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PROPERTIES AND APPLICATIONS OF CARBON NANOTUBES - A REVIEW

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Abstract:

Carbon nanotube is formed when graphene folds over itself to form a cylindrical shape with a diameter as small as 1 nanometer. Over the past two decades, CNTs have been extensively studied for their unique properties. Recently carbon nanotubes were successfully commercialized in lithium-ion batteries, also in color display by SAMSUNG. This review is based on a collection of journals such as Elsevier, Pergamon, Journal of Material Chemistry, Natural Resources, and other prestigious journals from 1990 to 2022. In this paper, we discuss the three main ways of CNT synthesis i.e laser ablation method, chemical vapor deposition, and arc discharge method. We also overview the applications of both single-walled carbon nanotubes and multiwalled carbon nanotubes and their properties such as very high tensile strength, high aspect ratio, high elasticity, and high electrical and thermal conductivity. They also have remarkable applications in the fields of energy storage, biomedical applications, optoelectronics, air and water filtration, nanotechnology, and structural composites. We also discuss recent commercialized applications of carbon nanotubes and challenges that have delayed their utility.

Keywords: Carbon nanotubes, Artificial implants, Tissue engineering, Solar cells, Polymers, etc.

Introduction

Carbon nanotubes are formed when graphene is curled upon itself to form a cylindrical shape with diameter as small as 1 nanometer. The number of concentric layers of CNTs are classed as single walled carbon nanotubes and multi walled carbon nanotubes. CNTs have immense commercial applications in the fields of energy storage, thermal conductivity, field emissions, polymers, molecular electronics, optoelectronics, gene therapy, filtration of air and water, probing, nanotechnology and structural composites. They have been extensively studied in the past few decades for their unique properties such as a large amount of electrical and thermal conductivity, high elasticity, and aspect ratio. CNTs have one of the highest tensile strength known to exist, which in comparison to steel of the same diameter is approximately 100 times more, as such there has been steady increase in its global production. Degree of twist and presence of impurities also changes their properties.

Properties

Elasticity

Elasticity of SWCNTs is significantly affected by the chirality.The Young's modulus of zigzag nanotubes is greater than that of armchair nanotubes with a tube diameter greater than 0.7 nm, hence the inclination is adjusted back to the tube diameters but by 0.7 nm. In zigzag nanotubes, around 33% of the bonds are aligned with the loading direction, while the complete bond is at an angle with the loading axis.The difference in nanotube elastic behavior may therefore be a direct result of the internal atomic structure. Young’s modulus of MWNTs is measured to be 0.81 0.41 TPa [1] while that of single-wall carbon nanotubes is about 1.25 TPa. The single-wall shear modulus of carbon nanotubes due to the complexity of the test methods, there is still no shear modulus rating of carbon nanotubes. There are also few theoretical predictions in the shear modulus of carbon nanotubes.When utilizing the empirical lattice dynamics model to predict the shear modulus of carbon SWNTs, it was discovered that the shear modulus (0.5 TPa) is comparable to diamond and is unaffected by tube width or chirality. Popov[2] also used the lattice- dynamics model and obtained the analytical shear modulus. Their results have shown that the shear modulus of carbon SWNTs is about the same as that of graphite for large radii but less than that of graphite for small radii, and tube chirality has some effect on shear modulus for small radii of tube.

Tensile strength

High-quality and lightweight materials have always been in demand for building materials in a wide range of research fields, such as the construction of safer and more fuel-efficient aircraft, or the construction of larger buildings. The single-wall carbon nanotubes have theoretical capacity of the intrinsic tensile at 100–200 GPa, among the highest in the material. However, all values reported in the experiments are very low and show a certain degree of dispersion, and a lack of structural information that prevents problems in the associated methods. The power depends on the nanal of the nanotube chiral. Single-walled carbon nanotubes, which can be viewed as cylindrical-coated graphene sheets [3], have been predicted as game-changing structures due to their outstanding theoretical strength per weight (strength ratio to weight; [4] predicted.This very dynamic number, combined with the lightweight nanotube structure, has also encouraged the construction of an atmosphere in the atmosphere (requiring 63 GPa [5]), which is not possible to use other available materials.

