Proceedings of the 5th International Conference on Materials Chemistry and Environmental Engineering
DOI: 10.54254/2755-2721/126/2025.20083

Performance Enhancement of Carbon Nanotube in Composites: An Analysis of Key Factors in Mechanical, Electrical, and Thermal Properties

Yifei Chen[1,a,*]

[1]*Faculty of Science, University of Waterloo, ON, Canada*
a. y2943che@uwaterloo.ca
**corresponding author*

Abstract: Carbon nanotubes are often utilized as reinforcing materials in composites due to their superior properties and extensive application potential. This essay reviews the current research related to carbon nanotubes and their composites, analyzing their superior mechanical, electrical, and thermal properties, as well as structural characteristics. The essay explores interactions such as interfacial bonding between carbon nanotubes and matrix, load transfer mechanisms, and the effects of small dimensions, which play a crucial role in enhancing the overall composite performance. Furthermore, the essay discusses practical applications of carbon nanotubes, including their use in electromagnetic shielding, flexible sensors, and advanced electronic devices. In addition, the potential for integrating carbon nanotube composites into energy storage technologies, such as batteries and supercapacitors, is considered. Lastly, this essay proposes various improvement strategies to enhance the performance of carbon nanotube composites, such as optimizing synthesis methods, improving dispersion techniques, and enhancing the interfacial bonding between nanotubes and matrix materials.

Keywords: Carbon nanotube, composite, property.

1. Introduction

Composite materials (often shorted as composite), are materials formed by using physical or chemical methods to combine multiple constituents in specific proportions. They consist of a matrix and one or more reinforced materials, which enhance the performance of the composite as filler. Composite materials consist of two main types: metal matrix composite and non-metal matrix composite, including glass fiber reinforced polymers (GFRP), carbon fiber reinforced polymers (CFRP), polymer matrix polymers (PMC), and Kevlar fiber reinforced plastics (KFRP) and so on.

Carbon nanotubes (CNTs), discovered by Japanese professor Sumio Iijima, are one of carbon's allotropes, typically ranging from 1-50nm. CNTs composed of folded and curled graphene layers in the shape of cylindrical nanotubes, carbon atoms form continuous hexagonal arrangement. This carbon-based material exhibits superior mechanical properties, including 5 times elastic modulus and 100 times ultimate strength of steel, while its density is significantly lower than steel[1]. Additionally, CNTs have superior thermal and electrical properties, with thermal conductivity approximately 8 times greater than copper and the capacity to carry current is three orders of

© 2025 The Authors. This is an open access article distributed under the terms of the Creative Commons Attribution License 4.0 (https://creativecommons.org/licenses/by/4.0/).

DOI: 10.54254/2755-2721/126/2025.20083

magnitude greater than copper wire[1]. Owing to these excellent characteristics, CNTs are widely used as reinforced material in composites to enhance the their performance. For instance, using physical mixing or physical mixing to add CNTs into ceramic materials can improve the mechanical properties of ceramic products, enhancing fracture toughness and mechanical strength either[2]. Moreover, He et al.[3] developed carbon nanotube paper-based composite materials by wet forming method, which improved the permittivity and reduced Electromagnetic interference (EMI). Due to these remarkable properties, CNTs composites have wide vista in the fields of aerospace, electronic devices and energy storage. This essay will explore the enhancement of mechanical, electrical and thermal properties of CNTs in composites, and explain the theory about why these enhancements occur.

2. The enhancement of mechanical properties in composite

CNTs are ideal reinforced materials due to their high strength and Young's modulus, significantly enhancing the mechanical properties of composites. This enhancement mainly because of their atomic structure and material properties. First, CNTs consist of sp^2 hybridized carbon atoms with the structure shaped in hexagonal honeycomb, where the C=C covalent bonds provide extremely high bond energy. This means that considerable external force is required to break these bonds[4]. Moreover, the hollow tubular structure and closed topology structure enable them to absorb more energy, particularly in the tensile direction. In addition to their strength, the high Young's modulus of CNTs implies less strain when deformation happens under load. The addition of CNTs in composite effectively disperses applied stress, reduces overall deformation of matrix and enhances the carrying capacity of materials.

