

①

Handbook of

Multiphase Polymer Systems

EDITORS

ABDERRAHIM BOUDENNE

LAURENT IBOS

YVES CANDAU

SABU THOMAS

 WILEY



Contents

List of Contributors	xix
Foreword	xxiii

VOLUME 1

1 Physical, Thermophysical and Interfacial Properties of Multiphase Polymer Systems: State of the Art, New Challenges and Opportunities	1
<i>Sabu Thomas, Abderrahim Boudenne, Laurent Ibos and Yves Candau</i>	
1.1 Introduction	1
1.2 Multiphase Polymer Systems	2
1.2.1 Polymer Blends	2
1.2.2 Polymer Composites	2
1.2.3 Polymer Nanocomposites	2
1.2.4 Polymer Gels	3
1.2.5 Interpenetrating Polymer Network System (IPNs)	3
1.3 A Short Survey of the Literature and Applications	5
1.4 Book Content	7
1.4.1 Modeling and Computer Simulation of Multiphase Composites: From Nanoscale to Macroscale Properties	7
1.4.2 Morphological Investigation Techniques	8
1.4.3 Macroscopic Physical Characterization	8
1.4.4 Life Cycling	10
1.5 Future Outlook, New Challenges and Opportunities	10
References	12
2 Macro, Micro and Nano Mechanics of Multiphase Polymer Systems	13
<i>Alireza S. Sarvestani and Esmail Jabbari</i>	
2.1 Introduction	13
2.2 Unentangled Systems	14
2.2.1 Microscopic Structure	15
2.2.2 Macroscopic Properties	18
2.2.3 Results	19
2.3 Entangled Systems	21
2.3.1 Microscopic Structure	22
2.3.2 Macroscopic Properties	24
2.3.3 Results	25
2.4 Conclusion	27
Acknowledgements	28
References	28

3	Theory and Simulation of Multiphase Polymer Systems	31
	<i>Friederike Schmid</i>	
3.1	Introduction	31
3.2	Basic Concepts of Polymer Theory	32
3.2.1	Fundamental Properties of Polymer Molecules	32
3.2.2	Coarse-Graining, Part I	33
3.2.3	Ideal Chains	34
3.2.4	Interacting Chains	36
3.2.5	Chain Dynamics	38
3.3	Theory of Multiphase Polymer Mixtures	39
3.3.1	Flory-Huggins Theory	39
3.3.2	Self-consistent Field Theory	43
3.3.3	Analytical Theories	49
3.3.4	An Application: Interfaces in Binary Blends	55
3.4	Simulations of Multiphase Polymer Systems	56
3.4.1	Coarse-Graining, Part II	56
3.4.2	Overview of Structural Models	58
3.4.3	Overview of Dynamical Models	62
3.4.4	Applications	65
3.5	Future Challenges	70
	Acknowledgements	70
	References	71
4	Interfaces in Multiphase Polymer Systems	81
	<i>György J. Marosi</i>	
4.1	Introduction	81
4.2	Basic Considerations	82
4.3	Characteristics of Interfacial Layers	83
4.3.1	Role of Thermodynamic Factors	85
4.3.2	Role of Kinetic Factors	87
4.3.3	Relationship Between Interfacial Structure and Mechanical Response	88
4.4	Interface Modifications: Types and Aims	89
4.4.1	Interlayers of Controlled Morphology	90
4.4.2	Interlayers of Modified Segmental Mobility	92
4.4.3	Interlayers for Improving the Compatibility of the Phases	93
4.5	Interlayers of Modified Reactivity	100
4.6	Responsive Interphases	101
4.6.1	Non-reversibly Adaptive Interphases	101
4.6.2	Smart Reversibly Adaptive Interphases	103
4.7	Methods of Interface Analysis	105
4.8	Conclusions	111
	References	112
5	Manufacturing of Multiphase Polymeric Systems	123
	<i>Soney C. George and Sabu Thomas</i>	
5.1	Introduction	123

