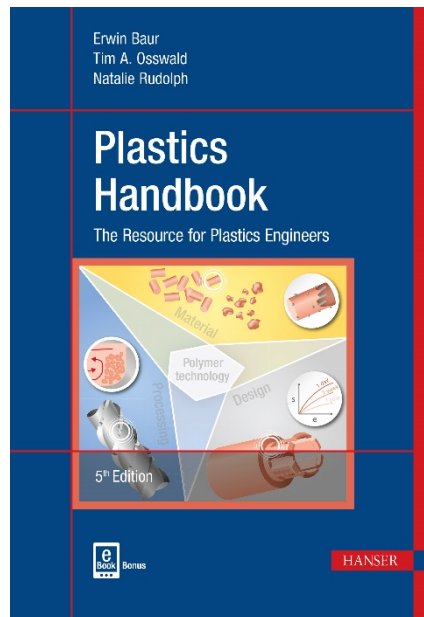


HANSER



Sample Pages

Plastics Handbook

Erwin Baur, Tim A. Osswald, Natalie Rudolph

ISBN (Book): 978-1-56990-559-3

ISBN (E-Book): 978-1-56990-560-9

For more information and to order visit

www.hanserpublications.com (in the Americas)

www.hanser-fachbuch.de (outside the Americas)

© Carl Hanser Verlag, München

Preface

This new and completely reworked edition of the *Plastics Handbook* finds its roots in the German Plastics Handbook (*Saechtling Kunststoff Taschenbuch*), first published in 1936, and now in its 31st edition. After years of working back and forth between the German and English language editions, updating the processing and materials chapters as well as upgrading the figures into color, we have finally achieved two synchronized handbooks, each designed for their specific geographical market. We realize that the plastics field is constantly in flux, with changes driven by major factors such as energy conservation, new materials, and new manufacturing techniques, such as additive manufacturing. Therefore, we know that this handbook is a never-ending project that will organically change over time. We look forward to the developments our industry will bring in the years to come, and to the work we will do together to bring you the next version of this handbook. It would have been impossible to produce this new edition without the irreplaceable contributions from Dr. Christine Strohm who helped with the translations, as well as those from Tobias Mattner who reworked all the figures. We thank both for their steadfast dedication. We are also thankful to Dr. Mark Smith for his meticulous work while combing through the whole manuscript and to Jörg Strohbach for his production work to generate a version that is so pleasing to the eye. We are grateful to our families for their unconditional love and support.

Winter 2018

Erwin Baur, Tim A. Osswald, and Natalie Rudolph

Contents

Preface	V
1 Common Acronyms in Plastics Technology	1
1.1 Table I: Alphabetical List of Plastics Acronyms, Chemical Notation ..	2
1.2 Table II: Common Units, ISO- and US-Units	9
2 Introduction	13
2.1 Economic Significance of Plastics	13
2.2 Classification of Plastics	15
2.3 Composition of Plastics	18
2.3.1 Chemical Structure (Constitution and Configuration of Macromolecules)	18
2.3.1.1 Conformation	19
2.3.1.2 Configuration	19
2.3.1.3 Constitution	21
2.3.1.4 Major Plastic Material Groups	25
2.3.2 Morphological Structure (Conformation and Aggregation of Macromolecules)	27
2.3.2.1 Different Classes of Plastic Materials	33
2.4 Effects of Processing on Material Properties	35
2.4.1 Residual Stress	36
2.4.2 Molecular Orientation	37
2.4.3 Crystallization Behavior	38
2.5 Modifications of Plastic Materials	40
2.5.1 Copolymers and Polymer Blends	40
2.5.2 Plastic Composites	41
3 Material Properties and Testing Methods	45
3.1 Significance of Characteristic Values	46

