Contents

Preface to the Third Edition V

Preface to the Second Edition VI

Preface to the First Edition VIII

The Authors XI

The Editors XI

Wolfgang Grellmann XI

Sabine Seidler XI

The Co-Authors XII

Nomenclature (Selection) XXVII

Terminology XXXVII

Materials – Symbols and Abbreviated Terms XLI

1 Introduction 1

1.1 The Genesis of Polymer Testing as a Science 1

1.2 Factors Influencing Data Acquisition 5

1.3 Classification of Polymer Testing Methods 6

1.4 Standards and Regulatory Codes for Polymer Testing 8

1.5 Compilation of Standards 11

2 Preparation of Specimens 15

2.1 Introduction 15

2.2 Testing Molding Materials 17

2.3 Specimen Preparation 18
2.3.1 General Remarks 18
2.3.2 Specimen Preparation by Direct Shaping 20
2.3.2.1 Production of Specimens from Thermoplastic Molding Materials 20
2.3.2.2 Production of Specimens from Thermosetting Molding Materials 26
2.3.2.3 Production of Specimens from Elastomeric Materials 28
2.3.3 Specimen Preparation by Indirect Shaping 29
2.3.4 Characterization of Specimen State 30
2.4 Specimen Preparation and Conditioning 33
2.5 Compilation of Standards 36

3 Determining Process-Related Properties 39
3.1 Molding Materials 39
3.2 Determining Bulk Material Properties 40
3.2.1 Bulk Density, Compacted Apparent Density, Fill Factor 40
3.2.2 Pourability, Repose Angle , Slide Angle 42
3.3 Determining the Properties of Fluids 43
3.3.1 Rheological Fundamentals 43
3.3.1.1 Viscosity of *Newtonian* and Non-*Newtonian* Fluids . . 43
3.3.1.2 Temperature and Pressure Dependence of Viscosity . 46
3.3.1.3 Molecular Mass Influence on Viscosity 46
3.3.1.4 Volume Properties 47
3.3.2 Measuring Rheological Properties 47
3.3.2.1 Rheometry/Viscometry 47
3.3.2.2 Rotational Rheometers 48
3.3.2.3 Capillary Rheometers 55
3.3.2.4 Extensional Rheometers 65
3.3.3 Selecting Measurement Methods for Characterizing Polymer Materials 67
3.4 Compilation of Standards 68

4 Mechanical Properties of Polymers 71
4.1 Fundamental Principles of Mechanical Behavior 71
4.1.1 Mechanical Loading Parameters 71
4.1.1.1 Stress 71
4.1.1.2 Strain 74
4.1.2 Material Behavior and Constitutive Equations 75
4.1.2.1 Elastic Behavior 75
4.1.2.2 Viscous Behavior 78
4.1.2.3 Viscoelastic Behavior 79
4.1.2.4 Plastic Behavior 85
4.2 Mechanical Spectroscopy 87
4.2.1 Experimental Determination of Time-Dependent Mechanical Properties 87
4.2.1.1 Static Testing Methods 87
4.2.1.2 Dynamic-Mechanical Analysis (DMA) 88
4.2.2 Time and Temperature Dependence of Viscoelastic Properties . 96
4.2.3 Structural Factors Influencing Viscoelastic Properties 99
4.3 Quasi-Static Test Methods 101
4.3.1 Deformation Behavior of Polymers 101
4.3.2 Tensile Tests on Polymers 106
4.3.2.1 Theoretical Basis of the Tensile Test 106
4.3.2.2 Conventional Tensile Tests 109
4.3.2.3 Enhanced Information of Tensile Tests 118
4.3.3 Tear Test 124
4.3.4 Compression Test on Polymers 125
4.3.4.1 Theoretical Basis of the Compression Test 125
4.3.4.2 Performance and Evaluation of Compression Tests .. 129
4.3.5 Bend Tests on Polymers 133
4.3.5.1 Theoretical Basis of the Bend Test 133
4.3.5.2 The Standardized Bend Test 139
4.4 Impact Loading 143
4.4.1 Introduction 143
4.4.2 *Charpy* Impact Test and Notched *Charpy* Impact Test 144

