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Influence of Carbon Nanotube Reinforcement on the Mechanical Behaviour of Polymer Composites

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Abstract

Carbon nanotubes (CNTs) have superior mechanical strength, stiffness, and aspect ratio, and thus useful as a nanofiller in the reinforcement of polymer. Their inclusion in polymers may enhance tensile strength, modulus, fracture toughness and fatigue resistance to a large extent. In this paper, the basic mechanisms that the CNTs improve the mechanical performance are the load transfer, crack bridging, and polymer chain restriction. Surprising factors affecting composite behavior: CNT dispersion, interfacial adhesion, alignment and loading concentration. The paper finds that dispersed and functionalized CNTs can significantly enhance the structural behavior of polymer composites and can be applied to the high-performance engineering processes.

Keywords

Carbon Nanotubes (CNTs); Polymer Composites; Mechanical Properties; Nanoreinforcement; Interfacial Adhesion; CNT Dispersion; Tensile Strength; Young's Modulus; Fracture Toughness; Nanomaterials.

1. Introduction

Polymer composites have found extensive application in the aerospace, automotive, marine, defense and structural fields because they have low density, excellent corrosion resistance, design flexibility and easy processing. These are their benefits that make them viable substitutes to conventional metallic substances. Nevertheless, a significant number of traditional polymers are characterised by intrinsic drawbacks of low tensile, less stiffness, low wear, and ineffectiveness at high mechanical loads. Due to the necessity to introduce lightweight materials with high mechanical strength, the requirement in conducting a better approach to reinforcement has been becoming more and more important in the context of engineering applications.

Carbon nanotube (CNT) has proved to be one of the most promising nanoscale reinforcement materials in polymer matrices. Their outstanding mechanical characteristics like tensile strength launched in the gigapascal grades, a Youngs modulus nearing 1 TPa and high flexibility, position them as one of the strongest known materials. The CNTs further have a very high aspect ratio, high surface area, and hollow tubular nanostructure, which are all contributing factors to an effective stress transfer between

the polymer framework and the nanotube structure. The properties make CNTs improve the stiffness, strength, fracture toughness and fatigue resistance of polymers dramatically even in their low loadings.

CNTs, in turn, undergo mechanical advantages along with multifunctional additions such as thermal, electrical conductivity, and wear-performance improvement, which makes CNT-polymer composites a viable choice of materials in the field of advanced engineering and smart materials. Although these benefits exist, the level of enhancement highly relies on the quality of CNT dispersion, the quality of interfacial bonding, alignment and the method used in the processing.

The paper will provide an analysis of the effects of reinforcement by CNT upon the mechanical behavior of polymer composites and the issues that govern the performance of the composite. The discussion incorporates the current trends in research, reinforcement mechanisms, and material design strategies to give a holistic picture on the role of CNTs to develop the next generation high-performance polymer composite.

2. Properties of Carbon Nanotubes

Two major types of carbon nanotube, single-walled carbon nanotubes (SWCNTs), and multi-walled carbon nanotubes (MWCNTs) are categorized according to the number of rolled sheets of graphene. SWCNTs are made of the same sheet of graphene that is rolled into a cylinder, and MWCNT is a multiple sheet of graphene that rolls into concentric sheets with varying diameters. Both are unusual in their physicochemical and mechanical properties and would therefore be one of the best as nanoscale reinforcement agents in polymer composite. The outstanding tensile strength is one of the prominent characteristics of CNTs which is reported to go up to the gigapascal magnitude owing to the existence of very close sp2 covalent bonding between the atoms of carbon (Ajayan and Tour, 2007). Moreover, CNTs have very high elastic modulus as it is in the range of about 1 TPa which means that they are very resistant to deformation due to the forces exerted on it (Thostenson et al., 2001). The aspect ratio is big, usually a number of hundreds or even thousands, that increases the stress-transfer efficiency between the polymer matrix and the nanotube surface that is needed to optimize the mechanical performance of composites (Coleman et al., 2006).