3.2	Processing Characteristics	52
3.2.1	Rheological Behavior	52
3.2.1.1	Flow Behavior, Viscosity	52
3.2.1.2	Viscosity Models	58
3.2.1.3	Melt Volume Flow Rate (MVR) and Melt Mass Flow Rate (MFR)	60
3.2.2	Solidification Behavior	60
3.2.2.1	Sealing Time	60
3.2.2.2	Shrinkage	61
3.2.2.3	Warpage	66
3.2.2.4	Tolerances	67
3.2.2.5	Filler Orientation	67
3.3	Mechanical Properties	69
3.3.1	Short-Term Behavior	69
3.3.1.1	Accelerated Tensile Test	69
3.3.1.2	Short-Term Bend Test	72
3.3.1.3	Compression Test	74
3.3.1.4	Indentation Test, Hardness Measurements	74
3.3.2	Impact Behavior	75
3.3.2.1	Characteristics	75
3.3.2.2	Impact, Flexural, and Tensile Tests According to CAMPUS	77
3.3.3	Static Long-Term Behavior	79
3.3.3.1	Tensile Creep Tests	79
3.3.3.2	Internal Pressure Creep Rupture Tests for Pipes	83
3.3.4	Dynamic Long-Term Behavior	84
3.3.5	Moduli and Poisson's Ratio	86
3.3.6	Density	89
3.4	Thermal Properties	90
3.4.1	Permissible Service Temperatures	90
3.4.1.1	Effect of Short-Term Temperature Influence	90
3.4.1.2	Effect of Long-Term Temperature Influence	97
3.4.2	Specific Heat Capacity, Specific Enthalpy, Heat Value	98
3.4.3	Thermal Conductivity	100
3.4.4	Thermal Effusivity	103
3.4.5	Thermal Diffusivity	104
3.4.6	Coefficient of Thermal Expansion	104
3.5	Electrical Properties	111
3.5.1	Electrical Insulation Properties	113
3.5.1.1	Volume Resistivity/Conductivity	113
3.5.1.2	Surface Resistivity	115

3.5.1.3	Electromagnetic Shielding	116
3.5.2	Dielectric Properties	117
3.5.2.1	Dielectric Strength	117
3.5.2.2	Long-Term Dielectric Strength	119
3.5.2.3	Tracking Index	120
3.5.2.4	Arc Resistance	121
3.5.2.5	Electrolytic Corrosion	121
3.5.3	Dielectric Behavior	121
3.5.4	Electrostatic Behavior	123
3.5.5	Conductive Plastics	123
3.6	Optical Behavior	125
3.6.1	Transparency	125
3.6.2	Gloss, Reflection, and Haze	126
3.6.3	Color	127
3.6.3.1	Fundamentals	127
3.6.3.2	Colorimetry	127
3.6.4	Index of Refraction, Birefringence	129
3.6.5	Surface Texture	132
3.7	Resistance to Environmental Influences	133
3.7.1	Water, Moisture	135
3.7.2	Chemical Resistance	139
3.7.3	Stress Cracking Resistance	139
3.7.4	Weathering	142
3.7.5	High-Energy Radiation	142
3.7.6	Resistance to Organisms	143
3.7.7	Migration and Permeation	144
3.7.7.1	Water Vapor Permeability	145
3.7.7.2	Gas Permeability	147
3.7.7.3	Water Vapor Diffusion Resistance	151
3.7.8	Fire Behavior	151
3.8	Friction and Wear Behavior	154
3.8.1	Friction	154
3.8.1.1	Friction Mechanisms	154
3.8.1.2	Stick-Slip Effect	155
3.8.2	Wear	156
3.8.3	Specimens and Testing Systems	157
3.8.4	Tribological Properties of Thermoplastics	158
3.9	Analytical Evaluations	162
3.9.1	Infrared (IR)- and Raman Spectroscopy	162
3.9.2	Nuclear Magnetic Resonance (NMR)	163
3.9.3	Dynamic-Mechanical Spectroscopy (DMA)	163