4.4.3 Tensile-Impact and Notched Tensile-Impact Tests 150
4.4.4 Free-Falling Dart Test and Puncture Impact Test 152
4.5 Fatigue Behavior 156
4.5.1 Fundamentals 156
4.5.2 Experimental Determination of Fatigue Behavior 158
4.5.3 Planning and Evaluating Fatigue Tests 162
4.5.4 Factors Influencing the Fatigue Behavior and Service-Life Prediction of Service Life for Polymers 164
4.6 Long-Term Static Behavior 167
4.6.1 Fundamentals 167
4.6.2 Tensile Creep Test 168
4.6.3 Flexural Creep Test 175
4.6.4 Creep Compression Test 176
4.7 Hardness Test Methods 178
4.7.1 Principles of Hardness Testing 178
4.7.2 Conventional Hardness Testing Methods 180
4.7.2.1 Test Methods for Determining Hardness Values after Unloading 180
4.7.2.2 Test Methods for Determining Hardness Values under Load 182
4.7.2.3 Special Test Methods 185
4.7.2.4 Comparability of Hardness Values 186
4.7.3 Instrumented Hardness Test 187
4.7.3.1 Fundamentals of Measurement Methodology 187
4.7.3.2 Material Parameters Derived from Instrumented Hardness Tests 190
4.7.3.3 Examples of Applications 192
4.7.4 Correlating Microhardness with Yield Stress and Fracture Toughness 194
4.8 Friction and Wear 198
4.8.1 Introduction 198
4.8.2 Fundamentals of Friction and Wear 200
4.8.2.1 Frictional Forces 200
4.8.2.2 Temperature Increase Resulting from Friction 201

4.8.2.3 Wear as a System Characteristic 201
4.8.2.4 Wear Mechanisms and Formation of Transfer Film . . 202
4.8.3 Wear Tests and Wear Characteristics 203
4.8.3.1 Selected Model Wear Tests 204
4.8.3.2 Wear Parameters and Their Determination 205
4.8.3.3 Wear Parameters and Their Presentation 206
4.8.4 Selected Experimental Results 207
4.8.4.1 Counterbody Influence 207
4.8.4.2 Influencing of Fillers 208
4.8.4.3 Influence of Loading Parameters 210
4.8.4.4 Predicting Properties via Artificial Neural Networks 212
4.8.5 Summary 213
4.9 Compilation of Standards 214

5 Fracture Toughness Measurements in Engineering Plastics . . 229
5.1 Introduction 229
5.2 Current State and Development Trends 230
5.3 Fundamental Concepts of Fracture Mechanics 231
5.3.1 Linear-Elastic Fracture Mechanics (LEFM) 231
5.3.2 Crack-Tip-Opening Displacement (CTOD) Concept 236
5.3.3 J-Integral Concept 239
5.3.4 Crack Resistance (R-) Curve Concept 241
5.4 Experimental Determination of Fracture Mechanical Parameters 243
5.4.1 Quasi-Static Loading 243
5.4.2 Instrumented *Charpy* Impact Test 246
5.4.2.1 Test Configuration 246
5.4.2.2 Maintenance of Experimental Conditions 248
5.4.2.3 Types of Load–Deflection Diagrams – Optimization of Diagram Shape 250
5.4.2.4 Special Approximation Methods for Estimating ***J*** Values 251
5.4.2.5 Requirements for Specimen Geometry 254
5.4.3 Instrumented Free-Falling Dart Test 256
5.5 Applications for Material Development 258

5.5.1 Fracture Mechanical Toughness Evaluation on Modified Polymers 258
5.5.1.1 Particle Filled Thermoplastics 258
5.5.1.2 Fiber-Reinforced Thermoplastics 262
5.5.1.3 Blends and Copolymers 266
5.5.2 Instrumented Tensile-Impact Testing for Product Evaluation . . 272
5.5.3 Consideration of Fracture Behavior for Material Selection and Dimensioning 275
5.6 Compilation of Standards 277

6 Testing of Physical Properties 283

6.1 Thermal Properties 283
6.1.1 Introduction 283
6.1.2 Determining Heat Conductivity 285
6.1.3 Differential Scanning Calorimetry (DSC) 289
6.1.4 Thermogravimetric Analysis (TGA) 294
6.1.5 Thermomechanical Analysis (TMA) 296
6.2 Optical Properties 299
6.2.1 Introduction 299
6.2.2 Reflection and Diffraction 300
6.2.2.1 Directed and Diffuse Reflection 300
6.2.2.2 Refractive Index Determination 301
6.2.3 Dispersion 305
6.2.4 Polarization 305
6.2.4.1 Optical Activity 306
6.2.4.2 Polarization of Optical Components 306
6.2.4.3 Polarization-Optical Testing Methods 308
6.2.5 Transmission, Absorption and Reflection 314
6.2.6 Gloss, Intrinsic Diffuse Reflectance and Haze 315
6.2.7 Color 319
6.2.8 Transparency and Translucency 322
6.2.9 Infrared Spectroscopy 325
6.2.10 Laser Technology 328
6.2.11 Testing the Stability of Optical Values 329

