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Mechanical Properties of Carbon Nanotubes and Their Applications in Composite Materials

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Abstract:

Carbon nanotubes (CNTs) are one of the most significant nanomaterials because of their remarkable mechanical properties and special structural features. The present review addresses carbon nanotube mechanical behavior, especially single-walled carbon nanotube (SWCNT) and multi-walled carbon nanotube (MWCNT) mechanical behavior, and their utilization in improving the strength and performance of composite materials. CNTs have excellent tensile strength, in excess of 50 GPa, and high Young's modulus of up to 1 TPa. Due to these factors, they are very suitable for applications in reinforcing polymers, metals, and ceramics in composites. The addition of CNTs to different matrices has resulted in remarkable improvements in load-carrying capability, stiffness, and toughness. This review further emphasizes principal fields in which the composites of CNTs are used, such as aerospace frames, automobile components, building materials, and high-performance sport apparatus. With advantages come limitations such as poor dispersion within matrices, production costliness, and limited interfacial bonding. Furthermore, issues regarding toxicity and environmental impact require further study. This article will assist in gaining a clear insight into the mechanical properties of CNTs and their role in new composite materials. Research areas for the future are to find low-cost methods of manufacturing, refine dispersion methods, and apply them in commercial sectors in a safe and sustainable manner.

Keywords: Carbon Nanotubes, Mechanical Properties, Single-Walled CNT, Multi-Walled CNT, Composite Materials, Applications.

1. Introduction

Nanomaterials are a new generation of materials in science and engineering with unprecedented physical, chemical, and mechanical properties. Nanomaterials are usually those having at least one dimension in the nanoscale range (1–100 nm) and display distinct behavior from their bulk counterparts. Of all the many types of nanomaterials synthesized over the past few decades, carbon-based nanomaterials have attracted significant interest because of their strength, electrical conductivity, and versatility. The most significant and well-researched type of carbon nanomaterial is the carbon nanotube (CNT). Carbon nanotubes were initially discovered by Sumio Iijima in 1991 while researching soot produced from arc-discharge evaporation. [1] Ever since, CNTs have been the center of interest in nanotechnology because of their

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unusual structure and very unique properties. CNTs are rolled graphene sheet tubes and are broadly divided into two categories: single-walled carbon nanotubes (SWCNTs), consisting of one graphene cylinder, and multi-walled carbon nanotubes (MWCNTs), composed of several concentric graphene cylinders. The mechanical behavior of CNTs is also quite impressive. They exhibit superior tensile strength, low weight, and high Young's modulus, making them prime materials for the reinforcement of other materials in structural applications. Their high aspect ratio and robust covalent bonding along the tube direction are the reasons for their load-carrying capacity and resistance to deformation. The purpose of this review is to investigate the mechanical properties of carbon nanotubes and how they contribute to improving the performance of composite materials. The review addresses the form of CNTs, their structural features, and the ways in which they enhance the mechanical performance of polymer, metal, and ceramic-based composites. The article also illustrates practical applications and touches on present challenges and future prospects in the field [2][3].

2. Mechanical Properties of Carbon Nanotubes

Carbon nanotubes (CNTs) have garnered significant attention as a result of their exceptional mechanical behavior. Their geometry rolled-up graphene sheet to create a seamless cylindrical tube confer mechanical characteristics much better than most traditional materials. Their tensile strength and stiffness, in particular, render CNTs very effective at reinforcing composite materials. The next section discusses the above properties in some depth and puts them into perspective with respect to traditional materials for use in structural applications[5].

Tensile Strength

One of the most outstanding mechanical properties of CNTs is that they have a very high tensile strength. The tensile strength of carbon nanotubes is normally in the range of 50 to 200 gigapascals (GPa). This is considerably higher than most conventional materials. For instance, high-strength steel can have a tensile strength of 0.4 to 2 GPa, carbon fibers stand from 3 to 7 GPa, and Kevlar, which is used in body armor, is around 3.6 GPa strong. The reason for the extraordinary strength of CNTs is the sp^2 carbon-carbon bonding that provides the backbone to their atomic structure. These covalent bonds are very strong and extend throughout the length of the nanotube, enabling the nanotube to withstand a lot of load without failure. Due to this characteristic, CNTs are utilized in environments with high stress, where other materials are likely to fail or deform irreversibly.

