

SPRINGER LABORATORY

Springer Laboratory Manuals in Polymer Science

Pasch, Trathnigg: HPLC of Polymers

ISBN: 3-540-61689-6 (hardcover)

ISBN: 3-540-65551-4 (softcover)

Mori, Barth: Size Exclusion Chromatography

ISBN: 3-540-65635-9

Pasch, Schrepp: MALDI-TOF Mass Spectrometry of Synthetic Polymers

ISBN: 3-540-44259-6

Kulicke, Clasen: Viscosimetry of Polymers and Polyelectrolytes

ISBN: 3-540-40760-X

Hatada, Kitayama: NMR Spectroscopy of Polymers

ISBN: 3-540-40220-9

Brummer, R.: Rheology Essentials of Cosmetics and Food Emulsions

ISBN: 3-540-25553-2

Mächtle, W., Börger, L.: Analytical Ultracentrifugation of Polymers
and Nanoparticles

ISBN: 3-540-23432-2

Heinze, T., Liebert, T., Koschella, A.: Esterification of Polysaccharides

ISBN: 3-540-32103-9

Koetz, J., Kosmella, S.: Polyelectrolytes and Nanoparticles

ISBN: 3-540-46381-X

Striebeck, N.: X-Ray Scattering of Soft Matter

ISBN: 3-540-69855-5

Schärrtl, W.: Light Scattering from Polymer Solutions
and Nanoparticle Dispersions

ISBN: 3-540-71950-2

Khulbe, K.C., Feng, C.Y., Matsuura, T.: Synthetic Polymeric Membranes

ISBN: 3-540-73993-7

Michler, G.H.: Electron Microscopy of Polymers

ISBN: 3-540-36350-7

Goerg H. Michler

Electron Microscopy of Polymers

With contributions by

Dr. R. Godehardt · Dr. R. Adhikari · Dr. G.-M. Kim

Dr. S. Henning · DP V. Seydewitz · DP W. Lebek

Prof. Dr. Goerg H. Michler
Institut für Physik
Institut für Polymerwerkstoffe e.V.
Martin-Luther-Universität Halle-Wittenberg
06099 Halle
Germany
goerg.michler@physik.uni-halle.de

ISBN 978-3-540-36350-7

e-ISBN 978-3-540-36352-1

DOI 10.1007/978-3-540-36352-1

Library of Congress Control Number: 2007942162

© 2008 Springer-Verlag Berlin Heidelberg

This work is subject to copyright. All rights are reserved, whether the whole or part of the material is concerned, specifically the rights of translation, reprinting, reuse of illustrations, recitation, broadcasting, reproduction on microfilm or in any other way, and storage in data banks. Duplication of this publication or parts thereof is permitted only under the provisions of the German Copyright Law of September 9, 1965, in its current version, and permission for use must always be obtained from Springer. Violations are liable to prosecution under the German Copyright Law.

The use of general descriptive names, registered names, trademarks, etc. in this publication does not imply, even in the absence of a specific statement, that such names are exempt from the relevant protective laws and regulations and therefore free for general use.

Cover design: WMXDesign, Heidelberg, Germany

Typesetting and production: le-tex publishing services oHG, Leipzig, Germany

Printed on acid-free paper

9 8 7 6 5 4 3 2 1

springer.com

Springer Laboratory Manuals in Polymer Science

Editor

Prof. Harald Pasch
Chair of Polymer Characterization
Department of Chemistry and Polymer Science
University of Stellenbosch
Private Bag X1
7602 Matieland
South Africa
e-mail: hpasch@sun.ac.za

Prof. Harald Pasch
Deutsches Kunststoff-Institut
Abt. Analytik
Schloßgartenstr. 6
64289 Darmstadt
Germany
e-mail: hpasch@dkl.tu-darmstadt.de

Editorial Board

PD Dr. Ingo Alig
Deutsches Kunststoff-Institut
Abt. Physik
Schloßgartenstr. 6
64289 Darmstadt
Germany
e-mail: ialig@dkl.tu-darmstadt.de

Prof. Josef Janca
Université de La Rochelle
Pole Sciences et Technologie
Avenue Michel Crépeau
17042 La Rochelle Cedex 01
France
e-mail: jjanca@univ-lr.fr

Prof. W.-M. Kulicke
Inst. f. Technische u. Makromol. Chemie
Universität Hamburg
Bundesstr. 45
20146 Hamburg
Germany
e-mail: kulicke@chemie.uni-hamburg.de