Electric conductivity, Thermal and magnetic properties :

CNTs have varying electrical conductivity all the way from semiconductivity to superconductivity. Electrical properties can also vary in the same CNT which can be used for various applications. Its controlled electronic performance is highly dependent on their alignment, width, aspect ratio, and friendliness. In regenerating and repairing bone tissue, CNTs are able to promote the electrochemical and electron-conductive interactions of suitable biomolecules with proteins thereby accelerating osteoblast proliferation and bone formation. In addition, CNT-based compounds are proposed as excellent electrical nanofibers, which can attract cells to adhere to the direction of electrical charge in both random and complementary fiber types, and exhibit excellent antibacterial activity [6,7]. These unique electrical properties of CNTs allow us to control call proliferation along with proper alignment of tissues for repairment of bones. Combined magnetic particles based on carbon nanotubes can effectively combine targeted magnetic technology with biological treatment, providing a new theoretical basis for targeted therapeutic treatment.

Synthesis

Electric arc discharge

The Arc-discharge technique uses high temperatures (over 1,700 ° C) in CNT combinations which often results in an increase in CNT with fewer structural defects compared to other methods. The most commonly used methods use arc extraction between high-purity graphite (6 to 10-mm optical density (OD)) electrodes are usually water-cooled electrodes with a diameter of between 6 and 12 mm and separated by 1 to 2 mm in a room filled with helium. (500 torr) in subatmospheric pressure (helium can be converted to hydrogen or methane in the atmosphere) [8]. Both anode and cathode are made of graphite along with specific amounts of metallic particles such as nickel and cobalt that act as catalyst particles. Current Direct is transferred to the camber (arcing process), and the chamber is compressed and heated to about 4,000 K. The remaining carbon (solid gray shell) is deposited in the surrounding environment and then forms a ‘chamber soot’ near the walls of the chamber and a ‘cathode soot’ in the cathode. The inner core, the cathode star and the cell membrane, which are dark and soft, produce single- or single-walled carbon nanotubes and polyhedral graphene particles embedded in the nest. Using scanning electron microscopy (SEM), two different textures and morphologies can be detected when studying the cathode deposit; internal black and soft deposits consist of mass-like structures, consisting of randomly arranged nanotube and gray outer shell, curved and layers of solid graphene. Typically, the integration of MWNTs can be done without the use of catalyst precursors but the integration of nanotubes in a single wall (SWNTs) uses different catalyst precursors and, in order to increase arc emissions, uses a complex anode, which acts as a graphite and metal structure, for example, Gd [9], Co, Ni, Fe, Ag, Pt, Pd, etc., or combinations of Co, Ni, and -Fe and other elements such as Co-Pt, Co-Ru [10]. Ni-Y-graphite compounds can produce high yields (<90%) of SWNTs (1.nm average) [11], and today, these compounds are used worldwide to create SWNTs with high yields. Although the capacity of production of nanotubes is very high in this method, the chirality of the CNTs show poor alignment which is critical as it affects a lot of desired properties of CNTs. In addition, due to the metal catalyst needed in the reaction, the purification of the obtained products is important.

Laser ablation method

By means of high-energy laser vaporization (YAG type), a quartz tube containing pure graphite block is fired inside a furnace at 1,200 ± C, in place of Ar [12]. The purpose of using a laser is to decompose graphite within quartz. As described in SWNT synthesis using an arc extraction method, to produce SWNTs, using a laser method to add metal particles such as catalysts for graphite targets is required. Studies have shown that the frequency of nanotubes depends on the strength of the laser. When the power of the laser pulse increases, the diameter of the tubes becomes smaller [13]. Other studies have shown that ultrafast (subpicosecond) laser pulses are powerful and can create a large number of SWNTs [14]. Many parameters that can affect CNTs structures include laser extraction methods such as structural and chemical composition of the target object, laser characteristics (high power, cw against pulse, energy fluence, oscillation wavelength, and multiplication rate), flow and pressure of the gas bath. As a result, this method can be used to produce CNTs that have very high purity. The principles and methods of the laser ablation method are similar to the arc extraction method, but in this method, the required energy is given to the laser hitting the pure graphite pellet containing catalyst materials (usually cobalt or nickel). The main benefits of this method are high yield and low metal contamination, as the metal atoms involved tend to vaporize at the tube's end once closed. On the other hand, the main disadvantage is that the nanotubes found in this process are not exactly the same but rather contain a certain branching. Unfortunately, the laser extraction method is not economically viable because the process includes graphite sticks of high purity, the required laser strength is good (in some cases two laser beams are required), and the number of nanotubes that can be assembled per day is not is as high as the process of arc extraction.

Chemical vapor deposition

Chemical vapor deposition (CVD) is among the most used methods to produce CNTS. Also, there are different types of CVD like catalytic chemical vapor deposition (CCVD) —either thermal [15] or plasma enhanced (PE) oxygen-assisted CVD, CVD-assisted water [16,17,18], microwave plasma (MPECVD) [19], radiofrequency CVD (RF-CVD) [20], or hot-filament (HFCVD) [21,22]. But catalytic chemical vapor deposition (CCVD) is currently the most common form of carbon nanotubes.