3.9.4	Dielectric Spectroscopy (DEA)	164
3.9.5	Differential Thermal Analysis (DTA) and Differential Calorimetry (DSC)	166
3.9.6	Thermogravimetric Analysis (TGA)	167
3.9.7	Dilatometry, Thermomechanical Analysis (TMA), Specific Volume (pvT)	168
3.9.8	Thermal Conductivity	171
3.9.9	Solution Viscosimetry	172
3.9.10	Chromatography	173
4	Plastic Processing Technologies	177
4.1	Compounding	178
4.1.1	Mixing Processes	179
4.1.1.1	Mixing Devices	181
4.1.1.2	Screw-Type Mixers for Viscous Materials	183
4.1.1.3	Other Mixers for Viscous Materials	189
4.1.2	Pelletizers	191
4.1.3	Mills, Granulators, or Pulverizers	193
4.1.4	Dryers	194
4.1.5	Compounding of Thermosetting Materials	196
4.1.6	Compounding of Recycled Materials	197
4.2	Extrusion	197
4.2.1	Extruder Concepts	197
4.2.1.1	Single-Screw Extruder	198
4.2.1.2	Grooved-Barrel Extruder	200
4.2.1.3	Barrier Screws	201
4.2.1.4	Degassing Extruders	201
4.2.1.5	Cascade- or Tandem Extruders	202
4.2.1.6	High-Speed Extruders (Adiabatic Extruders)	203
4.2.1.7	Planetary Gear Extruders	203
4.2.1.8	Twin-Screw Extruders	203
4.2.2	Auxiliary Devices for Extruders	204
4.2.3	Extrusion Dies and Subsequent Devices	205
4.2.3.1	Pipes and Symmetrical Hollow Profiles	205
4.2.3.2	Solid Profiles	205
4.2.3.3	Hollow Chamber Profiles	206
4.2.3.4	Sheathing	206
4.2.3.5	Sheets and Flat Films	207
4.2.3.6	Blown (Tubular) Film	209
4.2.3.7	Foamed Semi-Finished Products and Profiles	210
4.2.3.8	Monofilaments, Tapes, Fibers	211

4.2.3.9	Co- and Multi-Layer Extruded Products	212
4.2.3.10	Multi-Layer Films	214
4.2.4	Calendered Films	216
4.2.5	Extrusion Blow Molding of Hollow Parts with Variable Cross Sections	219
4.3	Injection Molding	221
4.3.1	The Injection Molding Process	222
4.3.2	Design of Injection Molding Machines	227
4.3.2.1	Clamping Unit	227
4.3.2.2	All-Electric Injection Molding Machines	228
4.3.2.3	Plasticizing Unit	228
4.3.3	Injection Molding – General Information	231
4.3.4	Cleaning of Screws and Barrels	234
4.3.5	Special Injection Molding Processes	234
4.3.5.1	Injection Compression Molding	235
4.3.5.2	Powder Injection Molding	235
4.3.5.3	Micro-Injection Molding	236
4.3.5.4	Injection Molding with Multiple Injection Units	236
4.3.5.5	Fluid Injection Technology	240
4.3.5.6	Foam Injection Molding	242
4.3.5.7	Injection Molding with Inserts	242
4.3.6	Injection Blow Molding	245
4.3.6.1	Stretch Blow Molding	245
4.4	Molds	246
4.4.1	General Introduction to Mold Design	246
4.4.2	Injection Molds and Sprue Types	248
4.4.3	Mold Standards	253
4.5	Foaming	254
4.5.1	Principles of Foaming	255
4.5.2	Manufacturing of Particle Foam	256
4.5.3	In-Mold Skinning	256
4.6	Casting	257
4.7	Polyurethane (PUR) Processing Technology	257
4.7.1	General Principles	257
4.7.2	Manufacturing Steps	259
4.7.2.1	Low- and High-Pressure Machines	260
4.7.2.2	Spraying Machines	264
4.7.2.3	Production Line Layouts	264
4.7.2.4	Continuous Manufacturing	264
4.7.2.5	Batch Manufacturing	266