Young's Modulus

Besides tensile strength, CNTs also exhibit extremely high Young's modulus, a property of the stiffness of a material. For carbon nanotubes, the number is about 1 tera pascal (TPa). For comparison, steel offers a Young's modulus of about 200 GPa, while carbon fiber lies between 230 and 600 GPa. CNTs are then five times stiffer than steel. Such stiffness proves extremely useful in designing composite materials where stiffness is paramount, like in aircraft bodies, car frames, or in building reinforcements. Additionally, while stiff, CNTs are very light. Their strength-to-weight ratio makes it possible for engineers to minimize material weight while maintaining performance.

Flexibility and Resilience

In addition to being stiff and strong, CNTs are highly resilient and flexible. Unlike brittle materials, they may be bent or twisted slightly and still spring back to their original shape when the load is discontinued. This ability is a consequence of their one-dimensional structure on the nanoscale level, which provides room for atomic mobility without leading to breakage. This characteristic makes CNTs a perfect choice for their application in vibration-absorbing structures, shock-resistant films, and dynamic applications like sporting goods or aerospace panels that have rapid changes in stress [4].

Comparison with Traditional Materials

To better understand the mechanical performance superiority of CNTs, it is helpful to compare them to standard structural materials. The following figure (Figure 1) compares tensile strength and Young's modulus for CNTs, steel, carbon fiber, and aluminum.

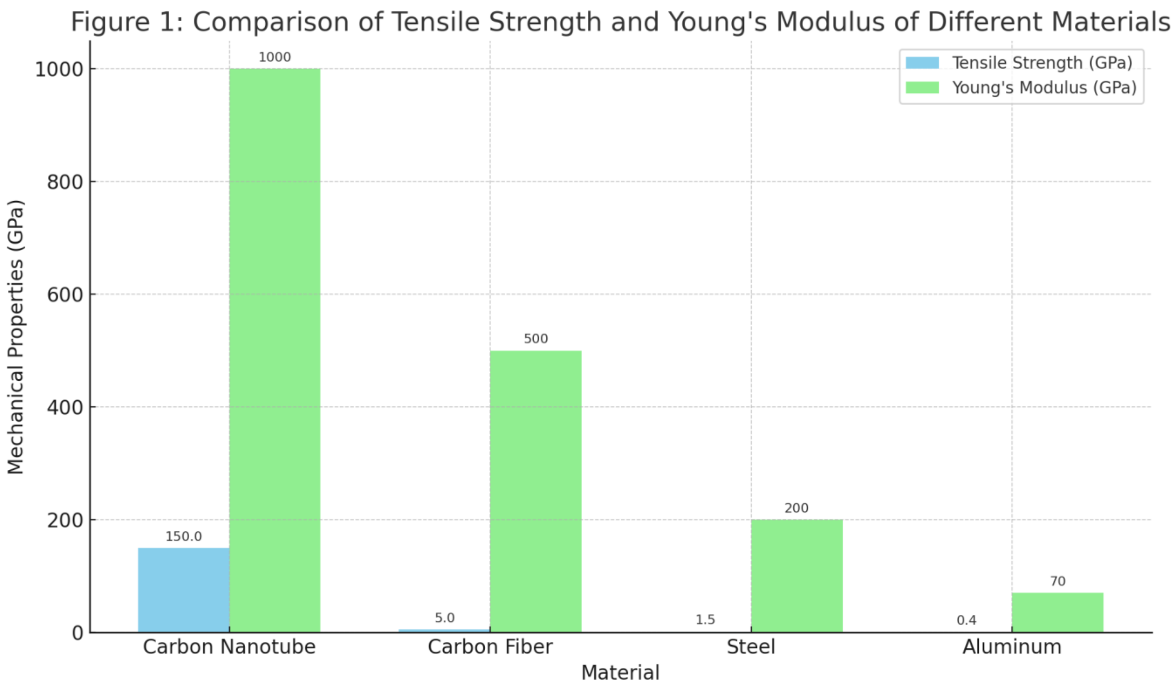

Fig 1: Comparison of Tensile Strength and Young's Modulus of Carbon Nanotubes with Steel, Carbon Fiber, and Aluminum.

