTs, the stiffest and toughest structure ever synthesised by scientists, offer significant potential since the carbon-carbon bonds seen in graphite are among the strongest in nature. The study of CNTs under TEM revealed that they are flexible and do not break when bent [53-57]. The mechanical characteristics of CNTs have previously been predicted using theoretical models [58-60]. Treacy et al. [28] made the first attempt to find the Young's modulus for individual MWNTs by measuring the amplitudes of CNTs thermal vibrations under TEM. They found that nanotubes have an average Young's modulus of 1 to 1.8 TPa, which is significantly higher than commercially available carbon fibres (800 GPa). Several research groups measured the bending forces of MWNTs directly as a function of displacement inside an AFM. The Young's modulus was discovered to be between 0.32 to 1.47 TPa [61-70]. Using an AFM tip, Falvo et al. [61] observed that MWNTs may be bent at extreme angles without shattering structurally. Endo et al. [62] discovered that when vapor-grown CNTs were broken in liquid nitrogen, an inner tubule could withstand the pressure. Yakobson [71] and Ru [72] hypothesised a method for CNT transformation under uniaxial tension, resulting in pentagon-heptagon defects in these tubes, when they were under high stress. Theoretically, Guanghua et al. [73] demonstrated that the mechanical properties of SWNTs are primarily determined by their diameter. The theoretical Young's modulus of nanotubes with a diameter of 1 nm is estimated to be in the region of 0.6–0.7 TPa. Hernandez et al. [74] likewise found theoretical Young's modulus values for MWNTs (1–1.2 TPa) that were very close to those measured experimentally. They also discovered that increasing the diameter improves mechanical properties, and that the tubes' Young's moduli approach those of planar graphite when the diameter is extended to a certain point.

The important thermal properties of the CNTs are discussed in this section. Although quantum effects are minor, they are significant, because low-temperature specific heat and thermal conductivity in CNTs offer direct evidence of 1-D quantization of the phonon band structure[56,70,75]. With only a 1% loading, pristine and functionalized nanotubes may quadruple thermal conductivity in various materials, implying that nanotube composite materials could be useful for thermal management applications in industry. Kim et al. [76] measured the thermal conductivity of individual MWNTs at room temperature and found it to be 3,000 W/K (greater than graphite). They also discovered that the value is two orders of magnitude larger than that found for bulk MWNTs. The number of phonon-active modes, the length of the phonons' free route, and boundary surface scattering are all factors that influence the thermal characteristics [77,79]. These characteristics are influenced by atomic arrangement, tube diameter and length, structural defects and morphology, and the presence of contaminants in the CNTs[80-82].

CNTs have been shown to have unique conducting characteristics by researchers. These findings were the first to demonstrate that geometric changes in the tubular structure, such as defects, chirality, diameters, and crystallinity, have a significant impact on the electrical properties of CNT [32,33]s. Metals resistivity ranging from 0.34x10–4 to 1.0x10–4 ohm-cm are known as SWNTs [27]. Each carbon atom in CNTs, which are organized in a hexagonal lattice is covalently connected to three neighbor carbons via sp2 molecular orbitals. As a result, each unit retains the fourth valence electron, which is delocalized over all atoms and contributes to the electrical character of CNTs. Depending on the type of chirality, CNTs can be conducting or semi-conducting [37]. P-type semiconductors are the most common variety of semiconducting SWNTs [38]. Because MWNTs are made up of multiple tubes of SWNTs, they are unlikely to be one-dimensional conductors. In I–V measurements, a pseudo-gap was discovered, indicating that it is conductive [39]. SWNTs can be regarded as quantum wires because of the ballistic nature of electron transport. MWNT transport, on the other hand, is shown to be fairly diffusive or quasi-ballistic [42]. CNTs can be employed in transistors and other switching applications in sophisticated electronics because of their electrical nature [43]. Nanotubes have most recently been used as an emitter. The ability to obtain emission at a lower threshold voltage is a key feature of CNT emitters [44]. Sensors, high-frequency micron-scale on-chip triodes (>200 MHz), vacuum microelectronics, and X-ray generation are all possible applications for CNTs [45,46].

3. Applications of CNTs in nanotechnology

Nanotechnology is one of the most advanced technologies available, with several advantages and benefits for new materials with considerably better qualities. Despite the fact that nanotechnology is wide and new materials are introduced on a daily basis, CNTs have the most promising potential. Due to their wide range of applications, CNTs have been the most quickly expanding nanomaterials in the field of nanotechnology since their discovery by Iijima [10] in 1991. Many scientists and researchers have worked hard to develop unique qualities and enhance the number of novel applications in sectors as diverse as medicine, materials science electronics, and energy storage, with many studies focused on nanotechnology and the use of carbon nanotubes as fillers [11]. CNTs can be used in high-strength composites, fuel cells, energy conversion devices, field-emission devices, hydrogen storage devices, and semiconductor devices [12] for more appealing applications. For those interested in adsorption investigations, wastewater treatment with CNTs is also a rapidly emerging subject [13]. The main issue with carbon nanotubes is their expensive cost and nonrenewable nature. Some of the important applications of CNTs are discussed below in detail.