	4.7.2.6	Manufacturing of Fiber-Reinforced Components . .	267
	4.7.2.7	Cleaning	268
4.8		Manufacturing of Fiber-Reinforced Plastics	268
	4.8.1	Short-Fiber Reinforced Composites	270
		4.8.1.1 Injection Molding	270
		4.8.1.2 Bulk Molding Compounds	270
	4.8.2	Long-Fiber Reinforced Composites	271
		4.8.2.1 Sheet Molding Compound	271
		4.8.2.2 Glass Mat-Reinforced Thermoplastics	273
		4.8.2.3 Long Fiber-Reinforced Thermoplastics	274
	4.8.3	Low Volume Liquid Composite Molding	275
		4.8.3.1 Manual Techniques	275
		4.8.3.2 Vacuum-Assisted Resin Infusion	275
	4.8.4	High Volume Liquid Composite Molding	276
		4.8.4.1 Resin Transfer Molding	277
		4.8.4.2 Vacuum Assisted Resin Transfer Molding	277
		4.8.4.3 Compression Resin Transfer Molding	278
		4.8.4.4 Structural Reaction Injection Molding	278
	4.8.5	Filament Winding	279
	4.8.6	Pultrusion	281
	4.8.7	Prepreg Layup	282
		4.8.7.1 Prepregging	282
		4.8.7.2 Automated Tape Layup	283
4.9		Compression Molding	284
	4.9.1	Laminating	286
	4.9.2	Extrusion Molding	288
	4.9.3	Transfer Molding	288
4.10		Additive Manufacturing	289
	4.10.1	Powder Bed Fusion (PBF)	291
	4.10.2	Material Extrusion (ME)	293
	4.10.3	Vat Photo-Polymerization (VP)	294
	4.10.4	Material Jetting (MJ)	295
	4.10.5	Binder Jetting	295
	4.10.6	Sheet Lamination	296
	4.10.7	Rapid Tooling (RT)	297
4.11		Secondary Shaping	298
	4.11.1	Bending	298
	4.11.2	Mechanical Forming	300
	4.11.3	Pressure Forming	301
4.12		Plastic Joining	303

4.12.1	Plastic Welding	303
4.12.1.1	Heated Tool Welding with Contact Heating	304
4.12.1.2	Heated Tool Welding with Non-Contact Heating	305
4.12.1.3	Hot Gas Welding	306
4.12.1.4	Friction Welding, Ultrasonic Welding	309
4.12.1.5	Radio-Frequency Welding	313
4.12.1.6	Implant Induction Welding	314
4.12.1.7	Laser Welding	315
4.12.2	Adhesive Joining of Plastics	317
4.12.2.1	Examples of Adhesive Bonds	318
4.12.3	Screws, Rivets, Snap-Fits	319
4.13	Surface Treatments	319
4.13.1	Pre-Treatment of Surfaces	319
4.13.1.1	Wet Chemical Treatments	320
4.13.1.2	Vapor Phase Treatment	320
4.13.1.3	Flame Oxidation	320
4.13.1.4	Radiation Treatment	320
4.13.1.5	Corona Treatment	321
4.13.1.6	Plasma Treatment	321
4.13.1.7	Mechanical Pre-Treatment	322
4.13.2	Polishing	322
4.13.3	Coating	322
4.13.4	Printing, Labeling, Decorating	324
4.13.5	Embossing, Hot-Embossing/Stamping	326
4.13.6	Flock-Coating/Flocking	326
4.13.7	Metallization of Film	327
4.13.8	Metallization of Molded Components	328
4.13.9	SiO _x -Coating of Films	329
4.13.10	Rubbing	329
4.13.11	Fluorination, Gas-Phase Fluorination	329
4.13.12	Plasma Polymerization/Chemical Vapor Deposition (CVD)	329
4.13.13	Thermal Spraying	330
4.14	Other Treatment Processes	331
4.14.1	Machining	331
4.14.2	Cutting, Machining	333
4.14.3	Radiation Crosslinking	334
4.14.4	Heat Treatment	334
4.14.5	Elimination of Electrostatic Charges	335
4.15	Recycling	335