Preface

Electron microscopy and atomic force microscopy have developed into powerful tools in the field of polymer science. By using different techniques and methods, morphological details at length scales from the visible (0.1 mm) up to a few 0.1 nm can be detected. Consequently, the microscopic techniques used in polymer research support the tendency, over the last two decades, to shift the level of interest from the μm -scale to the nm-scale region. Systems with at least one structural dimension below ~ 100 nm are now considered to comprise a new class of materials, the so-called *nanostructured polymers* or *nanocomposites*. In addition, the influence of several parameters can be studied by changing the morphology of the material. In particular, the influence of the actual, local morphology on mechanical loading effects can be determined. The micromechanical properties or mechanisms that occur at nano- and microscopic levels form the bridge between structure, morphology and mechanical properties. Therefore, electron microscopy and atomic force microscopy directly contribute to a better understanding of structure–property correlations in polymers.

Part I offers an overview of electron microscopy and atomic force microscopy techniques and summarises distinctive applications of polymeric materials. The wide variety of preparation methods used to study polymers with the different microscopic techniques are presented and illustrated with typical micrographs in the chapters of Part II. Each technique is discussed in detail, highlighting its application for solving specific problems arising in the characterisation of materials. The applicability of the microscopic techniques and preparation methods described in Parts I and II to the main classes of polymers is documented in Part III. All relevant groups of solid polymers used domestically, industrially, in research and in medicine are mentioned. The characteristic features and also the variety of structures and morphologies of the different polymer classes are illustrated with typical micrographs. In particular, the application of different microscopic techniques is shown to reveal similar polymeric structures, enabling laboratories that possess only some of the techniques to use them beneficially. As well as descriptions of characteristic morphologies and micromechanical properties the most commonly occurring defects and failures are also illustrated.

The volume is directed at polymer scientists from research institutes and industry, and aims to demonstrate the widespread possibilities enabled by the application of microscopic techniques in polymer research and development. Each of these techniques allows one to solve a number of problems, as even for the specialist it is not always evident which technique is best suited to solving a given problem. The mono-

graph is also directed at research and applied technicians, since it provides a basic understanding of the principles of the different microscopic techniques and exhausts all of the possibilities of using these techniques to solve specific research problems. All of the preparation methods applied for the study of a variety of polymeric materials using different techniques are described in depth, which will also aid laboratory assistants or students that are new to microscopy, as well as those that wish to improve their skills. Finally, the book will be also helpful for students of polymer physics, chemistry and engineering, as well as those researchers interested in the micro- and nanoscopic world of polymers.

This volume draws upon the experiences and studies of the working groups of the editor in research institutes, industry, and academia in the period from 1970 onwards (i.e. over three decades). The authors or coauthors of the various chapters are:

Dr. R. Godehardt (Chaps. 2, 3, 4, 5)

Dr. R. Adhikari (Chaps. 5, 19)

Dr. G.-M. Kim (Chaps. 18, 21, 22, 24)

Dr. S. Henning (Chaps. 9, 11, 16, 23)

DP V. Seydewitz (Chap. 4)

DP W. Lebek (Chaps. 7, 10, 12, 13)

For additional contributions and remarks, I thank Prof. Dr. F.J. Baltá-Calleja, Instituto de Estructura de la Materia, CSIC, Madrid, Dr. W. Erfurth, Max Planck Institut für Mikrostrukturphysik Halle (in Chap. 4), Dr. J. Lacayo-Pineda, Continental AG, Hannover (in Chap. 20), DI St. Scholtyssek (in Chaps. 16 and 24) and DI M. Buschnakowski (in Chap. 11). My former or current coworkers DI (FH) I. Naumann, DI (FH) H. Steinbach, Mrs I. Schülke, Dr. J. Starke, DP J. Laatsch, DI (FH) S. Goerlitz and Mrs C. Becker are gratefully acknowledged for providing many of the examples of microscopic investigations of different polymers and micrographs referred to in this book. I also thank DI W. Schurz for image processing many of the electron micrographs, Mrs B. Erfurt for typing many of the chapters, and DP W. Lebek for his valuable technical help during the completion of the manuscript.

Finally, I also wish to gratefully acknowledge the coworkers at Springer-Verlag for their understanding and help during the preparation of the manuscript.