As can be seen in Figure 1, carbon nanotubes surpass all these materials both in terms of strength and stiffness. Though steel and aluminum are found extensive use because they are available and affordable, their mechanical efficiency is much less. CNTs are more efficient than even the carbon fibers, which are already regarded as top-end materials in high-performance uses. This renders CNTs extremely apt for use as reinforcement agents in polymer, ceramic, and metal matrix composites. Finally, carbon nanotubes offer an unparalleled combination of strength, stiffness, toughness, and lightness that distinguishes them from most engineering materials. As challenging as present conditions are with dispersion, cost, and defects in synthesis, CNTs are still one of the most promising materials for next-generation structural and functional composite systems[6].

3. CNTs in Composite Materials

Carbon nanotubes (CNTs) are extensively researched for their capability to improve the mechanical, thermal, and electrical performance of composite materials. Based on their superior mechanical features, CNTs have the potential to enhance the strength, stiffness, and toughness of polymer, metal, and ceramic matrices. Their efficiency, however, largely relies on dispersion quality, bonding at the interface, and the processing procedure used. This part provides a description of the incorporation of CNTs into different types of composites and methods typically utilized to obtain these materials.

Polymer Matrix Composites

The most widely researched application of CNTs is polymer matrix composites. Polymers like epoxy, polyethylene, and nylon are light and flexible but do not have adequate mechanical strength. With the addition of CNTs, these polymers exhibit enhanced load-carrying capacity, tensile strength, and impact resistance. For example, epoxy-based composites of CNT are employed in aerospace and automotive applications due to their improved structure. An important aspect of the efficiency of polymer-CNT composites is the transfer of load from the CNTs to the polymer matrix. The quality of the interfacial bonding is responsible for this, and this can be enhanced by functionalization of CNT surfaces. Functionalization is the modification of the CNTs chemically in order to have a stronger adhesion with the polymer, so that stress is transferred effectively from the matrix to the nanotubes. This produces a more consistent and long-lasting composite material[4][7].

Metal Matrix Composites (MMCs)

CNTs are incorporated in metals such as aluminum and copper in metal matrix composites to enhance their thermal and mechanical properties. Metal-CNT combinations are found beneficial in applications where high strength coupled with good electrical or thermal conductivity is needed. Aluminum-CNT composites are, for instance, proposed for aerospace and automobile parts, whereas copper-CNT composites are investigated for electronic packaging. Although they have huge promises, there are a number of challenges that make large-scale manufacture of CNT-reinforced MMCs difficult. These are: inability to have uniform dispersion of the CNTs in molten metal, oxidation of the CNTs on high-temperature processing, and poor interfacial adhesion between the metal and the nanotubes. Researchers are turning to innovative methods such as powder metallurgy and surface coating of the CNTs to address these issues[8].

Ceramic Matrix Composites

Ceramic materials are hard and can resist high temperatures but are generally brittle. By incorporating CNTs into ceramics such as silicon carbide (SiC) and aluminum oxide (Al_2O_3), their flexural strength, fracture toughness, and resistance to crack propagation are enhanced. The CNT-reinforced ceramic matrix composites are suitable for use in high-temperature structural applications, including engine components and thermal protection systems. One of the main benefits of incorporating CNTs into ceramics is that they can bridge micro-cracks and accommodate mechanical energy. This gives the ceramic greater damage tolerance and makes it more suitable for application in harsh environments. But the production of such composites involves careful processing techniques to avoid damaging the CNTs during sintering [9].

Processing Techniques

The processing technique has a significant influence on the properties of CNT-reinforced composites. The most common methods are solution casting, melt mixing, and in-situ polymerization. Solution casting is achieved by dissolving the CNTs and polymer in a solvent and subsequent evaporation. It is ideal for small-scale film fabrication. Melt mixing incorporates CNTs and a molten polymer by applying shear force, which is widely employed in industrial processing. In-situ polymerization refers to the creation of the polymer while in contact with CNTs, which aids in obtaining good dispersion and adhesion. For further enhancement of the dispersion and interfacial interaction of CNTs within a matrix, surface modification processes are practiced. These include chemical and physical treatments that enhance the compatibility of CNTs with the host material. With improper dispersion, CNTs agglomerate and create weak interfaces, lowering the overall performance of the composite[10].