5	Plastic Materials	337
5.1	General Remarks	337
5.2	Polyolefins (PO), Polyolefin Derivatives and Copolymers	337
5.2.1	Polyethylene Standard Homo- and Copolymers (PE-LD, PE-HD, PE-HD-HMW, PE-HD-UHMW, and PE-LLD) ..	338
5.2.1.1	Polymerization, Chemical Constitution	338
5.2.1.2	Processing	340
5.2.1.3	Post-Processing Treatment	341
5.2.1.4	Properties	342
5.2.1.5	Applications	345
5.2.2	Polyethylene Derivatives (PE-X)	346
5.2.3	Chlorinated and Chloro-Sulfonated PE (PE-C, CSM)	348
5.2.4	Ethylene Copolymers (PE-ULD, EVAC, EVAL, EEA, EB, EBA, EMA, EAA, E/P, EIM, COC, ECB, ETFE)	348
5.2.4.1	Ultra-Light Polyethylene (PE-ULD, PE-VLD)	355
5.2.4.2	Ethylene Vinyl Acetate Copolymers (EVAC)	355
5.2.4.3	Ethylene Vinyl Alcohol Copolymers (EVAL)	357
5.2.4.4	Ethylene Acrylic Copolymers (EEA, EBA, EAA, EAMA, EMA)	358
5.2.4.5	PE α -Olefin Copolymers (PE α -PO-(M))	358
5.2.4.6	Cycloolefin Copolymers (COC, COP)	358
5.2.4.7	Ionomers (EIM)	359
5.2.4.8	Ethylene Copolymer Bitumen Blends (ECB, ECB/TPO)	360
5.2.5	Polypropylene Homopolymers (PP, PP-H)	360
5.2.5.1	Chemical Constitution, Polymerization	361
5.2.5.2	Processing	362
5.2.5.3	PP Foams (PP-E)	362
5.2.5.4	Post-Processing Treatments	362
5.2.5.5	Properties	363
5.2.5.6	Applications	366
5.2.6	Polypropylene Copolymers and Derivatives, Blends (PP-C, PP-B, EPDM, PP+EPDM)	366
5.2.6.1	Chlorinated PP (PP-C)	367
5.2.6.2	PP Copolymers (PP-B)	367
5.2.6.3	Ethylene-Propylene (Diene) Copolymers (EPDM) ..	367
5.2.6.4	PP+EPDM Elastomer Blends	368
5.2.6.5	Polypropylene Blends	368
5.2.7	Polypropylene, Special Grades	369
5.2.8	Polybutene (PB, PIB)	370
5.2.8.1	Polybutene-1 (PB)	371

5.2.8.2	Polyisobutene (PIB)	372
5.2.9	Higher Poly-(α -Olefins) (PMP, PDCPD)	373
5.2.9.1	Poly-4-Methylpentene-1 (PMP)	373
5.2.9.2	Polydicyclopentadiene (PDCPD)	374
5.3	Styrene Polymers	375
5.3.1	Polystyrene, Homopolymers (PS, PMS)	375
5.3.1.1	Polystyrene, PS; Poly-p-Methylstyrene (PPMS); Poly- α -Methylstyrene (PMS)	375
5.3.2	Polystyrene, Copolymers, Blends	376
5.3.2.1	Chemical Composition	376
5.3.2.2	Processing	377
5.3.2.3	Properties	377
5.3.3	Polystyrene Foams (PS-E, XPS)	384
5.4	Vinyl Polymers	385
5.4.1	Rigid Polyvinyl Chloride Homopolymers (PVC-U)	385
5.4.1.1	Chemical Composition	385
5.4.1.2	Delivery Forms, Processing	385
5.4.1.3	Identification	387
5.4.1.4	Properties and Applications	388
5.4.2	Plasticized Polyvinyl Chloride (PVC-P)	392
5.4.2.1	Chemical Composition	392
5.4.2.2	Delivery Forms, Processing	392
5.4.2.3	Plasticizers	393
5.4.2.4	Properties and Applications	395
5.4.3	Polyvinyl Chloride: Copolymers and Blends	397
5.4.4	Polyvinyl Chloride: Pastes, Plastisols, Organosol, Foams	398
5.4.4.1	Pastes, Plastisols, Organosol	398
5.4.4.2	Foams	399
5.4.5	Vinyl Polymers, Other Homo- and Copolymers (PVDC, PVAC, PVAL, PVME, PVFM, PVB, PVK, PVP)	399
5.4.5.1	Polyvinylidene Chloride (PVDC)	399
5.4.5.2	Polyvinyl Acetate (PVAC)	399
5.4.5.3	Polyvinyl Alcohol (PVAL)	400
5.4.5.4	Polyvinyl Methyl Ether (PVME)	400
5.4.5.5	Polyvinyl Butyral, Polyvinyl Formal (PVB, PVFM)	400
5.4.5.6	Polyvinyl Carbazole (PVK)	400
5.4.5.7	Polyvinyl Pyrrolidone and Copolymers (PVP)	401
5.5	Fluoro Polymers	401
5.5.1	Fluoro Homopolymers (PTFE, PVDF, PVF, PCTFE)	401
5.5.1.1	Polytetrafluoroethylenes (PTFE)	404
5.5.1.2	Polyvinylidene Fluoride (PVDF)	405