Halle/Merseburg, March 2008

Goerg H. Michler

Abbreviations

General techniques

AFM	Atomic force microscope
AM	Amplitude modulation
BSE	Backscattered electrons
CCD	Charge-coupled device
CRT	Cathode ray tube
EDX(A)	Energy dispersive X-ray analysis
EELS	Electron energy-loss spectroscopy, electron energy-loss spectrometer
EFTEM	Energy-filtered transmission electron microscopy
ELNES	Energy-loss near-edge structure
EM	Electron microscope
ESI	Electron spectroscopic imaging
ESD	Electron spectroscopic diffraction
ESEM	Environmental scanning electron microscope
FEG	Field-emission gun
FIB	Focussed ion beam
FM	Frequency modulation
GIF	Gatan imaging filter
GSED	Gaseous secondary electron detector
HRTEM	High-resolution transmission electron microscope
HVTEM	High-voltage transmission electron microscope
ID	Interparticle distance
LFM	Lateral force microscope
LVTEM	Low-voltage transmission electron microscope
M_w	Molecular weight
MCA	Multichannel analyser
MDS	Minimum-dose systems
MOS	Metal-oxide semiconductor
PE	Primary electrons
PEELS	Parallel electron energy-loss spectroscopy
PFM	Pulsed force mode
ROI	Region of interest
SE	Secondary electrons

SEM	Scanning electron microscope
SFM	Scanning force microscope
SNOM	Scanning near-field optical microscope
SPM	Scanning probe microscope
STEM	Scanning transmission electron microscope
STM	Scanning tunnelling microscope
TEM	Transmission electron microscope
T_g	Glass transition temperature
TM	Tapping mode
TMAFM	Tapping-mode atomic force microscope
WD	Working distance
WDX(A)	Wavelength dispersive X-ray analysis

Materials/polymers

ABS	Acrylonitrile-butadiene-styrene
ASA	Acrylonitrile-styrene-acrylate
BR	Butadiene rubber
AN	Acrylonitrile
COC	Cyclic olefin copolymer
EB	Ethylene-butadiene copolymer
EOC	Ethylene/1-octene copolymer
EPDM	Ethylene propylene diene rubber
EPR	Ethylene propylene rubber
HDPE	High-density polyethylene
HIPS	High-impact polystyrene
iPP	Isotactic polypropylene
LDPE	Low-density polyethylene
LLDPE	Linear low-density polyethylene
MMT	Montmorillonite
MWCNT	Multiwalled carbon nanotube
NBR	Acrylonitrile-butadiene rubber
NR	Natural rubber
OsO ₄	Osmium tetroxide
PBMA	Poly(<i>n</i> -butylmethacrylate)
PB	Polybutadiene
PC	Polycarbonate
PCH	Polyvinylcyclohexane
PE	Polyethylene
PET	Polyethylene terephthalate
PEB	Ethylene-butylene copolymer
PFS	Poly(ferrocenyl-dimethylsilane)

PI	Polyisoprene
PMMA	Polymethylmethacrylate
PnBA	Poly(<i>n</i> -butylacrylate)
PNC	Polymer nanocomposite
POSS	Polyhedral oligosilsesquioxane
PP	Polypropylene
PS	Polystyrene
PTFE	Polytetrafluoroethylene
PVC	Polyvinylchloride
PVDF	Polyvinylidene fluoride
RuO ₄	Ruthenium tetroxide
PVP	Poly(2-vinylpyridene)
SAN	Polystyrene-acrylonitrile
SIS	Polystyrene- <i>block</i> -polyisoprene- <i>block</i> -polystyrene
SBS	Polystyrene-polybutadiene-polystyrene triblock copolymer, polystyrene- <i>block</i> -polybutadiene- <i>block</i> -polystyrene <i>block</i> copolymer
TPE	Thermoplastic elastomer
UHMWPE	Ultrahigh molecular weight polyethylene
VLDPE	Very low density polyethylene