4. Applications of CNT-Based Composites

Carbon nanotube (CNT) composites have been widely utilized in many industries because of their high strength-to-weight ratio and resistance. In the aerospace industry, the use of these composites contributes to making light yet tough structural components, enhancing fuel economy and performance. The automotive sector uses CNT composites in producing crash-absorbing and high-performance components that improve the safety of vehicles without increasing weight. In sports gear, CNTs are added to tennis rackets, bicycles, and helmets to enhance strength while decreasing weight and giving athletes improved durability and performance. Civil engineering has begun to tap into CNT-enriched concrete, offering enhanced strength and longer lifespan for use in construction. Moreover, while still in its infancy, biomedical fields employ CNT composite with care in the development of prosthetics and implants, harnessing their mechanical toughness and biocompatibility.

5. Conclusion

Carbon nanotubes (CNTs) have remarkable mechanical characteristics, including high tensile strength and very high stiffness, making them good candidates for composite material reinforcement. With their incorporation in polymer, metal, or ceramic matrices, CNTs are able to considerably raise the overall strength, flexibility, and durability of the composites that result from such incorporation. The improvement enables the production of materials that are not only stronger but also lighter than conventional alternatives. These developments have opened up possibilities for novel applications in aerospace, automotive, sporting goods, and construction industries where performance and light weight are a must. The distinctive architecture of CNTs and the capability to well bond with different matrices are instrumental in these improvements. This review has emphasized the tremendous impact of CNTs in propagating composite materials and their high potential in developing more efficient, high-performance products in various industries. The research goes on to unveil the potential of the CNT-based composites in contemporary engineering uses.

6. References

[1] Iijima, S. (1991). Helical microtubules of graphitic carbon. Nature, 354(6348), 56–58. https://doi.org/10.1038/354056a0

[2] Yu, M. F., Lourie, O., Dyer, M. J., Moloni, K., Kelly, T. F., & Ruoff, R. S. (2000). Strength and breaking mechanism of multiwalled carbon nanotubes under tensile load. Science, 287(5453), 637–640. https://doi.org/10.1126/science.287.5453.637

[3] Zhang, X., Becton, M., Okawa, D., & Krishnan, R. (2015). Mechanical properties of carbon nanotube reinforced polymer composites: A review. Composites Part B: Engineering, 82, 56–70. https://doi.org/10.1016/j.compositesb.2015.08.015

[4] Thostenson, E. T., Ren, Z., & Chou, T.-W. (2001). Advances in the science and technology of carbon nanotubes and their composites: a review. Composites Science and Technology, 61(13), 1899–1912. https://doi.org/10.1016/S0266-3538(01)00094-X

[5] Coleman, J. N., Khan, U., Blau, W. J., & Gun'ko, Y. K. (2006). Small but strong: A review of the mechanical properties of carbon nanotube–polymer composites. Carbon, 44(9), 1624–1652. https://doi.org/10.1016/j.carbon.2006.05.038

[6] Ajayan, P. M., & Tour, J. M. (2007). Nanotube composites. Nature, 447(7148), 1066–1068. https://doi.org/10.1038/4471066a

[7] Moniruzzaman, M., & Winey, K. I. (2006). Polymer nanocomposites containing carbon nanotubes. Macromolecules, 39(16), 5194–5205. https://doi.org/10.1021/ma060733f

[8] Dalton, A. B., Collins, S., Munoz, E., Razal, J. M., Ebron, V. H., Ferraris, J. P., ... & Baughman, R. H. (2003). Super-tough carbon-nanotube fibres. Nature, 423(6941), 703. https://doi.org/10.1038/423703a

[9] Singh, C., Kumar, A., & Kumar, S. (2019). A review on mechanical properties of carbon nanotube reinforced polymer composites. Materials Today: Proceedings, 18, 4837–4842. https://doi.org/10.1016/j.matpr.2019.07.010

[10] Gojny, F. H., Wichmann, M. H. G., Fiedler, B., & Schulte, K. (2005). Influence of different carbon nanotubes on the mechanical properties of epoxy matrix composites–A comparative study. Composites Science and Technology, 65(15-16), 2300–2313. https://doi.org/10.1016/j.compscitech.2005.02.004.

7.Conflict of Interest

The authors declare that there are no conflicts of interest regarding the publication of this article.

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