The other important benefit of CNTs is that they are very thin and therefore, they can be used to strengthen polymers without adding too much weight to the composite- another feature that is very necessary in aerospace and automobile applications. The low mass combined with high covalent bonding that exists between their graphene lattice makes CNTs both mechanically strong and structurally stable. The CNTs do not only offer significant enhancement of mechanical properties, but they also offer significant enhancement of electrical and thermal conductivity because the structure has a highly conductive carbon skeleton that is applicable in multifunctional material systems (Moniruzzaman and Winey, 2006). It has been reported repeatedly that a very low loading of CNTs, usually less than 2 wt, can result in a large scale improvement in tensile strength, stiffness, fracture toughness and thermal stability of polymer composites (Kim et al., 2010). Such unique properties strongly make CNTs one of the most promising nanofillers to formulate a next-generation high-performance polymer composite.

3. Literature Review

In the last twenty years, much work has been done on the reinforcement of polymers using carbon nanotubes (CNTs) to enhance such properties as mechanical, thermal, and electrical ones. The CNTs, characterized by high tensile strength, aspect ratio and outstanding nanostructure, have been defined as one of the best nanofillers to polymer matrices. A number of experiments have proved that even at very low CNT loading levels, there are significant improvements in the polymer performance and it is important to note that dispersion, interfacial bonding, and alignment play a key role.

The structural peculiarities of CNTs and their outstanding mechanical properties were brought in the spotlight, where Ajayan and Tour (2007) pointed out the strong sp2 carbon-carbon bonds in the graphene structure, which lend an inherent tensile strength beyond the reach of any reinforcement. This original piece of information highlighted the promise of CNTs in the creation of high-performance polymer composites.

Thostenson et al. (2001) carried out a systematic review of processing methods as well as mechanical characterization of CNT-polymer composites. They said that uniform dispersion and high interfacial adhesion are necessary to achieve good transfer of the effective load of the polymer matrix to the CNTs. Inadequate dispersion means there is agglomeration that minimizes the effectiveness of stress transfer and it might establish stress concentration areas. CNTs have been chemically and physically functionalized to improve their compatibility with other polymer matrices resulting in improvement of mechanical properties.

Coleman et al. (2006) concentrated on the mechanical characteristics of CNT reinforced polymer and found that tensile strength, Youngs modulus and fracture toughness of epoxy and polypropylene among other polymer matrices are significantly enhanced by CNTs. They also emphasized on the aspect ratio and alignment of CNTs as being the key determinants of the level of reinforcement, where the aligned CNTs have better directional mechanical properties.

Moniruzzaman and Winey (2006) have offered an in-depth research on CNT-polymer nanocomposites, which revealed that the high tensile advantages of CNT (0.5-2 wt) can be achieved even at low concentrations of the nanocomposite (0.5-2 wt). They also reviewed articles that emphasized the significance of CNT dispersion that is attained by using ultrasonic, high-shear mixing and surfactants or functionalised CNTs.

Kim et al. (2010) extended the range to multifunctional properties, and found that CNT-reinforced polymer composites do not only have better mechanical behavior as it has been previously reported, but also better thermal conductivity, electrical conductivity, and fatigue resistance. They insisted that the orientation of CNTs, dispersion and interfacial bonding should be controlable to ensure reproducibility and reliability in property enhancement.

Recent reports researched also on synergistic reinforcement through hybrid fillers which combine CNTs with graphene or nanoparticles to enhance more on mechanical performance and multifunctionality. It has been demonstrated that hybrid nanofillers can reduce aggregation problems and optimize load transfer processes resulting in composites that are stronger, tougher and have better durability. Moreover, new opportunities to produce the complex and high-performance components are released due to the improvement of the processing methods, including the in-situ polymerization and 3D printing of the CNT-polymer composite.

4. Factors Affecting Mechanical Behavior

4.1 CNT Dispersion Quality

One of the most significant issues, which affect the composite performance, is the dispersion of carbon nanotubes (CNTs) in a polymer matrix. Lack of dispersion results in agglomeration or bundling which results in points of stress concentration and reduces the pressure of load transfer between the matrix and the nanotubes (Coleman et al., 2006). The uniform distribution of CNTs facilitates the proper transfer of loads to be applied and increases stiffness, tensile strength, and fracture toughness. Ultrasonication, high-shear mixing, ball milling, and surfactants are widely used in order to realize the dispersion of CNTs. Also, the surface functionalization of CNTs can enhance how well they can be compatible with the polymer matrix, improving distribution further (Thostenson et al., 2001).

