

Tim A. Osswald / Georg Menges

# Materials Science of Polymers for Engineers



Hanser Publishers, Munich Vienna New York

Hanser/Gardner Publications, Inc., Cincinnati

Fachbereich Materialwissenschaft  
der Techn. Hochschule Darmstadt

Inv.-Nr.: 1161

# Table of Contents

<b>Part I Basic Principles</b> .....	1
<b>1 Introduction to Polymers</b> .....	3
1.1 Historical Background.....	3
1.2 Statistical Data.....	6
1.3 General Properties.....	9
References.....	17
<b>2 Structure of Polymers</b> .....	19
2.1 Macromolecular Structure of Polymers.....	19
2.2 Molecular Bonds and Inter-Molecular Attraction.....	22
2.3 Molecular Weight.....	22
2.4 Conformation and Configuration of Polymer Molecules.....	28
2.5 Arrangement of Polymer Molecules.....	31
2.5.1 Thermoplastic Polymers.....	31
2.5.2 Amorphous Thermoplastics.....	32
2.5.3 Semi-Crystalline Thermoplastics.....	34
2.5.4 Thermosets and Cross-Linked Elastomers.....	43
2.6 Copolymers and Polymer Blends.....	45
2.7 Viscoelastic Behavior of Polymers.....	47
2.7.1 Stress Relaxation Test.....	47
2.7.2 Time-Temperature Superposition (WLF-Equation).....	48
2.7.3 The Boltzmann Superposition Principle.....	50
2.7.4 Applying Linear Viscoelasticity to Describe the Behavior of Polymers..	51
References.....	58
<b>3 Thermal Properties of Polymers</b> .....	59
3.1 Material Properties.....	60
3.1.1 Thermal Conductivity.....	60
3.1.2 Specific Heat.....	68
3.1.3 Density.....	71
3.1.4 Thermal Diffusivity.....	74
3.1.5 Linear Coefficient of Thermal Expansion.....	75
3.1.6 Thermal Penetration.....	76
3.1.7 Glass Transition Temperature.....	77
3.1.8 Melting Temperature.....	78
3.2 Measuring Thermal Data.....	78
3.2.1 Differential Thermal Analysis (DTA).....	78
3.2.2 Differential Scanning Calorimeter (DSC).....	80
3.2.3 Thermomechanical Analysis (TMA).....	82
3.2.4 Thermogravimetry (TGA).....	83

3.2.5	Density Measurements .....	83
	References.....	84
<b>Part II</b>	<b>Influence of Processing on Properties.....</b>	<b>85</b>
<b>4</b>	<b>Rheology of Polymer Melts.....</b>	<b>87</b>
4.1	Introduction.....	87
4.1.1	Continuum Mechanics .....	87
4.1.2	The Generalized Newtonian Fluid .....	89
4.1.3	Normal Stresses in Shear Flow .....	94
4.1.4	Deborah Number.....	96
4.2	Viscous Flow Models .....	98
4.2.1	The Power Law Model .....	98
4.2.2	The Bird-Carreau-Yasuda Model .....	100
4.2.3	The Bingham Fluid.....	101
4.2.4	Elongational Viscosity.....	101
4.2.5	Rheology of Curing Thermosets .....	103
4.2.6	Suspension Rheology .....	107
4.3	Viscoelastic Flow Models.....	108
4.3.1	Differential Viscoelastic Models .....	108
4.3.2	Integral Viscoelastic Models .....	111
4.4	Rheometry.....	116
4.4.1	The Melt Flow Indexer.....	116
4.4.2	The Capillary Viscometer .....	116
4.4.3	Computing Viscosity Using the Bagley and Weissenberg-Rabinowitsch Equations.....	119
4.4.4	Viscosity Approximation Using the Representative Viscosity Method.....	120
4.4.5	The Cone-Plate Rheometer.....	121
4.4.6	The Couette Rheometer.....	123
4.4.7	Extensional Rheometry .....	124
4.5	Surface Tension .....	127
	References.....	130
<b>5</b>	<b>Mixing of Polymer Blends, Solutions and Additives.....</b>	<b>133</b>
5.1	Mixing.....	134
5.1.1	Distributive Mixing.....	135
5.1.1.1	Effect of Orientation .....	137
5.1.1.2	Effect of Viscosity Ratios.....	140
5.1.2	Dispersive Mixing.....	142
5.1.2.1	Break-Up of Particulate Agglomerates .....	142
5.1.2.2	Break-Up of Fluid Droplets .....	144
5.1.3	Mixing Devices .....	148
5.1.3.1	Static Mixers.....	149
5.1.3.2	Banbury Mixer.....	150
5.1.3.3	Single Screw Extruders.....	152