Carbon nanotubes exhibit optoelectronic features that are valuable. Photoluminescence (fluorescence), Absorption, and Raman spectroscopy properties are among them. Spectroscopic approaches allow for the rapid and non-destructive characterization of huge quantities of carbon nanotubes. From an industrial standpoint, there is a great requirement for such characterization: several parameters of nanotube synthesis can be modified, either purposefully or unintentionally, to modify nanotube quality [35,36].

All nanotubes are expected to be excellent heat conductors along the tube axis, displaying a feature known as "ballistic conduction," but excellent insulators on the lateral side. A single SWNT has a thermal conductivity down its axis of roughly 3500 W m-1K-1 at room temperature; [70] compare this to copper, a well-known metal with strong thermal conductivity, which transmits 385 W m-1K-1.

A single SWNT has a thermal conductivity lateral to its axis of around 1.52 W m-1K-1 at ambient temperature[37,38].

Carbon nanotubes can potentially be used in medicine and pharmacy. Drug, biomolecule, gene delivery to cells or organs, tissue regeneration, and biosensor diagnostics and analysis are some of the most common uses of CNTs in pharmacy and medicine. Cancer treatment, infection treatment, gene therapy, tissue regeneration, neurological illnesses, antioxidants, and biosensors are just a few examples. Enantio separation of chiral medicines is also possible. Drugs and biochemicals are extracted. Three obstacles must be addressed before carbon nanotubes can be used in the pharmaceutical business. CNTs have three properties: functionalization, pharmacology, and toxicity. The lack of solubility of carbon nanotubes in aqueous systems is a problem. This challenge can be solved by using hydrophilic groups to functionalize carbon nanotubes. CNTs would be more water-soluble and biocompatible as a result of this. Another roadblock for carbon nanotubes is their biodistribution and pharmacokinetics, which are influenced by a variety of physicochemical properties such as form, size, chemical composition, aggregation, solubility surface, and functionalization. CNTs that dissolve in water are biocompatible with body fluids and do not cause hazardous side effects or death [39].

Nanomaterials in artificial implants show potential in regenerative therapy due to their appealing chemical and physical features [40]. The ability of nanotubes to attach to proteins and amino acids has shown promise. Tissue engineering is another area where carbon nanotubes can be used. Tissue engineering aims to replace damaged or diseased tissue with biological substitutes capable of repairing and preserving normal and original functions [41]. Nanodevices are being developed for cancer cell identification, with the potential to develop cancer treatment, detection, and diagnosis. Because nanostructures are so small (less than 100nm), the body excretes them too fast for them to be useful in imaging or detection, they can infiltrate cells and organelles to interact with DNA, RNA, and proteins [42-45]. CNTs offer unique features, such as ultrahigh surface area, that make them interesting options for drug, peptide, and nucleic acid delivery. The traditional administration of chemotherapeutic drugs has a number of drawbacks. Lack of selectivity, systemic toxicity, poor cell distribution, restricted solubility, medications' failure to pass cellular barriers, and a lack of clinical techniques for treating multidrug-resistant (MDR) cancer are among them.

The general process for drug distribution utilising CNTs can be summarised as follows. The medication is attached to the outside or inside of functionalized carbon nanotubes. The conjugate is subsequently administered into the animal body in traditional ways (oral, injection) or directly to the target spot using a magnetic conjugate, which is guided to the target organ, such as lymphatic nodes, by an external magnet. The drug CNT capsule is ingested by the cell, and the nanotube then spills its contents into the cell, delivering the medicine [46].

4. Conclusion

The important physico-chemical properties as well as different applications of CNTs were reviewed in this paper. CNTs' well-known features were also examined and presented, leading to the conclusion that CNTs have a unique collection of electrical, mechanical, and thermal capabilities. It is clear that unique technologies will arise in the near future as a result of CNTs' highest potential, however, the challenge with these technologies is the quantity and cost of CNTs. Cancer therapy, infection therapy, gene therapy, tissue regeneration, neurological illnesses, antioxidants, biosensors, diagnostic vehicles, and artificial implants are among them. Carbon nanotubes can be changed or functionalized to make them easier to work with. This increases their water solubility, allowing them to easily permeate tissues. These qualities have allowed carbon nanotubes to be used in medicine. They have the potential to be used in a variety of medical settings. The encapsulation of additional materials in carbon nanotubes will expand the scope of carbon nanotube applications in medicine.

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