Based on the number of graphene layers, CNTs can be classified into single-walled carbon nanotubes (SWCNTs) and multi-walled carbon nanotubes (MWCNTs). SWCNTs have a simpler structure, and symmetry and stability is higher, while MWCNTs often demonstrate lower stability because of the van der Waals forces between graphene layers, and MWCNTs are more likely to collapse due to external forces[5]. Additionally, MWCNTs have a larger specific surface area and higher surface activity, which is more likely to agglomerate in composites and reduce the properties in materials.

The dispersion and interface bonding of CNTs in composites are the key factors which influence reinforcement effectiveness. Strong interface bonding facilitates the effective transfer of stress from matrix to CNTs, which enhance the mechanical properties of materials. Interface bonding includes mechanical bonding, free diffusion bonding and chemical reaction bonding[6]. Mechanical bonding often fails easier under high stress because of its weak adhesion forces. In contrast, free diffusion bonding depend more on intermolecular forces, which lead to greater adhesion strength. Chemical reaction bonding has the strongest adhesion strength because of the formation of chemical bonds. For example, in carbon nanotube-reinforced aluminum matrix composite, the formation of Al4C3 films enhances the shear strength significantly, and improve the overall mechanical properties[7]. Ding et al.[8] used Calcium ion (Ca^{2+}) to combine 1wt% acidified CNT (aCNT) with Polyether ether ketone (PEEK), which results in a 15.7% increase in tensile strength.

Additionally, the enhancement of composites is related to load transfer, in other words, the load applied to the matrix can transfer to CNTs through the interface. The high strength and modulus of CNTs facilitate the formation of a network structure in the composites, which disperse stress in matrix effectively and avoid material damage caused by excessive local stress[4]. Gao et al.[9] combined and sintered CNTs with diamond particles to get the polycrystalline diamond compact (PDC) sheets. The results indicated that CNTs formed bridges at the fracture of materials, successfully transferring the energy for crack propagation and enhancing impact toughness of PDC.

DOI: 10.54254/2755-2721/126/2025.20083

The impact toughness of PDC with 1.4wt% CNTs had a 37.5% increase in compared with that of original PDC.

3. The enhancement of electrical properties in composite

CNTs has the similar structure with graphite and high current density (approximately 4×109A/cm²), which is about three orders of magnitude higher than that of common metallic materials[10]. High electron mobility of CNTs results in higher electrical conductivity compared to traditional metals such as copper, iron and aluminum. At low temperature, CNTs do not have scattering centers in theiir structure, which reduce obstruction when electrons traveling[11]. Additionally, the reduction in scattering phenomena leads to the increase in electron mobility and quantum effects. Kang et al.[10] used in-situ chemical vapor deposition to grow CNTs in Al2O3ceramic matrix, the electrical conductivity is about thirteen orders of magnitude higher than that of pure Al2O3. Zhang et al.[11] added 0.5% MWCNTs which was modified by sodium dodecyl benzene sulphonate into prepare poly(L-lactic acid)(PLLA), the electrical conductivity is about six orders of magnitude higher than that of pure PLLA.

CNTs have remarkable performance in electromagnetic shielding and increase the reflection and dissipation of electromagnetic waves in composites, because CNTs have high specific surface area and the small size effect. Consequently, CNTs can be used in the fabrication of electromagnetic shielding materials. Xia et al.[12] used ultrasonic dispersion assisted liquid deposition to add 5wt% CNTs into powdery dynamically modified polydimethylsiloxane. The shielding efficiency achieved 63.7dB, which can block out majority of electromagnetic waves. Ma et al.[13] combined zinc oxide(ZnO), carbon fiber(CF), infiltrating epoxy(EP) and CNTs to get CNT-ZnO-CF/EP hybrid composites, which electrical conductivity(5414 S/m) is much higher than pure CF/EP(2495 S/m). CNT film integrity is higher, leading to better electromagnetic shielding performance.