5.1.3.4	Cokneader .....	156
5.1.3.5	Twin Screw Extruders .....	157
5.1.4	Energy Consumption During Mixing .....	160
5.1.5	Mixing Quality and Efficiency .....	161
5.2	Plasticization .....	163
5.3	Other Polymer Additives .....	169
5.3.1	Flame Retardants .....	169
5.3.2	Stabilizers .....	171
5.3.3	Antistatic Agents .....	172
5.3.4	Fillers .....	172
5.3.5	Blowing Agents .....	173
	References .....	173
<b>6</b>	<b>Anisotropy Development During Processing .....</b>	<b>177</b>
6.1	Orientation in the Final Part .....	177
6.1.1	Processing Thermoplastic Polymers .....	177
6.1.2	Processing Thermoset Polymers .....	185
6.2	Predicting Orientation .....	190
6.2.1	Planar Orientation Distribution Function .....	191
6.2.2	Single Particle Motion .....	193
6.2.3	Jeffery's Model .....	195
6.2.4	Folgar-Tucker Model .....	198
6.2.5	Tensor Representation of Fiber Orientation .....	199
	6.2.5.1 Predicting Orientation in Complex Parts Using Computer Simulation .....	201
6.3	Fiber Damage .....	207
	References .....	209
<b>7</b>	<b>Solidification of Polymers .....</b>	<b>211</b>
7.1	Solidification of Thermoplastics .....	211
7.1.1	Thermodynamics During Cooling .....	211
7.1.2	Morphological Structure .....	214
7.1.3	Crystallization .....	215
7.1.4	Heat Transfer During Solidification .....	218
7.2	Solidification of Thermosets .....	223
7.2.1	Curing Reaction .....	223
7.2.2	Cure Kinetics .....	225
7.2.3	Heat Transfer During Cure .....	227
7.3	Residual Stresses and Warpage of Polymeric Parts .....	229
7.3.1	Residual Stress Models .....	231
	7.3.1.1 Residual Stress Model Without Phase Change Effects .....	235
	7.3.1.2 Model to Predict Residual Stresses with Phase Change Effects .....	235
7.3.2	Other Simple Models to Predict Residual Stresses and Warpage .....	239
	7.3.2.1 Uneven Mold Temperature .....	240
	7.3.2.2 Residual Stress in a Thin Thermoset Part .....	241

7.3.2.3 Residual Stress and Warpage in a Laminated Composite Plate.....	242
7.3.2.4 Anisotropy Induced Curvature Change.....	244
7.3.3 Predicting Warpage in Actual Parts.....	245
References.....	248

## Part III Engineering Design Properties ..... 251

<b>8 Mechanical Behavior of Polymers.....</b>	<b>253</b>
8.1 Basic Concepts of Stress and Strain .....	253
8.1.1 Plane Stress .....	254
8.1.2 Plane Strain .....	255
8.2 The Short-Term Tensile Test.....	255
8.2.1 Rubber Elasticity .....	255
8.2.2 The Tensile Test and Thermoplastic Polymers .....	260
8.3 Long-Term Tests.....	271
8.3.1 Isochronous and Isometric Creep Plots .....	274
8.4 Dynamic Mechanical Tests.....	276
8.4.1 Torsion Pendulum.....	276
8.4.2 Sinusoidal Oscillatory Test .....	280
8.5 Viscoelastic Behavior of Polymers.....	281
8.5.1 Kelvin Model .....	281
8.5.1.1 Creep Response .....	282
8.5.1.2 Stress Relaxation .....	283
8.5.1.3 Strain Recovery .....	283
8.5.1.4 Dynamic Response.....	284
8.5.2 Jeffrey Model.....	284
8.5.2.1 Creep Response .....	285
8.5.2.2 Stress Relaxation .....	286
8.5.2.3 Strain Recovery .....	286
8.5.3 Standard Linear Solid Model.....	287
8.5.3.1 Creep Response .....	288
8.5.3.2 Stress Relaxation .....	288
8.5.4 Maxwell-Wiechert Model.....	289
8.5.4.1 Stress Relaxation .....	290
8.5.4.2 Dynamic Response.....	291
8.6 Effects of Structure and Composition on Mechanical Properties .....	291
8.6.1 Amorphous Thermoplastics.....	292
8.6.2 Semi-Crystalline Thermoplastics.....	294
8.6.3 Oriented Thermoplastics .....	296
8.6.4 Cross-Linked Polymers .....	302
8.7 Mechanical Behavior of Filled and Reinforced Polymers .....	304
8.7.1 Anisotropic Strain-Stress Relation.....	306
8.7.2 Aligned Fiber Reinforced Composite Laminates.....	307
8.7.3 Transformation of Fiber Reinforced Composite Laminate Properties .....	310