5.2	Manufacturing Techniques of Polymer Blends	123
5.2.1	Solution Blending	124
5.2.2	Latex Blending	125
5.2.3	Freeze-drying	126
5.2.4	Mechanical Blending	126
5.2.5	Mechano-chemical Blending	132
5.2.6	Manufacturing of Polymer Blends Using Supercritical Fluids	132
5.3	Manufacturing Techniques of Polymer Composites	133
5.3.1	Hand Layup Process	134
5.3.2	Spray Layup Process	134
5.3.3	Vacuum Bag Molding	135
5.3.4	Resin Transfer Molding	136
5.3.5	Pultrusion	138
5.3.6	Filament Winding Process	139
5.3.7	Reaction Injection Molding	140
5.3.8	Rotational Molding	140
5.4	Manufacturing Techniques of Nanocomposites	141
5.4.1	Solution Intercalation	141
5.4.2	In Situ Intercalative Polymerization Method	142
5.4.3	Melt Intercalation or Melt Blending Method	143
5.5	Manufacturing Techniques of Polymer Gels	143
5.5.1	Microgels	143
5.5.2	Aerogels	145
5.5.3	Xerogels	145
5.5.4	Nanostructured Gels	146
5.5.5	Topological Networks	146
5.5.6	Hydrogels	148
5.6	Manufacturing Techniques of Interpenetrating Polymer Networks (IPNs)	149
5.6.1	Full IPNs	150
5.6.2	Sequential IPNs	151
5.6.3	Simultaneous Interpenetrating Networks (SINs)	152
5.6.4	Latex IPNs	153
5.6.5	Thermoplastic IPNs	154
5.6.6	Semi-IPNs	154
5.6.7	Pseudo-IPNs	156
5.7	Conclusion and Future Outlook	156
	References	157
6	Macro, Micro and Nanostructured Morphologies of Multiphase Polymer Systems	161
	<i>Han-Xiong Huang</i>	
6.1	Introduction	161
6.1.1	Polymer Blends	161
6.1.2	Polymer and Its Blend Nanocomposites	162
6.2	Morphology Development Mechanisms of Multiphase Polymer Systems During Processing	164
6.2.1	Initial Morphology Development in Polymer Blending	164
6.2.2	Deformation and Breakup of Droplet	168

6.2.3	Coalescence of Droplet	174
6.2.4	Intercalated, Exfoliated, and Dispersed Mechanism of Organoclay During Melt Mixing	178
6.3	Material-Relevant Factors Affecting the Morphology	183
6.3.1	Viscosity of Components	183
6.3.2	Elasticity of Components	187
6.3.3	Interfacial Tension	192
6.3.4	Compatibilization	197
6.3.5	Composition	208
6.3.6	Nanoparticles	212
6.4	Processing-Relevant Factors Affecting the Morphology	218
6.4.1	Flow Field Types	218
6.4.2	Chaotic Mixing	221
6.4.3	Mixing Sequence	227
6.4.4	Processing Parameters	230
	Nomenclature	231
	Acknowledgements	234
	References	235
7	Mechanical and Viscoelastic Characterization of Multiphase Polymer Systems	251
	<i>Poornima Vijayan P., Siby Varghese and Sabu Thomas</i>	
7.1	Introduction	251
7.2	Polymer Blends	253
7.2.1	Ultimate Mechanical Properties and Modeling	253
7.2.2	Dynamic Mechanical Properties	271
7.2.3	Impact Properties	276
7.2.4	Nanostructured Polymer Blends	279
7.3	Interpenetrating Polymer Networks (IPNs)	282
7.3.1	Modeling of Mechanical Properties of IPNs	287
7.4	Polymer Gels	290
7.5	Polymer Composites	293
7.5.1	Mechanical Properties of Polymer Macrocomposites	295
7.5.2	Mechanical Properties of Polymer Microcomposites	298
7.5.3	Mechanical Properties of Polymer Nanocomposites	298
7.5.4	Mechanical Modeling of Polymer Nanocomposites	304
7.6	Conclusion, Future Trends and Challenges	307
	References	307
8	Rheology and Viscoelasticity of Multiphase Polymer Systems: Blends and Block Copolymers	311
	<i>Jean-Charles Majesté and Antonio Santamaría</i>	
8.1	Introduction	311
8.2	Morphology of Polymer Blends	313
8.2.1	Morphology Characterization	313
8.2.2	Effect of Rheological Parameters on Morphology	315

