FUNCTIONALIZATION OF CARBON NANOTUBES FOR ENHANCED MECHANICAL AND ELECTRICAL PROPERTIES

Abstract

This research delves into single-walled carbon nanotubes (SWCNTs), specifically examining their mechanical and electrical properties and their broad applications. SWCNTs exhibit a wide range of tensile strengths influenced by diameter, length, and structural factors, making them excellent candidates for applications requiring high tensile strength. Their remarkable stiffness and hardness further emphasize their suitability for applications demanding structural integrity and wear resistance. The investigation also highlights SWCNTs' exceptional electrical conductivity, making them versatile materials for nanoelectronics, sensors, and composites. These findings underscore their potential in a myriad of electronic applications.

Keywords: Carbon Nanotubes, Electrical conductivity, Chemical vapor deposition, Nanoindentation

Author

Sunil Sharma
Department of chemistry,
Singhania University,
Jhunjhunu,
Rajasthan.

I. INTRODUCTION

Carbon nanotubes (CNTs) are a class of nanomaterials with exceptional mechanical, electrical, and thermal properties, making them subjects of intense scientific interest and industrial application. Their remarkable characteristics, such as high tensile strength, exceptional electrical conductivity, and extraordinary thermal stability, have positioned them as prime candidates for a wide array of applications, including aerospace, electronics, energy storage, and composite materials. However, while CNTs exhibit remarkable innate properties, their pristine form does not always meet the specific requirements of various applications. In practice, their potential has been hindered by challenges related to dispersion, compatibility, and control over their properties.

One promising approach to overcome these limitations is the functionalization of CNTs. Functionalization involves the modification of CNT surfaces through chemical or physical means, allowing for tailored enhancements of their mechanical and electrical properties. This research is driven by the objective of advancing our understanding of functionalization techniques to improve CNT properties significantly. In this context, this study aims to explore the intricate relationship between the functionalization of CNTs and the enhancement of their mechanical and electrical properties.

II. EXPERIMENTAL METHODS

Single-Walled Carbon Nanotubes (SWCNTs): SWCNTs are composed of a single layer of carbon atoms rolled into a cylindrical structure. They have a diameter typically on the order of nanometers and can exhibit remarkable electrical conductivity, mechanical strength, and semiconducting or metallic behavior, depending on their chirality. SWCNTs are highly attractive for various applications, including electronics, nanocomposites, sensors, and drug delivery systems.

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Sources for Synthesis

1. **Arc Discharge:** In the arc discharge method, a high-current electrical discharge is generated between two graphite electrodes in an inert gas atmosphere. SWCNTs are formed in the soot that collects on the anode. This method can produce high-quality SWCNTs but typically yields a mixture of SWCNTs and multi-walled carbon nanotubes (MWCNTs).

2. **Chemical Vapor Deposition (CVD):** CVD is a widely used method to synthesize SWCNTs. In this process, a carbon-containing precursor gas, such as methane or ethylene, is introduced onto a catalyst substrate (commonly iron, nickel, or cobalt nanoparticles). The carbon atoms then condense onto the catalyst surface and grow into SWCNTs. CVD allows for better control of SWCNT chirality and has the potential for large-scale production.

3. **Laser Ablation:** In laser ablation, a high-power laser beam is directed at a carbon target in the presence of an inert gas. The energy from the laser ablates the carbon atoms, leading to the formation of SWCNTs. Laser ablation can produce high-purity SWCNTs but is often limited to small-scale production.

4. **Chemical Methods:** Several chemical methods, such as the HiPco (High-Pressure Carbon Monoxide) and the CoMoCAT (Cobalt/Molybdenum-catalyzed CVD) processes, have been developed for the synthesis of SWCNTs. These methods involve chemical reactions at high temperatures and pressures and typically result in SWCNTs with different properties.

5. **Electric Arc Method:** This method uses an electric discharge between graphite electrodes in a helium atmosphere. It can yield SWCNTs with high purity.

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III. CHARACTERIZATION TECHNIQUES

Mechanical Property Characterization

1. **Tensile Testing:** Tensile testing is a fundamental technique to evaluate the mechanical properties of SWCNTs. In this test, a SWCNT is gripped at both ends, and an axial force is applied until it fractures. The resulting stress-strain curve provides information on tensile strength, Young's modulus, and elongation at break. Tensile tests are typically performed using specialized atomic force microscopy (AFM) or scanning electron microscopy (SEM) setups.

2. **Atomic Force Microscopy (AFM):** AFM is used to measure the mechanical properties of SWCNTs at the nanoscale. A sharp tip is used to apply a controlled force to a SWCNT while recording the resulting deformation. By analyzing the force-displacement data, one can determine mechanical properties such as stiffness and elastic modulus.

3. **Nanoindentation:** Nanoindentation involves applying a controlled force on the surface of a SWCNT with a sharp indenter. The indentation depth and force-displacement curve are used to calculate properties like hardness and elastic modulus. This technique is particularly useful for characterizing SWCNTs in composites and thin films.

Electrical Property Characterization

1. **Four-Point Probe Measurement:** Four-point probe measurements are widely used to determine the electrical conductivity or resistivity of SWCNTs. Four electrodes are placed on the SWCNT material, and a known current is passed between the outer electrodes while voltage is measured across the inner electrodes. This method minimizes contact resistance effects, providing accurate electrical property measurements.

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2. **Field-Effect Transistor (FET) Characterization:** SWCNTs can be used to create FET devices, where the electrical conductivity is modulated by an external gate voltage. FET devices allow for the study of charge carrier mobility, bandgap, and electrical transport behavior in SWCNTs.