8.7.4	Reinforced Composite Laminates with a Fiber Orientation Distribution Function.....	312
8.8	Strength Stability Under Heat.....	313
	References.....	315
<b>9</b>	<b>Failure and Damage of Polymers.....</b>	<b>317</b>
9.1	Fracture Mechanics.....	317
9.1.1	Fracture Predictions Based on the Stress Intensity Factor.....	317
9.1.2	Fracture Predictions Based on an Energy Balance.....	319
9.1.3	Linear Viscoelastic Fracture Predictions Based on J-Integrals.....	322
9.2	Short-Term Tensile Strength.....	324
9.2.1	Brittle Failure.....	324
9.2.2	Ductile Failure.....	329
9.2.3	Failure of Highly Filled Systems or Composites.....	333
9.3	Impact Strength.....	336
9.3.1	Impact Test Methods.....	343
9.3.2	Fracture Mechanics Analysis of Impact Failure.....	349
9.4	Creep Rupture.....	353
9.4.1	Creep Rupture Tests.....	353
9.4.2	Fracture Mechanics Analysis of Creep Rupture.....	357
9.5	Fatigue and Wear.....	357
9.5.1	Fatigue Test Methods.....	358
9.5.2	Fracture Mechanics Analysis of Fatigue Failure.....	367
9.6	Friction and Wear.....	368
9.7	Environmental Effects on Polymer Failure.....	372
9.7.1	Weathering.....	372
9.7.2	Chemical Degradation.....	377
9.7.3	Thermal Degradation of Polymers.....	379
	References.....	381
<b>10</b>	<b>Electrical Properties of Polymers.....</b>	<b>383</b>
10.1	Dielectric Behavior.....	383
10.1.1	Dielectric Coefficient.....	383
10.1.2	Mechanisms of Dielectrical Polarization.....	386
10.1.3	Dielectric Dissipation Factor.....	390
10.1.4	Implications of Electrical and Thermal Loss in a Dielectric.....	394
10.2	Electric Conductivity.....	394
10.2.1	Electric Resistance.....	394
10.2.2	Physical Causes of Volume Conductivity.....	396
10.3	Application Problems.....	398
10.3.1	Electric Breakdown.....	398
10.3.2	Electrostatic Charge.....	402
10.3.3	Electrets.....	403
10.3.4	Electromagnetic Interference Shielding (EMI Shielding).....	404
10.4	Magnetic Properties.....	404

---

10.4.1 Magnetizability.....	404
10.4.2 Magnetic Resonance .....	405
References.....	406
<b>11 Optical Properties of Polymers .....</b>	<b>407</b>
11.1 Index of Refraction .....	407
11.2 Photoelasticity and Birefringence.....	410
11.3 Transparency, Reflection, Absorption and Transmittance.....	414
11.4 Gloss.....	420
11.5 Color.....	422
11.6 Infrared Spectroscopy .....	424
11.7 Infrared Pyrometry.....	426
11.8 Heating with Infrared Radiation.....	428
References.....	430
<b>12 Permeability Properties of Polymers.....</b>	<b>431</b>
12.1 Sorption.....	431
12.2 Diffusion and Permeation.....	433
12.3 Measuring S, D and P.....	439
12.4 Corrosion of Polymers and Cracking.....	440
12.5 Diffusion of Polymer Molecules and Self-Diffusion.....	443
References.....	444
<b>13 Acoustic Properties of Polymers.....</b>	<b>445</b>
13.1 Speed of Sound.....	445
13.2 Sound Reflection.....	447
13.3 Sound Absorption .....	448
References.....	450
<b>Appendix.....</b>	<b>451</b>
<b>Subject Index.....</b>	<b>463</b>
<b>Author Index.....</b>	<b>471</b>