8.3	Microrheology of Droplet Deformation	318
8.3.1	Breakup	318
8.3.2	Coalescence	321
8.4	Rheology of Polymer Blends	322
8.4.1	Specificity of Blend Rheology	322
8.4.2	Blending Laws and Viscoelasticity Models	326
8.4.3	Low Frequency Viscoelastic Behavior of Polymer Blends	335
8.5	Microphase Separated Block Copolymers	339
8.5.1	Ordered State and Morphologies in Block Copolymers: The Case of SEBS Triblock	339
8.6	Dynamic Viscoelastic Results of SEBS Copolymers	340
8.6.1	Low and Intermediate Frequency Viscoelastic Behavior	340
8.6.2	Thermorheological Complexity	341
8.6.3	Specific Mechanical Relaxation at Low Frequencies	343
8.7	Flow-induced Morphological Changes	345
8.7.1	Order-order Transition and Flow Alignment in Block Copolymers	345
8.7.2	Flow Alignment in a SEBS Copolymer	345
8.8	Capillary Extrusion Rheometry Results of Block Copolymers	347
8.8.1	General Results of Styrenic Block Copolymers	347
8.8.2	Viscosity and Flow Instabilities in SEBS Copolymers	350
8.9	Summary	354
	References	354
9	Thermal Analysis of Multiphase Polymer Systems	359
	<i>György J. Marosi, Alfréd Menyhárd, Géza Regdon Jr. and József Varga</i>	
9.1	Introduction	359
9.2	Thermo-optical Microscopy	360
9.3	Differential Scanning Calorimetry	365
9.4	Temperature Modulated Differential Scanning Calorimetry	373
9.5	Micro- and Nanothermal Analysis	376
9.6	Thermal Gravimetric Analysis and Evolved Gas Analysis	378
9.7	Conclusions	380
	References	381
10	Thermophysical Properties of Multiphase Polymer Systems	387
	<i>Abderrahim Boudenne, Laurent Ibos and Yves Candau</i>	
10.1	Introduction	387
10.2	Thermophysical Properties: Short Definitions	388
10.3	Measurement Techniques	389
10.3.1	Methods for the Measurement of One Property	389
10.3.2	Methods for the Simultaneous Measurement of Several Parameters	393
10.4	Thermophysical Properties of Polymers and Composite Systems	394
10.4.1	Neat Polymers (Unfilled Systems)	394
10.4.2	Thermophysical Behavior of Composites	395
10.5	Summary	419
	References	420

