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Moones Rahmandoust · Majid R. Ayatollahi

Characterization of Carbon Nanotube-Based Composites Under Consideration of Defects

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Moones Rahmandoust
Griffith School of Engineering
Griffith University (Gold Coast Campus)
Southport
Queensland
Australia

and

Protein Research Center
Shahid Beheshti University, G.C.
Tehran
Iran

Majid R. Ayatollahi
Fatigue and Fracture Research Laboratory,
Center of Excellence in Experimental
Solid Mechanics and Dynamics, School
of Mechanical Engineering
Iran University of Science
and Technology
Tehran
Iran

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Preface

Composites are engineered materials that consist of two or more insoluble phases combined together: a continuous phase, known as the *matrix*, as well as some interdispersed components, known as the *reinforcing* elements. Now if at least one of the constituent phases of a composite material is less than 100 nm in size, this composite is commonly termed *nanocomposite*.

The matrix is typically the major constituent that provides durability for the overall composite and it can be for instance, a metallic, ceramic, or polymer material. The reinforcing inclusions are on the other hand, the structure's load carriers that can be in the form of fibers, particles, or flakes. This phase of the composite structure provides its stiffness and strength. Therefore, suitable selection of type, amount, and orientation of these components plays a very important role on the overall characteristics of the pertaining composite, such as its tensile and compressive strengths, fatigue strength and failure mechanisms, electrical and thermal conductivities, specific gravity, etc.

Composite materials mostly show more significant advantageous properties compared to monolithic materials. Monolithic metals and their alloys cannot always meet the demands of today's advanced technologies and performance requirements. It means that by incorporating reinforcements into, for instance, a metallic, ceramic, or polymer matrix, the properties of the matrix improves to a higher mechanical strength, more significant temperature stability, and better chemical durability. The existence of reinforcing elements, on the other hand, improves the structure's physical and chemical properties significantly.

Among all the variety of different fillers that can be used as a nanocomposite's reinforcing phase, *carbon nanotubes* (CNTs) have shown to be promising candidates for their very specific mechanical, electrical, optical, and thermal properties that will be explained later. Carbon nanotube-based nanocomposites, i.e., composite materials in which carbon nanotubes are used as the composite's reinforcing phase, are therefore very much interesting for scientists and scholars. There are many outstanding and remarkable applications that CNT-based composites can contribute to the world of science and industry. They are expected to influence many fields in terms of technology and industry. Either as stand-alone nanomaterials or as reinforcements in composites, they have applications in many diverse fields such as energy, signal processing, medicine, biotechnology, information technology, aerospace, agriculture, and environment. Therefore, exploring different properties of carbon nanotubes and carbon nanotube-based composite materials is of never-ending importance.

In the first three chapters of this volume, therefore, carbon nanotubes and carbon nanotube-based nanocomposites are introduced. Their material structure, major mechanical, electrical, and optical properties and their applications are further represented and the most common fabrication methods are also introduced. Finally, defects involved with carbon nanotubes, CNT-based composites are introduced, and the finite element techniques to model the introduced defects and to study their impact on the mechanical properties of the nanostructures are revealed for those who are interested in the area.

Chapter 4, then provides a detailed study on experimental aspects and challenges of fabricating carbon nanotube-based nanocomposites and controlling the appearance of defects in them. Finally, the major mechanical properties of the produced structures are reviewed and the effects of fabrication and processing steps on the resulted properties are introduced. Although mechanical properties of CNT-based composites are of major consideration in this volume, a specific subsection is devoted to highlight the special electrical conductance of the fabricated CNT composites.

The final chapter introduces CNT-fiber reinforced polymer composites specifically, as one of the most famous CNT-based composites and covers all major facts about the fabrication process of this nanocomposite type. The quality of the impact of modifying various fabrication factors of the polymer nanocomposites on its mechanical behavior is also explained with a detailed look at the tribological properties the composite.