5.5.1.3	Polyvinyl Fluoride (PVF)	406
5.5.1.4	Polychlorotrifluoroethylene (PCTFE)	406
5.5.2	Fluoro-Copolymers and Elastomers (ECTFE, ETFE, FEP, TFEP, PFA, AF, PTFEAF, TFEHFPVDF (THV, TFB), [FKM, FPM, FFKM])	407
5.5.2.1	Ethylene Chlorotrifluoroethylene Copolymers (ECTFE)	407
5.5.2.2	Ethylene Tetrafluoroethylene Copolymers (ETFE) . .	408
5.5.2.3	Polyfluoroethylene Propylene (FEP); Tetrafluoro- ethylene Hexafluoropropylene Copolymers (TFEP)	408
5.5.2.4	Perfluoropropyl Vinyl Ether Copolymer, Perfluoroalkoxy (PFA)	408
5.5.2.5	PTFE Copolymers with AF (PTFEAF)	409
5.5.2.6	Tetrafluoroethylene Hexafluoropropylene Vinylidene Fluoride Terpolymers (TFEHFPVDF (THV, TFB))	409
5.5.2.7	Other Fluoro Copolymers	410
5.6	Polyacrylic- and Methacrylic Polymers	410
5.6.1	Polyacrylates, Homo- and Copolymers (PAA, PAN, PMA, PBA)	410
5.6.1.1	Polyacrylonitrile (PAN)	410
5.6.1.2	Polyacrylates, Special Products	410
5.6.2	Polymethacrylates, Homo- and Copolymers (PMMA, AMMA, MABS, MBS)	411
5.6.2.1	Polymethylmethacrylate (PMMA)	411
5.6.2.2	Methyl Methacrylate Copolymers (AMMA)	415
5.6.2.3	Methyl Methacrylate Acrylonitrile Butadiene Styrene Copolymers (MABS); Methacrylate Butadiene Styrene Copolymers (MBS)	416
5.6.3	Polymethacrylates, Modifications and Blends (PMMI, PMMA-HI, MMA-EML Copolymers, PMMA+ABS) . . .	416
5.6.3.1	Polymethacrylmethylimide (PMMI)	416
5.6.3.2	Impact Resistant PMMA (PMMA-HI)	417
5.6.3.3	Methyl Methacrylate Exo-Methylene Lactone Copolymers (MMA-EML-Copol., MMAEML)	418
5.6.3.4	PMMA+ABS	418
5.7	Polyoxymethylenes (Polyacetal, Polyformaldehyde) (POM)	418
5.7.1	Polyoxymethylene Homo- and Copolymers (POM-H, POM-C)	418
5.7.2	Polyoxymethylene, Modifications and Blends (POM+TPU) . . .	427
5.8	Polyamides (PA)	430

5.8.1	Polyamides, Homopolymers (AB and AA/BB Polymers); (PA 6, 11, 12, 46, 66, 69, 610, 612 (PA 7, 8, 9, 1313, 613))	430
5.8.1.1	Chemical Composition	430
5.8.1.2	Properties	438
5.8.1.3	Processing	440
5.8.1.4	Applications	443
5.8.2	Modifications	446
5.8.3	Copolyamides	450
5.8.3.1	Semi-Aromatic, Semi-Crystalline Copolyamides (Polyphthalamides, PPA)	453
5.8.3.2	Semi-Aromatic, Amorphous Copolyamides	453
5.8.3.3	Elastomeric Block Copolyamides (Polyether Block Amides, PEBA)	454
5.8.4	Cast Polyamides (PA6-C, PA12-C)	455
5.8.5	Polyamides for Reaction Injection Molding (PA-RIM)	455
5.8.6	Aromatic Polyamides, Aramids	455
5.9	Aromatic (Saturated) Polyesters	456
5.9.1	Polycarbonates (PC)	456
5.9.1.1	Polycarbonates Based on Bisphenol A (PC)	456
5.9.1.2	Polycarbonate Copolymers	461
5.9.1.3	Blends	462
5.9.2	Polyesters of Terephthalic Acid, Block Copolymers	464
5.9.2.1	Polyethylene Terephthalate (PET)	464
5.9.2.2	Polybutylene Terephthalate (PBT)	470
5.9.2.3	Cyclic Polybutylene Terephthalates (CBT)	471
5.9.2.4	Polytrimethylene Terephthalates (PTT)	472
5.9.2.5	Thermoplastic Polyester Elastomers (TPC)	472
5.9.2.6	Polyterephthalate Blends (PET+: PBT, MBS, PMMA, PSU, Elastomer)	472
5.9.3	Polyesters of Aromatic Diols and Carboxylic Acids (PAR, PBN, PEN)	472
5.9.3.1	Polyarylates (PAR)	472
5.9.3.2	Polybutylene Naphthalates (PBN)	474
5.9.3.3	Polyethylene Naphthalates (PEN)	474
5.10	Aromatic Polysulfides and Polysulfones (PPS, PSU, PES, PPSU)	475
5.10.1	Polyphenylene Sulfides (PPS)	475
5.10.2	Polyaryl Ether Sulfones (PAES, PSU, PSU+ABS, PES, PPSU)	478
5.11	Aromatic Polyethers, Polyphenylene Ethers, and Blends (PPE)	480
5.12	Aliphatic Polyesters (Polyglycols) (PEOX, PPOX, PTHF)	483
5.13	Poly(aryl)ether Ketones (Aromatic Polyether Ketones) (PAEK; PEK; PEEK; PEKEEK; PEKK)	483