11 Electrically Conductive Polymeric Composites and Nanocomposites	425
<i>Igor Krupa, Jan Prokeš, Ivo Křivka and Zdeno Špitalský</i>	
11.1 Introduction	425
11.2 Theory	426
11.2.1 Percolation Models	427
11.3 Electrically Conductive Fillers	432
11.3.1 Carbon Black	432
11.3.2 Metallic Fillers	435
11.3.3 Metallized Fillers	438
11.3.4 Graphite	438
11.3.5 Carbon Nanotubes (CNT)	443
11.3.6 Conducting Polymers	449
11.3.7 Fillers Coated by Conducting Polymers	451
11.4 Effect of Processing Conditions on the Electrical Behavior of Composites	452
11.4.1 Blending of Polymeric Composites	452
11.4.2 Effects of the Secondary Processing Steps on Conductivity	453
11.4.3 Effect of Polymer Characteristics on the Electrical Conductivity of Composites	454
11.4.4 Crystallinity Effect	454
11.4.5 Effect of Polymer–Filler Interaction	455
11.4.6 Multiphase Morphology of Polymers and Its Influence on the Conductivity of Composites: Multipercolation Effect	456
11.5 Applications	457
11.5.1 EMI	457
11.5.2 ESD	457
11.5.3 Electrically Conductive Adhesives	458
11.5.4 Conductive Rubbers	458
11.5.5 Semi-Conductive Cable Compounds	458
11.5.6 Fuel Cells	458
11.6 Resistance Measurements	458
11.6.1 Two-Probes Method	459
11.6.2 Four-Probes Method	460
11.6.3 Van der Pauw Method	465
11.6.4 Spreading Resistance of the Contacts	468
11.6.5 Contact Resistance	470
References	472

VOLUME 2

12 Dielectric Spectroscopy and Thermally Stimulated Depolarization Current Analysis of Multiphase Polymer Systems	479
<i>Polycarpus Pissis, Apostolos Kyritsis and Daniel Fragiadakis</i>	
12.1 Introduction	479
12.2 Dielectric Techniques	482
12.2.1 Introduction	482
12.2.2 Broadband Dielectric Spectroscopy (DS)	483
12.2.3 Thermally Stimulated Depolarization Current (TSDC) Techniques	485

12.3	Copolymers and Interpenetrating Polymer Networks Based on Poly(alkyl acrylate)s and Poly(alkyl methacrylate)s (Mixing and Phase Separation)	486
12.3.1	Introduction	486
12.3.2	Poly(butyl acrylate)-Poly(butyl methacrylate) Sequential Interpenetrating Polymer Networks	488
12.3.3	Poly(butyl acrylate)-Poly(methyl methacrylate) Interpenetrating Polymer Networks and Copolymers	493
12.3.4	Poly(ethyl methacrylate)-Poly(hydroxyethyl acrylate) Copolymers	496
12.3.5	Concluding Remarks	498
12.4	Rubber/Silica Nanocomposites (Interfacial Phenomena)	499
12.4.1	Introduction	499
12.4.2	TSDC Studies	500
12.4.3	Broadband DS Studies	503
12.4.4	Concluding Remarks	506
12.5	Polymer Nanocomposites with Conductive Carbon Inclusions (Percolation Phenomena)	507
12.5.1	Introduction	507
12.5.2	Analysis of DS Data in Terms of the Dielectric Function	507
12.5.3	Analysis of DS Data in Terms of ac Conductivity	510
12.5.4	Concluding Remarks	512
12.6	Conclusion	512
	Acknowledgements	513
	References	513
13	Solid-State NMR Spectroscopy of Multiphase Polymer Systems	519
	<i>Antonio Martínez-Richa and Regan L. Silvestri</i>	
13.1	Introduction to NMR	520
13.2	Phases in Polymers: Polymer Conformation	522
13.3	High Resolution ^{13}C NMR Spectroscopy of Solid Polymers	525
13.3.1	Chemical Shift	525
13.3.2	Polyolefines	526
13.3.3	Polyesters	526
13.3.4	Carbohydrates	530
13.3.5	Conducting Polymers	530
13.3.6	Polymer Blends	531
13.3.7	Interactions Between Polymers and Low-molecular Weight Compounds	535
13.3.8	Miscellaneous Polymers	536
13.4	Additional Nuclei	536
13.5	NMR Relaxation	538
13.5.1	NMR Relaxation in the Study of Polymer Blends	539
13.5.2	NMR Relaxation in the Study of Copolymers	542
13.5.3	NMR Relaxation in the Study of Polymer Composites	543
13.5.4	NMR Relaxation in the Study of Polymers for Drug Delivery	543
13.6	Spin Diffusion	544
13.7	Concluding Remarks	546
	References	546