In order to increase the surface area and thus the rate of reaction between metal particles and carbon, nanoparticles of various metals can be used along with catalysts like Al_2O_3 and MgO. In the first step of the expansion of the nanotube, two types of gasses have an impact on the reactor (the most widely used fluidized bed reactor [23,24]: carbon dioxide (such as ethylene, acetylene). At the surface of the catalyst particles, carbon-containing gasses are separated and therefore carbon was observed at the edges of the nanoparticle where nanotubes can produce. This process is still under discussion [25]. Studies have shown generally accepted models for basic growth and tip growth [26].

Depending on the adhesion and bonding between the substrate and the catalyst particle, catalyst particles can remain in the base of the nanotube or nanotube during growth and expansion [27] Compared to laser extraction, CCVD is an economically viable method- scale and pure CNT production and therefore an important benefit of CVD is the high purity acquired properties and easy control of the reaction course [28].

Applications

Biomedical Applications

Ever since Carbon nanotubes have been identified as allotropic type of carbon by Iijima they have been widely researched and used for a wide range of applications such as reinforcement, electrode materials and / or components of nanoelectronics (biosensors) or even (non-synthetic) carriers of biomedicine. They can be combined in a variety of ways including arc-history extraction, laser extraction and a broad family of catalytic chemical vapor deposition (CCVD) techniques [29]. CNT can be defined as a layer of coated graphene, sometimes closed at the end with full caps. The number of fixed walls that make up the CNT (if more than one) is an important parameter that determines multiple structures. The diameter of MWCNT is around 100 times (~100 nm) that of SWCNT which is about 1 or 2 nm. Increasing the number of layers in the MWCNT inevitably also increases the value of these faults and thus makes them easier to repair and operate, often at the expense of the deterioration of their tangible structures. It is well known that the internal chemical structure and crystalline structure of the nanoparticle will lead to different surface areas such as charging, hydrophobicity or hydrophilicity, possible dispersion, (photo) catalytic activity and more [30]. It has also been shown that the surface decoration of any nanoparticle can change their surface areas and ultimately lead to very different biological behaviors, which has a significant impact on its biological distribution [31]. The use of CNT in the medical field requires a number of challenges that must be met. The first is safety-related and means using CNT for very high purity to limit potentially toxic release ions during operation in any biological environment. Another challenge is the normal viscosity growth associated with the proper dispersion of CNT fluid, even at low concentrations [32], which can make it difficult to fix nanocomposite substances that are part of a well-distributed CNT volume. Depending on their electronic structure, SWCNT may behave as semiconductors or as metals.

Artificial implants

Nanomatadium exhibits potential and promise in regenerative medicine due to its attractive chemical and physical properties [33]. Both SWCNTs and MWCNTs can be used along with other implants to make artificial joints and this can be done without rejection from the host's body. In addition, due to unique structures such as high energy, CNTs can act as bone substitutes and implants when they are full of calcium and set up / arranged in bone structure [34,35].

Tissue engineering

Carbon nanotubes can be utilized in tissue engineering especially in areas of cell sensitivity, labeling and tracking as well as tissue matrix formation. Labeling embedded cells not only helps to monitor the performance of tissue engineers but also helps to understand bio distribution, migration, and regenerative cell pathways. Because of the time-consuming and manageable challenges in using traditional methods such as flow cytometry, unconventional methods are popular methods. It has been shown that Carbon nanotubes can be used as comparative agents for magnetic resonance, optical, and radiotracer processes. Another important feature used for carbon nanotubes in tissue engineering is its ability to measure the distribution of the environment and to adjust gamma scintigraphy radiotracers. Singh et al. binds SWNTs to. It is also stored in BALB / c mice to test the natural distribution of nanotubes. The improved tissue design enhances and helps to better monitor the natural sciences such as enzyme / cofactor interactions, protein and metabolite storage, cellular behavior, and ion flow. Nanosensors are likely to be used to provide continuous monitoring of engineer tissue activity. Carbon nanotubes exhibit many of the most popular features that make them ideal for nanosensors including their large size and binding capacity of DNA or other proteins, as well as electrical structures. Carbon nanotube has distinct electronic components that, as the nerve power of carbon nanotube electrochemical, facilitates the investigation of redox-reactive proteins and amino acids that allow for the observation of cell structures.

Advances in the field of tissue engineering require careful monitoring of new tools and the need for new biomaterials to accelerate tissue growth. Carbon nanomaterials provide similar features regarding the chemical structure and structure associated with the biological extracellular matrix, making CNTs a prominent feature in the development of synthetic scaffolding [36]. CNTs can achieve tissue formation through magnetic resonance and radiotracer differentiation agents [37].