5.14	Aromatic Polyimides (PI)	487
5.14.1	Thermosetting Polyimides (PI, PBMI, PBI, PBO, and Others) .	488
5.14.1.1	Polyimides (PI)	488
5.14.1.2	Polybismaleinimides (PBMI)	493
5.14.1.3	Polybenzimidazoles (PBI)	493
5.14.1.4	Polytriazines	493
5.14.2	Thermoplastic Polyimides (PAI, PEI, PISO, PMI, PMMI, PESI, PARI)	494
5.14.2.1	Polyamide Imides (PAI)	494
5.14.2.2	Polyetherimides (PEI)	495
5.14.2.3	Polyimide Sulfones (PISO)	495
5.14.2.4	Polymethacrylimides (PMI, Rigid Foams)	496
5.14.2.5	Polymethacrylate Methylimides (PMMI)	497
5.14.2.6	Polyesterimides (PESI)	497
5.15	Self-Reinforcing Liquid Crystalline Polymers (LCP)	497
5.15.1	Chemical Constitution	497
5.15.2	Processing	498
5.15.3	Properties	499
5.15.4	Applications	499
5.16	Ladder Polymers: Two-Dimensional Polyaromates and -Heterocyclenes	500
5.17	Polyurethanes (PUR)	503
5.17.1	Fundamentals	503
5.17.1.1	Chemical Constitution	503
5.17.1.2	Manufacture of the Polymer	505
5.17.1.3	Flammability	506
5.17.1.4	Raw Material Handling, Safety	506
5.17.1.5	Environmental Protection, Safety, and Recycling ..	507
5.17.2	Raw Materials and Additives	507
5.17.2.1	Di- and Polyisocyanates	508
5.17.2.2	Polyols, Polyamines	508
5.17.2.3	Crosslinking Agents and Chain Extenders	509
5.17.2.4	Additives	509
5.17.3	PUR Polymers	511
5.17.3.1	Flexible Foams (PUR-F)	512
5.17.3.2	Rigid Foams (PUR-R)	515
5.17.3.3	Integral Foams (PUR-I)	515
5.17.3.4	Solid PUR Polymers, PUR-S	518
5.18	Biopolymers and Derivatives	519
5.18.1	Cellulose- and Starch-Derivatives; CA, CTA, CP, CAP, CAB, CN, EC, MC, CMC, CH, VF, PSAC	520