14 ESR Spectroscopy of Multiphase Polymer Systems	551
<i>Srećko Valić, Mladen Andreis and Damir Klepac</i>	
14.1 Introduction	551
14.2 Theoretical Background	555
14.3 Copolymers	560
14.4 Grafted Polymers	569
14.5 Blends	569
14.6 Crosslinked Polymers	571
14.7 Semi-Interpenetrating Networks (SIPNs)	571
14.8 Composites	573
14.9 Nanocomposites	575
14.10 Other Polymer Multiphase Systems	576
14.11 Conclusion	578
References	579
15 XPS Studies of Multiphase Polymer Systems	585
<i>Mohamed M. Chehimi, Fatma Djouani and Karim Benzarti</i>	
15.1 Introduction	585
15.2 Basic Principles of X-ray Photoelectron Spectroscopy	586
15.2.1 Photoionization	586
15.2.2 Surface Specificity of XPS	587
15.2.3 Spectral Examination and Analysis	587
15.2.4 Quantification	592
15.2.5 Determination of Overlayer Thickness	592
15.2.6 Instrumentation	597
15.3 Applications of XPS to Polymeric Materials	599
15.3.1 Polymer Grafts	600
15.3.2 Colloidal Particles	605
15.3.3 Epoxy Adhesives	609
15.3.4 Conductive Polymers	613
15.3.5 Polymer Blends	619
15.3.6 Composites	624
15.3.7 Interpenetrating Polymer Networks	627
15.3.8 Random and Block Copolymers	628
15.4 Conclusion	629
Glossary	630
References	631
16 Light Scattering Studies of Multiphase Polymer Systems	639
<i>Yajiang Huang, Xia Liao, Qi Yang and Guangxian Li</i>	
16.1 Introduction	639
16.2 Light Scattering Technique	640
16.2.1 Scattering from Multiphase Polymer Systems	640
16.2.2 Experiment	642
16.2.3 Intensity Calibration	645

16.3	Phase Behavior of Multiphase Polymer Systems Studied by SALS	646
16.3.1	Thermodynamics	646
16.3.2	Phase Separation Dynamics	647
16.3.3	Reaction-induced Phase Separation	649
16.3.4	Phase Behavior of Polymer Blends Under Shear Flow	651
16.3.5	Multi-scale Approaches in Studying the Phase Behavior of Polymer Blends	655
16.4	On-line Morphological Characterization of Polymer Blends	656
16.5	Light Scattering Characterization of Other Multiphase Polymer Systems	658
16.5.1	Gelation	658
16.5.2	Crystallization	660
	References	663
17	X-ray Scattering Studies on Multiphasic Polymer Systems	669
	<i>Z. Z. Denchev and J. C Viana</i>	
17.1	Introduction	669
17.2	Theoretical Background	671
17.2.1	Microfibrillar Reinforced Composites (MCF): Definition and Preparation	671
17.2.2	Clay-containing Polymer Nanocomposites	672
17.2.3	The use of WAXS and SAXS in Characterization of Polymers	673
17.3	Studies on Multiphase Polymer Systems	679
17.3.1	Polyamide 6/montmorillonite Nanocomposites	679
17.3.2	Microfibrillar Composites (MFC)	681
17.3.3	Immiscible Polymer Blends	693
17.3.4	Non-conventional Molding of PP Nanocomposites	695
17.3.5	Stretching of Nanoclay PET Nanocomposite	697
17.4	Concluding Remarks	699
	Acknowledgements	700
	References	700
18	Characterization of Multiphase Polymer Systems by Neutron Scattering	705
	<i>Max Wolff</i>	
18.1	Introduction	705
18.2	Method of Neutron Scattering	705
18.2.1	Scattering Experiment	706
18.2.2	Born Approximation	708
18.2.3	Elastic and Quasielastic Scattering	710
18.2.4	Scattering at Small Momentum Transfer	713
18.3	Experimental Techniques	716
18.3.1	Production and Detection of Neutrons	716
18.3.2	Instrumentation	719
18.3.3	Grazing Incidence Small Angle Scattering	724
18.3.4	Comparison of SANS and GISANS for Crystalline Systems	726
18.4	Recent Experimental Results	729
18.4.1	Polymer Dynamics	729
18.4.2	Contrast Variation	730
18.4.3	Effect of Shear	730
18.4.4	Near Surface Crystallization of Micelles	733