Additionally, CNTs are widely used in flexible strain sensors, measuring the variation in pressure, temperature, humidity and human health. Three-dimensional conductive network results in rapid response to external changes, enhancing the performance of flexible strain sensors significantly. Liu et al.[14] mixed pre-vulcanized concentrated and CNTs in emulsion and casting to create a composite used in strain sensors, converting deformation into a visible electrical signal. The conductivity increased with CNT content, reaching the peak at 56S/m when 20% CNTs were added. The relative change in resistance decreased, which can bu used in high-strain environments.

However, the aggregation phenomenon caused by the strong intermolecular forces in CNTs leads to uneven conductive layer, which degrade sensor performance. Therefore, existing fabrication methods(such as chemical vapor deposition and laser cladding) should be improved[15]. Chemical vapor deposition is covering the substrate surface with metal catalyst, and then adding carbon-containing gas at high temperatures to form CNTs. The CNTs are oriented, having high purity and superior sensor performance. However, this method needs high requirements in catalyst selection, because the substrate structure can be damaged easily[15,16]. Huang et al. [16] calcined Co-Mo/Al2O3catalysts prepared by sol-gel method at 550°C, which increased CNTs on the surface of lithium iron phosphate, therefore increasing the conductivity. Laser cladding is using the precisely controlled laser to modify the material surface. This method avoids material dilution and deformation, enhancing wear resistance. However, cladding layer will form pores easier, and aggregation phenomenon is more serious than the former[17]. Therefore, the addition of CNTs should be controlled accurately.

DOI: 10.54254/2755-2721/126/2025.20083

4. The enhancement of thermal properties in composite

The thermal properties of CNTs are superior, primarily due to their high aspect ratio. As a result, the thermal conductivity along the axial direction is significantly lower than that in the radial direction, which exhibit strong anisotropy. Furthermore, the stable C=C bonds within CNTs reduce thermal scattering during heat conduction, which ensure the material's thermal conductivity. The addition of trace amounts of CNTs into composites can effectively enhance their thermal conductivity. Additionally, CNTs have superior thermal flow response and react swiftly to thermal changes, which is suitable for applications in aerospace and electronic devices where thermal management is critically important.

CNTs can create better thermal conduction pathways in composites. As fillers, CNTs form a thermal network structure in matrix, improving the transmission efficiency and the speed of phonons. An et al. [18] used vacuum infiltration method to incorporate 2.2% CNTs into rubber, resulting in a three-dimensional porous network structure and an increase in thermal conductivity to 1.58 W $m^{-1}K^{-1}$, which 7 times more than that of pure rubber. Zhu et al. [19] used hotdisk thermal constants analyser to measure the thermal conductivity of single-walled carbon nanotubes / epoxy resin (SWCNTs/EP), achieving a maximum value of 0.30 W $m^{-1}K^{-1}$, which is significantly higher than that of pure EP (0.21 W $m\text{-}^{1}K^{-1}$).

The alignment direction of CNTs can influence the effective thermal conductivity of composites. CNTs have strong anisotropy, so they achieve the highest thermal current density and most efficient thermal conduction when they are aligned in the direction of heat conduction. In contrast, when they perpendicular to the heat conduction direction, the thermal resistance will increasea and the thermal current density will reach minimum. The thermal current density ofmatrix is independent, but it is considerably lower than that of the CNTs, thus has little effect on thermal conductivity[20]. Additionally, different volume element structure of CNTs and matrix also result in different thermal conductivity. Layered CNT-aluminum composites exhibit higher thermal conductivity compared with random, uniformly oriented, bundled, or networked CNT-aluminum composites, achieving a 54% increase over aluminum alloys[20].

Moreover, the dispersion of CNTs in composite can determine their thermal performance. CNTs are agglomerated due to π-π interaction, which makes the heat transfer path discontinuous, disrupting the continuity of thermal pathways, reducing the contact area with matrix and adversely affecting the heat transfer efficiency[21]. Researchers have developed various techniques to improve the dispersion of CNTs, which mainly include physical and chemical methods. Physical methods include ball milling, ultrasonic dispersion and high-pressure shear. The ball milling utilizes a mill to grind and mix CNT powder to enhance its dispersion[21,22]. This approach is straightforward, resulting in more uniform distribution in composite, reducing entangled aggregates and resulting in shorter nanotube lengths that facilitate bridging structures. So it can lead to higher thermal conductivity[21]. Chemical methods mainly involve covalent modification with hydrophilic functional groups and non-covalent modification using surfactants. The former will damage the nanotube structure, while the latter maintains it, only relying solely on surfactants for dispersion. Physical methods are easier to execute, but the produced CNTs have lower aspect ratios and poorer dispersion, meanwhile have a higher equipment cost. Conversely, chemical methods produce more stable outcomes, and scientists can select higher solubility dispersants, which further enhance the dispersion effectiveness. Consequently, researchers often choose chemical dispersion methods or a combination of both approaches.