Table of Contents

INTRODUCTION	1
References	3
Part I Techniques of Electron Microscopy	
1 OVERVIEW OF TECHNIQUES	7
References	14
2 TRANSMISSION ELECTRON MICROSCOPY: FUNDAMENTALS OF METHODS AND INSTRUMENTATION	15
2.1 A Brief History	15
2.2 Fundamentals of Electron Optics and Instrumentation	17
2.2.1 Some Fundamental Properties of Electrons	17
2.2.2 Electron Lenses	19
2.2.3 Electron-Optical Aberrations and Resolution	22
2.2.4 Vacuum System	26
2.3 The Instrument	27
2.3.1 Electron Gun	30
2.3.2 Illumination System	33
2.3.3 Objective Lens and Specimen Stage	35
2.3.4 Image-Forming System	36
2.3.5 Viewing Chamber and Image Acquisition	37
2.3.6 Alignment and Operation of Transmission Electron Microscopes	39
2.4 Fundamentals of Image Formation	40
2.4.1 Scattering Mechanism and Contrast Formation	41
2.4.2 Electron Diffraction and Diffraction Contrast	44
2.4.3 Fundamentals of the Imaging Process	46
References	50
3 TRANSMISSION ELECTRON MICROSCOPY: CONVENTIONAL AND SPECIAL INVESTIGATIONS OF POLYMERS	53
3.1 Conventional Investigations Utilising Mass-Thickness Contrast	53
3.2 Electron Diffraction	55

3.2.1	Selected Area Diffraction	55
3.2.2	Structure Analysis	55
3.3	High-Resolution Transmission Electron Microscopy	57
3.3.1	Introduction	57
3.3.2	Evaluation and Reduction of Radiation Damage	57
3.3.3	Application of HRTEM	58
3.4	Phase Contrast Transmission Electron Microscopy	60
3.4.1	Phase Contrast at Large Defocus Values	60
3.4.2	Phase Contrast by Means of Phase Plates	60
3.5	Electron Holography	62
3.5.1	Introduction	62
3.5.2	Image Plane Off-Axis Holography	62
3.5.3	Examples	64
3.6	Low-Voltage Transmission Electron Microscopy	64
3.6.1	Introduction	64
3.6.2	A Dedicated Low-Voltage TEM and its Application	64
3.7	High-Voltage Transmission Electron Microscopy	65
3.7.1	Introduction	65
3.7.2	Advantages and Applications of HVTEM	65
3.8	Scanning Transmission Electron Microscopy	66
3.8.1	Introduction	66
3.8.2	Similarities and Differences between STEM and TEM	67
3.8.3	Application of Bright-Field and Dark-Field Modes	68
3.9	Analytical Transmission Electron Microscopy	70
3.9.1	Introduction	70
3.9.2	EELS Investigations	72
3.9.3	Electron Spectroscopic Imaging	75
3.10	Electron Tomography	78
3.10.1	Introduction	78
3.10.2	Data Acquisition, Image Alignment and Reconstruction ...	79
3.10.3	Resolution of Reconstructed Data	80
3.10.4	Application of Electron Tomography	81
	References	81
4	SCANNING ELECTRON MICROSCOPY (SEM)	87
4.1	A Brief History of SEM	87
4.2	Fundamentals of Electron Optics and Signal Generation	88
4.2.1	Principle of SEM	88
4.2.2	The Lateral Resolution Power of SEM	89
4.2.3	Comparison of Various Cathode Types	92
4.2.4	Depth of Focus	92
4.2.5	Interaction of Primary Electrons with Sample	92
4.3	The Instrumentation of SEM	95
4.3.1	The Column	95
4.3.2	Specimen Chamber and Goniometer	97

4.3.3	Detectors	98
4.3.4	Signal Display and Magnification	99
4.4	Contrast Formation and Charging Effects	100
4.4.1	Secondary Electron Contrast	100
4.4.2	Contrast of Backscattered Electrons (Solid State Detector) ..	103
4.4.3	Charging Effect	103
4.5	X-Ray Microanalysis	105
4.5.1	Physical Fundamentals of the Generation of X-Rays	105
4.5.2	X-Ray Microanalysis Techniques	107
4.5.3	Detector for EDX Analysis	108
4.5.4	Quantitative EDX Analysis	111
4.5.5	X-Ray Mapping	112
4.5.6	Wavelength Dispersive X-Ray Microanalysis (WDX)	112
4.6	Environmental Scanning Electron Microscope (ESEM™)	116
4.6.1	Low-Vacuum SEM and ESEM™	116
4.6.2	Avoiding Charging	116
4.6.3	The Wet Mode	117
4.6.4	The Gaseous Secondary Electron Detector (GSED)	119
	References	120
5	ATOMIC FORCE MICROSCOPY (AFM)	121
5.1	Introduction	121
5.2	Methodical and Instrumental Fundamentals	124
5.3	Modes of Operation	127
5.3.1	Contact Mode	127
5.3.2	Force Modulation Mode	130
5.3.3	Dynamic Operational Modes	131
5.3.4	Tapping Mode	132
5.4	Typical and Special AFM Applications	137
	References	142
6	IN SITU MICROSCOPY	145
6.1	Overview	145
6.2	Micromechanical In Situ Tests	147
6.2.1	Technical Equipment	147
6.2.2	In Situ Microscopy in (E)SEM	148
6.2.3	In Situ Microscopy in (HV)TEM	150
6.3	In Situ Microscopy in AFM	154
	References	158
7	IMAGE PROCESSING AND IMAGE ANALYSIS	161
7.1	Overview	161
7.2	Image Processing	162
7.3	Image Analysis	163
7.4	Fourier Transformation	165

