

# CARBON NANOTUBES FOR POLYMER REINFORCEMENT



Peng-Cheng Ma • Jang-Kyo Kim

# Contents

---

Contents.....	v
Foreword .....	ix
Preface.....	xi
Acronyms and Symbols .....	xiii
<b>1 Introduction .....</b>	<b>1</b>
1.1 Introduction to Carbon Nanotubes (CNTs) .....	1
1.1.1 Family of Carbon Materials .....	1
1.1.2 History of CNTs.....	3
1.1.3 Synthesis of CNTs .....	3
1.2 Properties of CNTs.....	5
1.2.1 Structure of CNTs .....	5
1.2.2 Mechanical Properties of CNTs.....	8
1.2.3 Electrical Properties of CNTs.....	11
1.2.4 Thermal Properties of CNTs.....	12
1.2.5 Optical Properties of CNTs.....	15
1.2.6 Defects in CNTs .....	18
1.3 Characterization of CNTs .....	19
1.3.1 Structural and Morphological Characterization of CNTs ...	19
1.3.2 Characterization of Surface Functionalities on CNTs.....	23
1.3.3 Summary .....	28
1.4 Other Carbon Nanofillers .....	28
1.4.1 Carbon Nanofibers.....	28
1.4.2 Spherical Carbonaceous Nanofillers .....	31
1.5 Other Nanotubes.....	33
References .....	34
<b>2 Dispersion of CNTs.....</b>	<b>39</b>
2.1 Introduction.....	39
2.2 Dispersion Behavior of CNTs.....	39
2.2.1 Dispersion and Distribution of CNTs .....	39
2.2.2 Nature of Dispersion Problems for CNTs.....	40
2.2.3 Surface Area and Interactions between CNTs .....	42
2.3 Techniques for Mechanical CNT Dispersion .....	44
2.3.1 Ultrasonication .....	44
2.3.2 Calendering.....	45
2.3.3 Ball Milling.....	48
2.3.4 Stirring and Extrusion .....	49
2.3.5 Other Techniques .....	50

2.4	Characterization of CNT Dispersion.....	50
2.4.1	Microscopic Methods .....	50
2.4.2	Light Methods .....	53
2.4.3	Zeta Potential.....	54
2.5	Dispersion of CNTs in Liquid Media .....	55
2.5.1	Dispersion of CNTs in Water and Organic Solvents .....	55
2.5.2	Dispersion of CNTs in Polymers.....	57
2.6	CNT Dispersion Using Surfactants .....	57
2.6.1	Role of Surfactants in CNT Dispersion.....	57
2.6.2	Nonionic Surfactant-Assisted CNT Dispersion.....	60
2.6.3	Ionic Surfactant-Assisted CNT Dispersion .....	63
	References .....	65
<b>3</b>	<b>Functionalization of CNTs .....</b>	<b>69</b>
3.1	Introduction.....	69
3.2	Covalent Functionalization of CNTs.....	70
3.2.1	Direct Sidewall Functionalization .....	70
3.2.2	Defect Functionalization .....	75
3.3	Noncovalent Functionalization of CNTs .....	77
3.3.1	Surfactant Adsorption .....	78
3.3.2	Polymer Wrapping.....	79
3.3.3	Endohedral Method.....	80
3.4	CNT Interactions with Biomolecules .....	82
3.4.1	Interaction with DNA.....	82
3.4.2	Interaction with Proteins.....	84
3.4.3	Interaction with Living Cells.....	86
3.4.4	Interaction with Carbohydrates.....	87
3.5	CNT Functionalization in Different Phases .....	88
3.5.1	CNT Functionalization in the Liquid Phase.....	88
3.5.2	CNT Functionalization in the Solid Phase .....	89
3.5.3	CNT Functionalization in the Gas Phase.....	90
3.6	Effects of Functionalization on the Properties of CNTs .....	94
3.6.1	Dispersability and Wettability of CNTs .....	94
3.6.2	Mechanical Properties .....	97
3.6.3	Electrical/Electronic Properties .....	99
3.6.4	Thermal Properties .....	101
3.7	Nanoparticle (NP)/CNT Nanohybrids .....	103
3.7.1	Introduction to NPs .....	103
3.7.2	Fabrication of NP/CNT Nanohybrids.....	105
3.7.3	Applications of NP/CNT Nanohybrids .....	111
	References .....	111



<b>4 CNT/Polymer Nanocomposites</b> .....	115
4.1 Introduction .....	115
4.1.1 Polymer Nanocomposites.....	115
4.1.2 Classification of CNT/Polymer Nanocomposites.....	116
4.2 Fabrication for CNT/Polymer Nanocomposites.....	117
4.2.1 Solution Mixing .....	117
4.2.2 Melt Blending .....	117
4.2.3 In-Situ Polymerization .....	118
4.2.4 Latex Technology .....	118
4.2.5 Resin Transfer Molding.....	119
4.2.6 Other Methods.....	120
4.3 Effects of CNT Dispersion and Functionalization on the Properties of CNT/Polymer Nanocomposites .....	122
4.3.1 Dispersion Behavior of Functionalized CNTs in Polymer Matrices .....	122
4.3.2 Mechanical Properties .....	125
4.3.3 Electrical Properties .....	133
4.3.4 Thermal Properties .....	139
4.3.5 Optical Properties .....	144
4.3.6 Rheological Properties.....	147
4.3.7 Damping Properties.....	151
4.4 CNT/Polymer Interface.....	153
4.4.1 Importance of the Interface.....	153
4.4.2 Methodologies for Studying the CNT–Polymer Interface .....	154
References .....	163
<b>5 Application of CNT/Polymer Nanocomposites</b> .....	169
5.1 Structural Application of CNT/Polymer Nanocomposites.....	169
5.1.1 Hybrid CNT and Fiber-Reinforced Polymer Composites.....	169
5.1.2 Automobile Applications.....	173
5.1.3 Aerospace Applications.....	175
5.1.4 Other Structural Applications .....	176
5.2 Functional Application of CNT/Polymer Nanocomposites .....	177
5.2.1 Conducting Films and Coatings .....	177
5.2.2 Electromagnetic Interference Shielding.....	178
5.2.3 Sensors and Actuators .....	180
5.2.4 Applications for Energy Storage.....	186
5.2.5 Other Functional Applications.....	189
References .....	189
<b>Index</b> .....	193