Drug vectors and gene delivery

There are many barriers to the general management of chemotherapeutic agents such as selective inhibition, systemic toxicity, improper distribution of cells, limited solubility, drug resistance to cross-cell barriers, and a lack of clinical processes to overcome multidrug resistant cancer (MDR). Researchers have introduced many different types of drug delivery systems to overcome these problems such as polymers, silica nanoparticles, quantum dots, emulsions, dendrimers, liposomes, molecular conjugates, and micelles [38]. A specific drug or gene can be attached to the walls and tips of CNTs and detect cancer-related receptors in the cell area, in such a way that CNTs can cross mammalian cell membranes with endocytosis or other mechanisms [39] and administer therapeutic drugs or genes safely and efficiently to previously inaccessible cells [40]. Recently, researchers developed a more effective novel SWNT-based tumor-targeted drug delivery system (DDS) that contains tumor-targeting ligands, anti-cancer drugs, and active SWNTs.

Electrical, Electronic and Optoelectronic Applications Transistors

The transistor — an important semiconducting tool — is a major component of many digital electronics. A suitable semiconductor for transistors should have the following features: i) good company network performance, ii) good ON / OFF ratio, and iii) high efficiency. SWCNTs with flexible electronic structures can be a promising candidate for future transistor devices. Key objectives for development are ways to integrate, improve device performance, and composite elements in SWCNTs.[41]. In addition, Hersam's team reported CNT screening, bandwidth, and electronic model use using a structure that discriminates surfactants. [42] In this work, a small distribution of isolated SWCNTs was obtained with> 97% of nanotubes within a range of 0.02 nm. The main objectives are to improve integration methods, improve device performance, design and production including SWCNTs-based composites. [43]. In addition, the Hersam team reported CNT screening by bandgap, bandwidth and electronic type using a structure that discriminates surfactants. [44] In this work, a small distribution of isolated SWCNTs was obtained with> 97% of nanotubes within a range of 0.02 nm. The resistance of a semiconducting device is increased by more than 4 orders by changing the voltage applied across the dielectric capacitor gate. Metal appliances, on the other hand, were shown to be less sensitive to the used gate sliding.

Optoelectronics

It was found that SWCNTs promised candidates to be used as nanoscale light sources. By studying the black body radiation of SWCNTs, the response rate upto 10 Gbps have been observed, which is hundred times higher than that of LEDs and in comparison. via laser diode (LDs). It is noteworthy that although PL can only be found in s-SWCNTs as the excitons made in the image are composed of non-radio computers in m-SWCNTs, EL is visible from both s-SWCNTs and m-SWCNTs. The spectra emitted due to the large number of chirality types in the nanotube-based filter is a major obstacle that may impede further development. This can be effectively prevented by using a one-sided nanotube that weakens the process of transferring exciton energy between tubes. Therefore, the use of split SWCNTs is a promising way to improve device performance as it has well-defined lengths and narrow peaks. Here, p- and n n circuits in CNTs are formed using a number of techniques such as electrostatic doping and chemical doping to form p – n combinations. In comparison to traditional field effect transistors, this device has very small power reduction, low threshold current and insensitivity to heating. CNT-based trackers can be classified into types two main ones: i) Photographic detectors (e.g., photoconductors, photodiodes) there signals generated due to excitons (electron-hole pairs), while ii) thermal detectors (e.g., thermopile, bolometers) rely on the output of an electrical signal generated by temperature changes in light intensity. Those generated excitons can be broken down into free network companies using external bias or internal field on Schottky bars or p-n combinations.

Energy Storage Applications

Carbon nanomaterials have higher surface properties, aspect ratios, excellent conductivity, Electrochemical stability, as well as low density, making them highly efficient in energy-efficient applications. Significantly, integration efforts can be tailored to improve these visible properties for the efficient use of carbon nanomaterials in energy storage systems. One of the most exciting uses of these materials lies in the electrochemical double-layer layer capacitors, where a high carbon nanomaterial surface combined with excellent electrochemical stability creates a high voltage of double layer storage. This may increase the energy density at the cellular level but this should be offset by the higher costs of CNTs or graphene compared with carbon black, emphasizing the need for additional energy and cost effective integration processes. Alternatively, many efforts have focused on using CNT and graphene as a substitute for graphite anode in Li-ion batteries. The advantage of the improved volume can be deduced from the large area of solid-electrolyte interphase (SEI) layer formation in these high-density materials. As the cost of Li-ion batteries has dropped by 70% over the past five years, the biggest challenge for installing SWCNTs and graphene in energy storage is the need for less expensive materials and cheaper and uncontrolled processing methods where CNTs or graphene end up with unusual properties.