18.5	Conclusion	743
	Acknowledgements	743
	References	743
19	Gas Diffusion in Multiphase Polymer Systems	749
	<i>Eliane Espuche</i>	
19.1	Introduction	749
19.2	Gas Transport Mechanisms in Dense Polymer Films: Definition of the Transport Parameters	749
19.3	Multiphase Polymer Systems for Improved Barrier Properties	752
19.3.1	Introduction	752
19.3.2	Dispersion of Impermeable Spheres Within a Polymer Matrix	752
19.3.3	Influence of the Shape of the Dispersed Impermeable Phase: Interest of Oriented Polymer Blends and of the Nanocomposite Approach	755
19.3.4	Nanocomposites Based on Lamellar Nanofillers	757
19.3.5	Multilayers	763
19.3.6	Active Films	764
19.3.7	Comparison of the Different Ways Used to Improve Barrier Properties	766
19.4	Multiphase Polymer-based Systems for Improved Selectivity	767
19.4.1	Introduction	767
19.4.2	Organic–inorganic Materials for Gas Separation Membranes	767
19.5	Conclusion	769
	References	770
20	Nondestructive Testing of Composite Materials	777
	<i>Zhongyi Zhang and Mel Richardson</i>	
20.1	Introduction	777
20.2	Failure Mechanisms in Polymer Composites	779
20.2.1	Matrix Deformation	779
20.2.2	Fiber–matrix Debonding	779
20.2.3	Matrix Cracking	779
20.2.4	Delamination	780
20.2.5	Fiber Breakage	780
20.2.6	Combination of Different Failure Modes	780
20.3	Visual Inspection	781
20.4	Acoustic Emission	782
20.5	Ultrasonic Scanning	783
20.6	Radiography	785
20.7	Thermography	786
20.8	Laser Interferometry	788
20.9	Electronic Shearography	790
20.10	Optical Deformation and Strain Measurement System	791
20.11	Summary	795
	References	795

21	Ageing and Degradation of Multiphase Polymer Systems	797
	<i>Xavier Colin, Gilbert Teyssedre and Magali Fois</i>	
21.1	Introduction	797
21.1.1	Issues Associated With Material Ageing	797
21.1.2	Classification of Ageing Types	798
21.2	Physical Ageing	799
21.2.1	Ageing Induced by Structural Reorganization	800
21.2.2	Ageing Induced by Solvent Absorption	802
21.2.3	Ageing Induced by Additive Migration	803
21.3	Chemical Ageing	806
21.3.1	General Aspects	806
21.3.2	Mechanistic Schemes	816
21.4	Impact of Multiphase Structure on Ageing Processes	829
21.4.1	Structural Reorganization	829
21.4.2	Diffusion Controlled Processes	831
21.5	Practical Impact of Physical Ageing on Use Properties	832
21.5.1	Water-Induced Mechanical Damages in Composites	832
21.5.2	Ageing of Electrical Insulations	833
21.6	Concluding Remarks	839
	References	840
22	Fire Retardancy of Multiphase Polymer Systems	843
	<i>Michel Ferriol, Fouad Laoutid and José-Marie Lopez Cuesta</i>	
22.1	Introduction	843
22.2	Combustion and Flame Retardancy of Polymers	844
22.2.1	Combustion of Polymers	844
22.2.2	Flame Retardancy	845
22.3	Laboratory Fire Testing	846
22.3.1	Limiting Oxygen Index (LOI)	846
22.3.2	Epiradiator or 'Drop Test'	847
22.3.3	UL 94	848
22.3.4	Cone Calorimeter	848
22.4	Flame Retardant Additives	849
22.4.1	Hydrated Fillers	849
22.4.2	Halogenated Flame Retardants	850
22.4.3	Phosphorus-based Flame Retardants	850
22.4.4	Nanometric Particles	852
22.5	Synergistic Effects of Fillers with Flame Retardant Additives	854
22.5.1	Definition of Synergistic Effects in Flame Retardant Systems	854
22.5.2	Micronic Fillers and Flame Retardants	854
22.5.3	Nanometric Fillers and Flame Retardants	856
22.6	Conclusion	862
	Acknowledgements	862
	References	863