6.3 Electrical and Dielectrical Properties 330
6.3.1 Introduction 330
6.3.2 Physical Fundamentals 333
6.3.3 Electrical Conductivity and Resistance 336
6.3.3.1 Volume Resistivity 336
6.3.3.2 Surface Resistivity 339
6.3.3.3 Insulation Resistance 340
6.3.3.4 Contacting and Specimen Preparation 343
6.3.4 Dielectrical Properties and Dielectrical Spectroscopy 344
6.3.4.1 Relaxation Processes 345
6.3.4.2 Alternating Current Conductivity (AC Conductivity) 353
6.3.4.3 Broadband Dielectric Measurement Techniques 354
6.3.5 Special Technical Testing Methods 361
6.3.5.1 Electrostatic Charge 361
6.3.5.2 Electric Strength 362
6.3.5.3 Creep Resistance and Arc Resistance 366
6.4 Compilation of Standards 369

7 Evaluating Environmental Stress Cracking Resistance 383

7.1 General Remarks on the Failure of Polymers in Aggressive Fluids . . . 383
7.2 Testing Environmental Stress Cracking Resistance 387
7.2.1 Test Methods for Determining Environmental Stress Crack Formation 387
7.2.2 Examples for Evaluating Environmental Stress Cracking Resistance with Standardized Test Methods 391
7.2.3 Fracture Mechanics Test Methods 394
7.3 Modeling Plastics Failure in Fluids Caused by Stress Cracking 398
7.4 Factors Influencing Stress Cracking Behavior 402
7.4.1 Crosslinking 402
7.4.2 Molecular Weight and Molecular Weight Distribution 403
7.4.3 Branching 404
7.4.4 Crystalline Regions 405
7.4.5 Molecular Orientation 407
7.4.6 Physical-Chemical Interaction Processes 410

7.4.7 Viscosity of the Immersion Fluid 416
7.4.8 Influence of Test Specimen Thickness 421
7.4.9 Temperature Influence 422
7.5 Compilation of Standards 425

8 Non-Destructive Polymer Testing 431
8.1 Introduction 431
8.2 Non-Destructive Testing by Electromagnetic Waves 433
8.2.1 X-Ray Radiation 433
8.2.1.1 Projection Methods by Means of Absorption 434
8.2.1.2 *Compton* Backscatter 436
8.2.1.3 X-Ray Refractometry 437
8.2.2 Spectral Range of Visible Light 440
8.2.2.1 Measuring Thickness of Transparent Components . . 440
8.2.2.2 Photoelastic Imaging of Transparent Components . . . 440
8.2.2.3 Confocal Laser Scan Microscopes 441
8.2.2.4 Line Projection for Detecting Contour 442
8.2.2.5 Interferometric Methods 443
8.2.3 Thermography 449
8.2.4 Microwaves 449
8.2.5 Dielectric Spectroscopy 453
8.2.6 Eddy Current 454
8.3 Non-Destructive Testing with Elastic Waves 456
8.3.1 Elastic Waves under Linear Material Behavior 457
8.3.1.1 Ultrasound 457
8.3.1.2 Mechanical Vibrometry 468
8.3.2 Elastic Waves with Non-Linear Material Behavior 471
8.3.2.1 Fundamentals on Elastic Waves in Non-Linear Materials 471
8.3.2.2 Non-Linear Air-Ultrasound 472
8.3.2.3 Non-Linear Vibrometry 475
8.4 Non-Destructive Testing by Dynamic Heat Transport 477
8.4.1 External Excitation 478

8.4.1.1 Heat-Flux Thermography by Non-Periodical Heat Transport 478
8.4.1.2 Thermography with Periodical Heat Transport 480
8.4.2 Internal Excitation 484
8.4.2.1 Thermography with Excitation by Elastic Waves 484
8.4.2.2 Thermography with Other Types of Internal Excitation 489
8.5 Outlook 489

9 Hybrid Methods of Polymer Diagnostics 497
9.1 Objectives 497
9.2 Tensile Test, Acoustic Emission Test and Video Thermography 499
9.3 Tensile Test and Laser Extensometry 502
9.4 Fracture Mechanics and Non-Destructive Testing 507

10 Testing of Composite Materials 515
10.1 Introduction 515
10.2 Theoretical Background 517
10.2.1 Anisotropy 517
10.2.2 Elastic Properties of Laminates 518
10.2.3 Influence from Moisture and Temperature 518
10.2.4 Laminate Theory and *St. Venant*'s Principle 519
10.2.5 Applying Fracture Mechanical Concepts to Fiber Composites . 520
10.3 Specimen Preparation 522
10.3.1 Manufacture of Laminates 522
10.3.2 Preparing Specimens for Unidirectional Loading 524
10.4 Determining Fiber Volume Content 526
10.5 Mechanical Test Methods 527
10.5.1 Tensile Tests 527
10.5.2 Compression Tests 530
10.5.3 Flexural Tests 534
10.5.4 Interlaminar Shear Strength 537
10.5.5 Shear Tests 538
10.5.5.1 ± 45° Off-Axis Tensile Test 538