Finally, we appreciate the moment to express our sincere gratitude to Professor Dr.-Ing. Andreas Öchsner, editor-in-chief of the Springer book series on "Advanced Structured Materials" for his helpful guidance. We would like to thank Dr. Shahin Shadlou, Dr. Mohsen Khalily, Mr. Iman Eslami Afrouz, Mr. Mehdi Mavalizadeh, Mr. Morteza Farsadi, Mr. Ali Ghavamian and Mr. Reza Barbaz for their valuable assistance. Dr. Mostafa Rahmandoust, Mrs. Azar Rezaie and Dr. Hamidreza Kazempour should also be appreciated here for their kind support. In conclusion, we are grateful to many scientists worldwide, for their novel contributions to the topic, and for devoting their lives to keep the flame of knowledge and science burning brightly and beautifully through human history. We also thank Springer publisher for recognizing the necessity of the topic and the importance of characterization of defects in nanostructured materials.

Moones Rahmandoust
Majid R. Ayatollahi

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Synopsis

Composites are engineered materials that consist of two or more insoluble phases combined together, i.e., a continuous phase, known as the matrix, as well as interdispersed component known as the reinforcing phases. If at least one of the constituent phases of a composite material is less than 100 nm in size, e.g., the reinforcing phase, this composite is commonly termed a nanocomposite. Among all the variety of different fillers that can be used as a nanocomposite's reinforcing phase, carbon nanotubes have shown to be promising candidates for their very specific and remarkable mechanical and physical properties. Carbon nanotube-based nanocomposites, i.e., composite materials in which carbon nanotubes are used as the composite's reinforcing phase, are therefore very much interesting for many outstanding applications that they can contribute to the world of science and industry. This volume represents the characterization methods involved with carbon nanotubes and carbon nanotube-based composites, with a more detailed look on computational mechanics approaches, namely the finite element method. Special emphasis is given to studies that consider the influence of the existence of some imperfections in the structure of the nanomaterials on their mechanical properties. These defects may include random distribution of fibers in the composite structure, as well as atom vacancies, perturbation, and doping in the structure of individual carbon nanotubes.

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Abbreviations

AFM	Atomic force microscope
BEM	Boundary element method
CFRP	Carbon fiber reinforced polymer
CNF	Carbon nanofiber
CNT	Carbon nanotube
DOS	Density of states
DWCNT	Double-walled carbon nanotube
ERM	Effective reinforcing modulus
FEM	Finite element method
FRP	Fiber-reinforced polymer
GFRP	Glass fiber-reinforced polymer
HDPE	High-density polyethylene
HRTEM	High-resolution transmission electron microscope
MD	Molecular dynamics
MWCNT	Multi-walled carbon nanotubes
Nano-Al	Nanocrystalline-aluminum
OAS	Optical absorption spectroscopy
PET	Poly ethylene terephthalate
PMC	Polymer-matrix composites
RM	Rule of mixture
RVE	Representative volume element
SPS	Spark plasma sintering
SWCNT	Single-walled carbon nanotube
TEM	Transmission electron microscope
UHMWPE	Ultrahigh molecular weight polyethylene

Symbols

$\vec{C}_h$	Chiral vector
θ	Chiral angle
a_0	Length of each unit vector
b	Carbon-carbon bond length
D, d	Diameter
t	Thickness
r	Distance
L	Length
A	Area
$\bar{m}$	Mass density
V_{LJ}	Lennard-Jones potential
F_{LJ}	Lennard-Jones force
σ	Stress
ε	Strain
F	Force
T	Torque
P_{cr}	Critical load
f	Resonance frequency
E	Young's modulus
G	Shear modulus
υ	Poisson's ratio
V_{CNT}	Volume fraction of CNTs
U	Strain energy
P	Pure axial load
M	Pure bending moment
T	Pure twisting moment
I	Second moment of area
J	Polar moment
Δb, $\Delta\alpha$ and $\Delta\beta$	Tensile, bending, and twist angle deformations

η_L	Length efficiency factor
η_o	Orientation efficiency factor
k_r, k_θ and k_φ	Molecular mechanics force constants
k	Spring constant
K	Effective length constant