DOI: 10.54254/2755-2721/126/2025.20083

5. Conclusion

CNT composites have garnered significant attention due to their superior mechanical, electrical and thermal properties. Their hexagonal honeycomb structure and high Young's modulus considerably enhance load-bearing capacity, effectively dispersing stress through interfacial bonding and load transfer. In terms of electrical properties, the high current density and electron mobility of CNTs improve conductivity, and their three-dimensional structure is suitable for flexible sensors. However, methods such as vapor deposition or laser cladding are necessary to mitigate aggregation. In terms of thermal performance, the high aspect ratio and excellent thermal response create an efficient thermal conduction network, increasing phonon propagation speed. In the future, CNT composites are expected to find broader applications in high-performance electronic devices and sensors.

References

[1] *Tang, J. (2011). Carbon nanotube composites in aerospace applications. Spacecraft Environment Engineering, 28(03), 218-221. https://doi.org/10.3969/j.issn.1673-1379.2011.03.002.*

[2] *Wu, Y., & Ding, T. (2024). Research Progress in Carbon Nanotube Reinforced Ceramic Matrix Composites. Journal of Cangzhou Normal University, 40(01), 10-14+26. https://doi.org/10.13834/j.cnki.czsfxyxb.2024.01.018.*

[3] *He, Y., Liu, S., Mai, Q., Wang, Y., Long, J., & Hu, J. (2024). Research of Preparation and EMI Shielding Properties of Carbon Nanotube Paper-based Composite Materials. China Pulp & Paper, 43(08), 74-80. https://doi.org/10.11980/j.issn.0254-508X.2024.08.009.*

[4] *Jiang, Q., Lin, H., Ding, Y., Shao, C., Zhao, J., & Feng, J. (2024). Investigation of Graphene and Carbon Nanotube Enhanced Copper-Based Composite Materials. Copper Engineering, 1-16. http://kns.cnki.net/kcms/detail/36.1237.TF.20240730.1613.006.html.*

[5] *Li, H. (2022). Mechanical Properties of Carbon Nanotubes and Influence Analysis of Size an Temperature. Yanshan University, (01), 1-79. https://doi.org/10.27440/d.cnki.gysdu.2021.000331.*

[6] *Zeng, M. (2024). Interface Design and Mechanical Properties of Carbon Nanotubes Reinforced Aluminum Matrix Composites. Nanchang University, (03), 1-144. https://doi.org/10.27232/d.cnki.gnchu.2023.001491.*

[7] *Shi, Z., Ma, F., Tan, Z., Fan, G., & Li, Z. (2024). Research progress on the interface and grain control in carbon nanotubereinforced aluminum matrix composit. Powder Metallurgy Technology, 42(01), 14-28. https://doi.org/10.19591/j.cnki.cn11-1974/tf.2021090008.*

[8] *Xu, J., Mei, Q., Jiang, D., Cai, Y., Liu, B., & Ding, G. (2024). Ca2+ assisted enhancement of CNT/PEEK interfacial bonding and its conductive composites preparation and performance study. Acta Materiae Compositae Sinica, 1-15. https://doi.org/10.13801/j.cnki.fhclxb.20240507.001.*

[9] *Gao, Z., Duan, D., Peng, L., Feng, D., Wang, B., & Gao, Z. (2024). Effect of Carbon Nanotubes on Thermal Stability and Mechanical Properties of PDC. Rare Metal Materials and Engineering, 53(08), 2321-2330. https://doi.org/10.12442/j.issn.1002-185X.20230437.*