10.5.5.2 10° Off-Axis Tensile Test 540
10.5.5.3 Two- and Three-Rail Shear Test 541
10.5.5.4 Iosipescu Shear Test 543
10.5.5.5 Plate-Twist Shear Test 544
10.5.5.6 Torsional Loading on Thin-Walled Tubes 545
10.6 Fracture Mechanical Test Methods 546
10.6.1 Experimental Tests on Fiber Composite Materials 546
10.6.2 Special Specimen Configuration 547
10.6.2.1 Specimens for Mode I Loading 547
10.6.2.2 Specimen for Mode II Loading 548
10.6.2.3 Mixed-Mode Specimens 551
10.6.3 Fracture Mechanical Values of Fiber Composite Materials 554
10.7 Dedicated Test Methods 555
10.7.1 Edge Delamination Test (EDT) 555
10.7.2 Boeing Open-Hole Compression Test 556
10.8 Peel Strength of Flexible Laminates 557
10.9 Impact Loading and Damage Tolerance 559
10.10 Compilation of Standards and Guidelines 562

11 Technological Testing Methods 569
11.1 Heat Distortion Resistance 569
11.1.1 Fundamentals and Definitions 569
11.1.2 Determining Heat Distortion Resistance Temperature *HDT* and *Vicat* Softening Temperature 570
11.1.3 Practical Examples for the Informational Value of the *Vicat* and *HDT* Test 573
11.2 Fire Behavior 577
11.2.1 Introduction 577
11.2.2 Stages of a Fire and Fire-Determining Parameters 579
11.2.3 Fire Tests 581
11.2.3.1 Smoldering Fire 582
11.2.3.2 Ignitability 583
11.2.3.3 Flame Spread 587
11.2.3.4 Heat Release 590

11.2.3.5 Fire Resistance 592
11.2.3.6 Ease of Extinction 592
11.2.4 Utilization of Cone Calorimeter to Characterize Fire Behavior 594
11.3 Component Testing 600
11.3.1 Introduction 600
11.3.2 Basic Testing Methods 601
11.3.2.1 General Remarks 601
11.3.2.2 Testing Visible Features 601
11.3.2.3 Testing Materials Properties 603
11.3.2.4 Testing Serviceability 605
11.3.3 Testing Plastic Piping 606
11.3.3.1 Quality Assurance for Plastic Piping 606
11.3.3.2 Testing Hydrostatic Rupture Strength for Plastic Pipes 608
11.3.4 Testing Plastics Components for Application in Vehicle Design 611
11.3.4.1 Test Requirements 611
11.3.4.2 Mechanical Tests 611
11.3.4.3 Permeation and Emission Tests 613
11.3.5 Testing Plastics Components for Application in Building Construction 616
11.3.5.1 Introduction 616
11.3.5.2 Testing Sandwich Panels 617
11.3.5.3 Testing Plastic Casing Pipes 620
11.4 Implant Testing 624
11.4.1 Introduction 624
11.4.2 Push-out Tests for Implants 626
11.4.3 Testing the Application Behavior of Pharyngotracheal Voice Prostheses 629
11.4.4 Determining the Mechanical Properties of Human Cartilage . . 632
11.5 Compilation of Standards 634

12 Testing of Polymeric Films ... 643
12.1 Basics ... 643
12.2 Determination of Mechanical Properties of Films ... 644
12.2.1 Tensile Test ... 644
12.2.2 Tear Test ... 647
12.2.3 Impact Behavior ... 648
12.2.3.1 Tensile-Impact Test ... 648
12.2.3.2 Dynamic Tear Testing ... 651
12.2.3.3 Puncture Tests ... 653
12.3 Characterization of Separation Behavior ... 657
12.3.1 Peel Tests ... 657
12.3.2 Cling Test ... 666
12.4 Fracture Mechanics Characterization ... 668
12.5 Characterization of Film Surfaces ... 672
12.6 Compilation of Standards and Guidelines ... 675

13 Testing of Microcomponents ... 679
13.1 Introduction ... 679
13.2 Microspecimen Testing ... 682
13.2.1 Micro-Tensile Tests ... 682
13.2.2 Fracture Mechanics Investigations Using Mini Compact Tension (CT) Specimens ... 687
13.3 Nanoindentation Testing ... 689
13.4 Testing Methods on Their Way to the Nanoworld ... 691
13.4.1 Non-Contacting Displacement Field Analysis Using Digital Image Correlation (Gray-Value Correlation Analysis) ... 691
13.4.2 In-Situ Deformation Measurement with Atomic Force Microscopy (AFM) ... 693

Index ... 701