4.2 Interfacial Adhesion

The mechanical reinforcement is highly dependent on the strength of the interface between CNTs and the polymer matrix. The high interfacial adhesion guarantees effective transfer of the stress between the polymer chains and the high strength nanotubes. Functionalization techniques, including carboxylation, amination and hydroxylation, place functional groups on the surface of CNT and these groups of the CNT can interact with the polymer by forming covalent or hydrogen bonds, thereby increasing adhesion (Moniruzzaman and Winey, 2006). Poor inter facile bonding on the other hand may result in nanotube pull-out under stress decreasing reinforcement efficiency.

4.3 CNT Loading Percentage

The concentration of CNT in a polymer matrix is one of the factors that play a significant role in determining mechanical properties. Simple low to medium level CNT loadings (usually 0.1-3 wt% and so on) may produce significant increases in tensile strength, modulus and fracture toughness. Nevertheless, at elevated loadings, the polymer melt or solution viscosity can rise and cause processing challenges and agglomeration (Kim et al., 2010). Hence, a streamlined CNT concentration is important to trade off mechanical reinforcement and processability.

4.4 CNT Alignment

Directional enhancement of mechanical properties depends on the orientation of the CNTs in the polymer matrix. The aligned CNTs have excellent tensile strength and stiffness direction along the line of alignment and, therefore, are well suited to load-bearing applications (Spitalsky et al., 2010). Conversely, the randomly oriented CNTs offer isotropic reinforcement but can fail to reach the optimum strength along a particular axis. Controlling the CNT orientation in polymer composites has been done using such techniques as shear flow processing, magnetic alignment, and the use of electric field-assisted alignment.

5. Findings from Reported Studies

Extensive experimental investigations always show mechanical advantage of CNT reinforcement:

* Low loadings of CNT (20-60 per cent) lead to tensile strength improvement (Coleman et al., 2006).

* Huge modulus of Young growth in thermoplastic and thermoset polymer matrices (Thostenson et al., 2001).

* Both CNT-reinforced epoxy and other matrices have improved fracture toughness (15-40% better) (Moniruzzaman & Winey, 2006).

* Better fatigue capability through crack deflection and energy dissipation characteristics offered by the nanotubes (Kim et al., 2010).

These findings substantiate the claim that CNTs are better nanoscale fillers than the conventional reinforcements like the carbon fibers or glass fibers, and provide the lightweight solution and the high-performance solution.

6. Applications of CNT-Reinforced Polymer Composites

The multifunctional nature has seen CNT-reinforced polymer composite find application in various industries:

- Aerospace and automotive lightweight structures, eliminating weight, but maintaining strength and stiffness.
- Sporting goods: sporting goods may be made of high-performance bicycle frames, tennis rackets and helmets in which increased toughness and impact resistance are derived.
- Flexible and conductive electronics, in which CNTs are used to offer both electrical conductivity and mechanical support.
- Corrosion and wear coating of high strength.
- Biomedical equipment, such as implants and prosthetics, where mechanical strength and biocompatibility are very important.
- Highly durability, fracture toughness, fatigue resistant structural components needed to operate in demanding environments (Ajayan and Tour, 2007; Spitalsky et al., 2010).

7. Conclusion

CNTs have a great impact to enhancing the mechanical properties of polymer composites such as tensile strengths, stiffness, fracture toughness and fatigue life. The success of the improvement heavily relies on the CNT dispersion, interfacial adhesion, loading concentration and alignment. The best methods to be used in processing and functionalization of the surface must be used to ensure an optimal reinforcing efficiency. Polymer composite reinforced with CNTs have a lot of potential in the future that could see lightweight high-performance material in aerospace, automobile, electronics, and medical products. Future studies need to be on scalable processing, hybride reinforcement and multifunctional utilization to increase the applications of these advanced composites.

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