[10] *Kang, Y., He, X., Yin, Z., & Li, Y. (2018). Fabrication of carbon nanotubes/Al2O3 ceramic composites by in-situ chemical vapor deposition growth method. Acta Materiae Compositae Sinica, 35(01), 150-157. https://doi.org/10.13801/j.cnki.fhclxb.20170406.001.*

[11] *Zhang, Q., Quan, H., Liu, J., Gao, D., & Zhang, S. (2022). Preparation and properties of PLA/SMCNTs composites. China Synthetic Resin and Plastics, 39(02), 5-10+24. https://doi.org/10.19825/j.issn.1002-1396.2022.02.02.*

[12] *Liu, C., Liang, T., Fei, G., & Xia, H. (2024). Preparation and Properties of Self-Healing Polydimethylsiloxane/Single-Walled Carbon Nanotubes Electromagnetic Shielding Materials. Polymer Materials Science & Engineering, 1-13. https://doi.org/10.16865/j.cnki.1000-7555.2024.0147.*

[13] *Ma, Y., Wang, H., Ni, Z., Zhang, J., Zhang, R., Sun, X., Li, C., Liu, C., & Zeng, Y. (2024). Synergistic Effect of Carbon Nanotubes with Zinc Oxide Nanowires for Enhanced Electromagnetic Shielding Performance of Hybrid Carbon Fiber/Epoxy Composites. Chinese Journal of Materials Research, 38(01), 61-70. https://doi.org/10.11901/1005.3093.2023.158.*

[14] *Liu, Z., & Chen, Y. (2024). Flexible and stretchable strain sensors based on concentrated natural latex/carbon nanotube composite materials. China Elastomerics, 34(01), 1-6. https://doi.org/10.16665/j.cnki.issn1005-3174.2024.01.009.*

[15] *Zhang, Y., Wen, J., Dong, L., Wang, H., Guo, W., & Huang, F. (2024). Research Progress of High Performance Strain Sensors Based on Carbon Nanotubes and Their Composite. Materials Reports, 38(14), 70-80. https://doi.org/10. 11896/cldb. 23050046.*

DOI: 10.54254/2755-2721/126/2025.20083

[16] Huang, S., Li, X., Li, C., & Lin, J. (2023). Synthesis of Carbon Nanotubes by Chemical Vapor Deposition and Its Application in Lithium-ion Batteries. Guangzhou Chemical Industry, 51(11), 58-61. https://doi.org/10.3969/j.issn. 1001-9677.2023.11.019.

[17] Liu, Y. (2023). Study on Laser Cladding of Carbon NanotubesReinforced Cobalt-based WC Composite Coating. North China University of Science and Technology, https://doi.org/10.27108/d.cnki.ghelu.2023.000926.

[18] An, D., Chen, J., & He, R. (2024). Preparation of carbon nanotube/natural rubber thermal interface materials and study of the thermal management performance. Journal of Functional Materials, 55(04), 4185-4190. https://doi. org/10.3969/j.issn.1001-9731.2024.04.023.

[19] Zhu, C., & Wang, D. (2007). Experimental Study on Thermal Conduction Performance of CNTs Materials. Guangdong Chemical Industry, (08), 5-9. https://doi.org/10.3969/j.issn.1007-1865.2007.08.003.

[20] Yuan, T. (2021). Analysis of Thermal Properties of Carbon NanotubeAluminum Matrix Composites with DifferentConfigurations. Yantai University, (09), 1-73. https://doi.org/10.27437/d.cnki.gytdu.2021.000389.

[21] Zhang, D., Jin, Q., Li, W., Li, S., Wang, T., & Yan, P. (2022). Performance comparison between ball-mill dispersion and ultrasonic dispersion for carbon nanotube reinforced natural rubber. Applied Chemical Industry, 51(04), 971-975. https://doi.org/10.16581/j.cnki.issn1671-3206.20220311.001.

[22] Zhang, H., Wu, Y., Zhang, A., Wang, L., & Hou, S. (2024). Research status of carbon nanotube dispersion and functionalization characterization methods. Carbon Techniques, 43(02), 1-5+70. https://doi.org/10.14078/j.cnki. 1001-3741.2024.02.001.