7.5 Stereoscopic Imaging	167
References	171

Part II Preparation Techniques

8 PROBLEMS ASSOCIATED WITH THE ELECTRON MICROSCOPY OF POLYMERS	175
8.1 Overview	175
8.2 Irradiation Sensitivity of Polymers	176
8.3 Low Contrast of Polymers	177
8.4 Methods of Investigating the Morphologies of Polymers	178
8.4.1 Powders, Particles, Fibres	178
8.4.2 Bulk Polymers	178
8.5 Methods for Studying Micromechanical Processes	180
References	183
9 PREPARATION OF SURFACES	185
9.1 Overview	185
9.2 Surfaces in Their Natural Form	185
9.3 Smooth and Etched Surfaces	186
9.3.1 Chemical Etching	187
9.3.2 Physical Etching	191
9.4 Fracture Surfaces	192
9.5 Investigation of Surfaces	195
References	196
10 PREPARATION OF THIN SECTIONS: (CRYO)ULTRAMICROTOMY AND (CRYO)MICROTOMY	199
10.1 Overview	199
10.2 Instrumentation	200
10.2.1 Microtomes	200
10.2.2 Ultramicrotomes	200
10.2.3 Cryomicrotomes and Cryoultramicrotomes	200
10.2.4 Knives	200
10.2.5 Modern Trends	202
10.3 Working with a Microtome and an Ultramicrotome	203
10.4 Specimen Preparation	204
10.4.1 Embedding	204
10.4.2 Specimen Trimming	205
10.4.3 Fixation and Staining	205
10.5 Ultrathin Sectioning	206
10.5.1 Sectioning Parameters	206
10.5.2 Wet and Dry Sectioning Techniques	206
10.5.3 Room Temperature Ultramicrotomy	208

10.5.4	Cryoultramicrotomy	208
10.5.5	Collecting Sections on Grids	209
10.6	Problems, Errors and Solutions	212
10.6.1	Overview	212
10.6.2	Typical Errors and Possible Solutions	212
	References	217
11	SPECIAL PREPARATION TECHNIQUES	219
11.1	Preparation of Polymer Films from Solutions	219
11.1.1	Introduction	219
11.1.2	Solution Behaviour of Polymers	220
11.1.3	Spin-Coating	220
11.1.4	Dip-Coating	222
11.1.5	Solution Casting	223
11.1.6	Examples and Problems	224
11.2	Preparation Using the Focussed Ion Beam Technique	227
11.2.1	Introduction	227
11.2.2	Principle	228
11.2.3	Examples	229
	References	230
12	PREPARATION FOR (IN SITU) DEFORMATION TESTS	231
12.1	Overview	231
12.2	Specimen Preparation	234
	References	240
13	CONTRAST ENHANCEMENT	241
13.1	Overview	241
13.2	Hardening (Fixation)	241
13.2.1	Physical Hardening (Fixation)	242
13.2.2	Chemical Fixation	243
13.3	Chemical Staining Procedures	243
13.3.1	Media Used to Perform Chemical Staining of Polymers	243
13.3.2	Chemical Staining of Compact Specimens Before Sectioning	246
13.3.3	Chemical Staining of Thin Sections	248
13.4	Enhancement of Contrast Through Physical Effects	248
13.4.1	Contrast Enhancement by γ - or Electron Irradiation	248
13.4.2	Straining-Induced Contrast Enhancement	254
13.5	Problems and Artefacts	256
	References	259