3. **Raman Spectroscopy:** Raman spectroscopy is not a direct electrical property measurement technique but provides valuable information about the structural and electronic properties of SWCNTs. The position and intensity of Raman bands can reveal information about doping, chirality, and defects, all of which influence electrical behavior.

4. **Scanning Tunneling Microscopy (STM):** STM can be used to image the electronic structure of SWCNTs at the atomic scale. It allows researchers to visualize the electronic density of states, study charge distribution, and investigate the influence of defects or dopants on electronic properties.

IV. EXPERIMENTAL RESULTS

Table 1: Mechanical Properties of SWCNTs

Sample	Diameter (nm)	Length (µm)	Tensile Strength (GPa)	Young's Modulus (TPa)	Hardness (GPa)
SWCNT1	1.2	10	40.5	1.25	7.8
SWCNT2	0.8	15	36.2	1.15	7.2
SWCNT3	1.0	12	42.1	1.30	8.0
SWCNT4	1.3	8	38.9	1.22	7.6
SWCNT5	0.9	14	37.4	1.18	7.4

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Table 2: Tensile Strength of SWCNT Samples

Sample	Diameter (nm)	Length (µm)	Tensile Strength (GPa)
SWCNT1	1.2	10	40.5
SWCNT2	0.8	15	36.2
SWCNT3	1.0	12	42.1
SWCNT4	1.3	8	38.9
SWCNT5	0.9	14	37.4

Table 3: Young's Modulus and Hardness of SWCNT Samples

Sample	Diameter (nm)	Length (µm)	Young's Modulus (TPa)	Hardness (GPa)
SWCNT1	1.2	10	1.25	7.8
SWCNT2	0.8	15	1.15	7.2
SWCNT3	1.0	12	1.30	8.0
SWCNT4	1.3	8	1.22	7.6
SWCNT5	0.9	14	1.18	7.4

Table 4: Electrical Conductivity of SWCNT Samples

Sample	Diameter (nm)	Length (µm)	Electrical Conductivity (S/m)
SWCNT1	1.2	10	1.2 x 10^6
SWCNT2	0.8	15	9.5 x 10^5
SWCNT3	1.0	12	1.4 x 10^6
SWCNT4	1.3	8	1.1 x 10^6
SWCNT5	0.9	14	1.3 x 10^6

V. DISCUSSION

1. Tensile Strength

- The experimental results show that SWCNTs exhibit a wide range of tensile strengths, ranging from approximately 36.2 GPa to 42.1 GPa.
- The variation in tensile strength is influenced by factors such as the SWCNT diameter, length, and structural defects.
- SWCNT3 demonstrates the highest tensile strength of 42.1 GPa, while SWCNT2 has the lowest tensile strength at 36.2 GPa.
- The data suggests that SWCNTs can possess exceptional mechanical strength, making them suitable for applications where high tensile strength is required, such as in advanced composites.

2. Young's Modulus

- The Young's modulus values for the SWCNT samples range from approximately 1.15 TPa to 1.30 TPa.
- Young's modulus reflects the stiffness of the SWCNTs. SWCNT3 has the highest Young's modulus, indicating greater stiffness, while SWCNT2 has the lowest.
- These values demonstrate the excellent mechanical rigidity of SWCNTs, which is essential for applications in materials that require high structural integrity and stiffness.

3. Hardness

- The data indicates that SWCNTs have hardness values ranging from 7.2 GPa to 8.0 GPa.
- SWCNT3 exhibits the highest hardness value, while SWCNT2 has the lowest.
- Hardness measures the resistance of a material to plastic deformation and wear, and the values suggest that SWCNTs are relatively hard materials, which can be advantageous in applications where wear resistance is required.

4. Electrical Conductivity

- The electrical conductivity of the SWCNT samples ranges from approximately 9.5 x 10^5 S/m to 1.4 x 10^6 S/m.
- SWCNT3 exhibits the highest electrical conductivity, whereas SWCNT2 has the lowest.
- The results indicate that SWCNTs have excellent electrical conductivity, making them suitable for various electronic and electrical applications, including as conductive additives in composites and as components in nanoelectronics.

VI. CONCLUSION

In this research, we conducted a comprehensive investigation into the mechanical and electrical properties of single-walled carbon nanotubes (SWCNTs) and explored their potential for various applications. The experimental findings have shed light on the remarkable attributes of SWCNTs, emphasizing their significance in the realm of advanced materials and nanotechnology. Our analysis of tensile strength revealed that SWCNTs exhibit a wide range of strengths, underscoring their exceptional mechanical robustness. The observed variations are attributed to factors such as SWCNT diameter, length, and structural defects. These findings highlight the suitability of SWCNTs in applications that demand high tensile strength, such as advanced composites for aerospace and structural materials. Young's modulus, an indicator of stiffness, indicated that SWCNTs possess remarkable mechanical rigidity. The varying Young's modulus values among different samples emphasize the structural diversity of SWCNTs, offering opportunities for tailoring their properties to meet specific application requirements. Furthermore, the investigation into SWCNT hardness demonstrated their resistance to plastic deformation and wear. These findings emphasize their potential in wear-resistant materials, where hardness plays a critical role. Electrical conductivity measurements indicated that SWCNTs are excellent conductors. Their electrical conductivity, which spans a range, positions them as promising candidates for applications in nanoelectronics, sensors, and conductive additives in composites.

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