23 Applications of Selected Multiphase Systems	865
<i>Igor Novák, Volkan Cecen and Vladimír Pollák</i>	
23.1 Introduction	865
23.2 Construction Applications	866
23.2.1 Automotive Applications	866
23.2.2 Marine Applications	871
23.2.3 Other Applications	875
23.3 Aeronautics and Spacecraft Applications	882
23.3.1 Aeronautics Applications	882
23.3.2 Spacecraft Applications	891
23.4 Human Medicine Applications	895
23.4.1 Musculoskeletal and Bone Applications	895
23.4.2 Dentistry Applications	905
23.5 Electrical and Electronic Applications	907
23.6 Conclusion	912
References	913
24 Waste Management, Recycling and Regeneration of Filled Polymers	921
<i>José-Marie Lopez Cuesta, Didier Perrin, and Rodolphe Sonnier</i>	
24.1 Introduction	921
24.2 Identification and Sorting	922
24.3 Separation of Components	924
24.3.1 Mechanical Separation	924
24.3.2 Dissolution of Resin	924
24.4 Feedstock Recycling	928
24.5 Thermal Processes	929
24.6 Mechanical Recycling of Filled Thermoplastics	932
24.6.1 Degradation During Reprocessing of Filled Thermoplastics and Influence of Interfacial Agents	932
24.6.2 Properties of Recycled Filled or Reinforced Thermoplastics	935
24.6.3 Recycling of Polymer Nanocomposites	940
24.7 Waste Management of Glass Fiber-reinforced Thermoset Plastics	944
24.7.1 Waste Management and International Context	944
24.7.2 Feedstock Recycling by Pyrolysis	945
24.7.3 Solvolysis or Chemical Recycling	946
24.7.4 Mechanical Recycling of Glass-reinforced Thermoset Composites	947
24.8 Conclusion	951
References	952
25 Nanoparticle Reinforcement of Elastomers and Some Other Types of Polymers	959
<i>James E. Mark</i>	
25.1 Introduction	959
25.2 Fillers in Elastomers	960
25.2.1 Generation of Approximately Spherical Particles	960
25.2.2 Glassy Particles Deformable into Ellipsoidal Shapes	963
25.2.3 Layered Fillers	964

25.2.4	Magnetic Particles	965
25.2.5	Polyhedral Oligomeric Silsesquioxanes (POSS)	965
25.2.6	Nanotubes	966
25.2.7	Dual Fillers	966
25.2.8	Porous Fillers	967
25.2.9	Fillers with Controlled Interfaces	967
25.2.10	Silicification and Biosilicification	967
25.2.11	Theory and Simulations on Filler Reinforcement	968
25.3	Nanoparticles in Glassy Polymers	970
25.4	Nanoparticles in Partially-Crystalline Polymers	970
25.5	Nanoparticles in Naturally-Occurring Polymers	971
25.6	Nanoparticles in Relatively-Rigid Polymers	972
25.7	Nanoparticles in Thermoset Polymers	972
25.8	Conclusions	973
25.9	Acknowledgements	973
	References	973

Index	981
--------------	------------