Part III Main Groups of Polymers

14	STRUCTURAL HIERARCHY OF POLYMERS	263
14.1	Overview	263
14.2	Macromolecular Structures	263
14.2.1	Constitution	265
14.2.2	Configuration	265
14.2.3	Conformation	265
14.2.4	Macromolecule Size	267
14.3	Supramolecular Structures	269
14.4	Morphology	271
14.5	Basic Relationships Between Macromolecular Parameters and (Micro)mechanical Properties	273
	References	276
15	AMORPHOUS POLYMERS	277
15.1	Overview	277
15.2	Morphology	277
15.3	Micromechanical Behaviour	281
15.4	Additional Examples of Amorphous Polymers	287
	References	293
16	SEMICRYSTALLINE POLYMERS	295
16.1	Overview	295
16.2	Morphology	296
16.2.1	Structural Hierarchy in Semicrystalline Polymers	296
16.2.2	Methods of Morphological Analysis	299
16.3	Micromechanical Behaviour	310
16.3.1	Brittle Behaviour	310
16.3.2	Ductile Behaviour	313
16.3.3	High-Strength Fibres and Parts	319
16.4	Additional Examples of Semicrystalline Polymers	321
	References	327
17	POLYMER BLENDS	329
17.1	Overview	329
17.2	Morphology	331
17.3	Micromechanical Behaviour	338
17.4	Examples	341
17.4.1	Blends of Amorphous Polymers	341
17.4.2	Blends of Amorphous and Semicrystalline Polymers	343
17.4.3	Blends of Semicrystalline Polymers	343
	References	349

18	HIGH-IMPACT RUBBER-MODIFIED POLYMERS	351
18.1	Overview	351
18.2	Morphology	352
18.3	Micromechanical Processes	357
18.4	Additional Toughening Mechanisms	368
	References	370
19	BLOCK COPOLYMERS	373
19.1	Overview	373
19.2	Morphology	375
19.2.1	Block Copolymer Nanostructures via Self-Assembly	375
19.2.2	Examples of Tailored Block Copolymer Morphology	379
19.3	Deformation Mechanisms in Block Copolymers	385
19.4	Special Cases of Self-Assembly and Applications	389
	References	391
20	RUBBERS AND ELASTOMERS	393
20.1	Overview	393
20.2	Morphology of Rubbers and Elastomers	395
20.3	Micromechanical Deformation Behaviour	398
	References	402
21	POLYMER COMPOSITES	405
21.1	Overview	405
21.2	Particle-Reinforced Polymer Composites	406
21.3	Fibre-Reinforced Polymer Composites	414
	References	417
22	POLYMER NANOCOMPOSITES	419
22.1	Overview	419
22.2	Examples of Different Classes of Nanocomposites	422
22.2.1	Polymer Nanocomposites Based on Zero-Dimensional Filler Particles (POSS)	422
22.2.2	Polymer Nanocomposites Based on One-Dimensional Filler Particles (MWCNT)	424
22.2.3	Polymer Nanocomposites Based on Two-Dimensional Filler Particles (MMT)	425
22.2.4	Polymer Nanocomposites Based on Three-Dimensional Filler Particles (SiO ₂)	427
	References	428
23	BIOMATERIALS	429
23.1	Overview	429
23.2	Electron Microscopy of Polymeric Biomaterials: Specific Problems and Solutions	431

23.3 Examples..... 432

23.3.1 Natural Biomaterials: Bone 432

23.3.2 UHMWPE in Orthopaedics 433

23.3.3 Acrylic Bone Cements..... 434

23.3.4 Bioactive Composites for Bone Replacement 435

23.3.5 Dental Composites..... 436

23.3.6 Sutures, Scaffolds and Meshes 437

23.3.7 Ureter Stents 439

23.3.8 Silicone-Based Tracheal Stents and Voice Prostheses 439

References..... 443

24 SPECIAL PROCESSING FORMS 445

24.1 Overview 445

24.2 Multilayered Films 446

24.2.1 Introduction..... 446

24.2.2 Morphology 446

24.2.3 Micromechanical Deformation Mechanisms 448

24.3 Hot-Compacted Self-Reinforced Polymers 451

24.3.1 Overview 451

24.3.2 Morphology 452

24.4 Nanofibres by Electrospinning 455

24.4.1 Overview 455

24.4.2 Morphology 456

24.4.3 Micromechanical Deformation Mechanism 458

24.5 Microformed Materials..... 460

24.5.1 Overview 460

24.5.2 Several Examples 460

References..... 462

SUBJECT INDEX 465