Fuel cells

Reactions to permeability (OER) and oxygen-reducing reactions (ORR) are becoming increasingly important electrochemical reactions due to increased emphasis on sustainable energy production technologies. [45,46,47] An example of this technology is the proton exchange membrane (PEM) fuel cell where hydrogen (fuel) is injected into an anode that produces electrons transported by electrolyte (membrane) to the cathode where oxygen is reduced there by the formation of water. [48,49]. OER Catalysts development is a major obstacle in production of liquid electrolyzers and Hydrogen fuel cells because of their inefficient and expensive development process.[50]

Solar cell applications

Organic Solar Cells

Organic Solar Cells are renewable, lightweight, bulky, and flexible equipment made using roll-to-roll production by means of low-cost processing solutions.[51,52,53]. To date, SWCNTs have emerged as a potential substitute for i) fullerene computers act as an electron receiver, [54,55] ii) an polymer acting as an electron supplier, iii) holes for the extraction holes, [56,57] and iv) transparent electrodes. [58,59] However, the diversity of electronic nanotube structure has been shown to have a detrimental effect on photovoltaic performance and the overall health of the charging companies. [60] .

Quantum Dot Solar Cells

CQDs also known as Colloidal quantum dots is an important technology as it has the potential to reduce the cost, insertion mechanism, their solution and optoelectronic properties which are a function of particle size, thus making it easily mass producible technology. [61] Such high-density structures enable the formation of an efficient solar cell PCE that recently exceeded 16%. light emitting diodes, [62] photodetectors, [63,64] and transistors. [65,66] Although CQD solar cell performance has seen significant progress over the past few years, poor device stability in ambient conditions remains an important obstacle[67] In this context, the use of carbonaceous materials such as carbon paste [68] and graphene [69] has been introduced as a promising way to improve the efficiency and stability of CQD solar cells.

Polymers and composites

Carbon nanotubes-conducting polymer composites -

Running polymer altered electrodes has been one of the most preferred methods of electrochemical sensor repair for many years [70]. The combination of well-known features of polymer conduction (good stability, reproduction, high number of active surfaces, strong adhesion and homogeneity in electrochemical inserts) and those of CNTs leads to improved performance of the resulting sensing equipment. Composition compounds of polymers and CNTs are chemically bonded or electrochemical polymerization before CNTs.

Fibers and wires

The integration of SWCNTs into multi-functional fibers has been in process since the early 2000s. .The superior combination of architecture makes SWCNT conductors attractive to a number of military and aerospace systems. SWCNT fibers exhibit textile-like handling, making them ideal for wearable electronics and medical systems. All recent fiber work reinforces the idea that fiber performance can only be continuously improved with SWCNT integration. Unlike solid state spinning, spinning solution using true solvents (superacids) allows independent development of SWCNT synthesis and fiber spinning, making it an optional way to produce high performance SWCNT fibers. Both low-density compression and impurities low (amorphous carbon, catalyst fossils) SWCNTs are essential for the successful disintegration of nanotubes, a high degree of characteristic is essential for obtaining high power strands. At present, the SWCNT length plays a regulatory role in determining electrical properties as measurement of conductivity by aspect ratio appears to be almost linear. Therefore, consolidation efforts aimed at improving performance challenges for efficient fibers should address high yields, low pollution (carbon and metals), high quality jewelry, and high CNTs features.

Conclusion

Carbon nanotubes have the potential for extensive observation, as well as the progress made in the use of CNTs. However, continuous improvement in integration methods is necessary to obtain CNT for the desired applications. For example, catalyst size influences CNT scope as compounded by CVD. So, continuous work can be done to find the most effective ways to prepare a catalyst of the same size particles, so that the production of a certain range of SWCNTs is achieved. In addition, costs of higher CNTs, compared to other nano-carbon materials. Search efforts must make new and less expensive carbon sources, so that the price of CNTs is reduced at the right level. The constant miniaturization of electrical materials is a powerful microelectronic power supply industry. All over the world, the goal of scientists is to make small machines of equal size in those molecules or masses of atoms. The use of unusual features of SWCNTs can lead to electronic devices with a nanometer diameter. One day, CNTs will replace metal strips on X-ray machines, which used to burn faster. This may improve Portable X-ray equipment that can be used in ambulances, sales, and security at airports. There is no doubt that CNTs in ad-future will be the most important thing, not only commercially, but especially will receive applications in energy conservation and conversion.

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