5.18.1.1	Chemical Constitution	520
5.18.1.2	Processing	521
5.18.1.3	Properties, Applications	522
5.18.2	Polyhydroxy Fatty Acids/Polyhydroxyalkanoates (PHA)	526
5.18.3	Casein Polymers, Casein Formaldehyde, Artificial Horn (CS, CSF)	526
5.18.4	Poly lactides, Polylactic Acids (PLA)	526
5.18.5	Electrically Conductive/Luminescent Polymers	527
5.18.6	Aliphatic Polyketones (PK)	530
5.19	Thermoplastic Elastomers (TPE)	532
5.19.1	Physical Constitution	533
5.19.2	Chemical Constitution, Properties, Applications	533
5.19.2.1	Copolyamides (TPA)	535
5.19.2.2	Copolyesters (TPC)	535
5.19.2.3	Polyolefin Elastomers (TPO)	536
5.19.2.4	Polystyrene Elastomers (TPS)	536
5.19.2.5	Polyurethane Elastomers (TPU)	537
5.19.2.6	Polyolefin Blends with Crosslinked Rubber (TPV) .	538
5.19.2.7	Other TPEs, TPZs	538
5.20	Thermosets, Curable Resins, Formaldehyde Molding Resins (PF, RF, CF, XF, FF, MF, UF, MUF, MUPF), Other Resins (UP, VE (PHA), EP, PDAP, SI)	538
5.20.1	Chemical Constitution	539
5.20.1.1	Formaldehyde Molding Resins (PF, RF, CF, XF, FF, MF, UF, MUF, MUPF)	539
5.20.1.2	Unsaturated Polyester Resins (UP)	541
5.20.1.3	Vinyl Ester Resins (VE); Phenyl Acrylate Resins; Vinyl Ester Urethanes (VU)	542
5.20.1.4	Epoxy Resins (EP)	542
5.20.1.5	Diallyl Phthalate Resins, Allyl Esters (PDAP)	544
5.20.1.6	Silicone Resins (Si)	544
5.20.2	Processing, Forms of Delivery	544
5.20.3	Properties	546
5.20.3.1	General Properties	546
5.20.3.2	Phenoplastic Molding Compounds (PF, CF, RF, XF)	547
5.20.3.3	Aminoplastic Molding Compounds (UF, MF)	548
5.20.3.4	Melamine Phenolic Molding Compounds (MPF) ...	549
5.20.3.5	Melamine Polyester Resin Molding Compounds (MF+UP)	550
5.20.3.6	Polyester Resin Molding Compounds (UP)	550

5.20.3.7	Vinyl Ester Molding Compounds (VE)	550
5.20.3.8	Epoxy Resin Molding Compounds (EP)	551
5.20.3.9	Diallyl Phthalate Molding Compounds (PDAP)	551
5.20.3.10	Silicone Resin Molding Compounds (SI)	551
5.20.4	Applications	551
5.20.4.1	Phenoplastic Molding Compounds (PF, RF, CF, XF, FF)	551
5.20.4.2	Aminoplastic Molding Compounds (MF, UF, MPF)	554
5.20.4.3	Unsaturated Polyester Resin Molding Compounds (UP)	555
5.20.4.4	Epoxide Resin Molding Compounds (EP)	556
5.20.4.5	Diallyl Phthalate Molding Compounds (PDAP)	556
5.20.4.6	Silicone Molding Compounds (SI)	557
5.21	Curable Casting and Laminating Resins	557
5.21.1	Phenoplastics (PF, CF, RF, XF)	557
5.21.1.1	Phenolic- (PF), Cresol- (CF), Resorcinol- (RF), Xylenol-Formaldehyde Resins (XF)	557
5.21.2	Aminoplastics (UF, MF)	558
5.21.2.1	Urea (UF), Melamine Formaldehyde Resins (MF)	558
5.21.3	Furan Resins (FF)	559
5.21.4	Unsaturated Polyester Resins (UP)	559
5.21.5	Vinyl Ester Resins (VE); Phenacrylate Resins	562
5.21.6	Epoxy Resins (EP)	563
5.21.7	Dicyclopentadiene Resins (DCPD)	564
5.21.8	Diallyl Phthalate Resins (PDAP)	564
5.21.9	Hydrocarbon Resins (HCR)	564
5.22	Elastomers	565
5.22.1	General Description	565
5.22.2	General Properties	566
5.22.3	R-Elastomers (NR, IR, BR, CR, SBR, NBR, NCR, IIR, PNR, SIR, TOR, HNBR)	568
5.22.4	M-Elastomers (EPM, EPDM, AECM, EAM, CSM, CM, ACM, ABR, ANM, FKM, FPM, FFKM)	572
5.22.5	O-Elastomers (CO, ECO, ETER, PO)	574
5.22.6	Q-(Silicone) Elastomers (MQ, MPQ, VMQ, PVMQ, MFQ, FVMQ)	575
5.22.7	T-Elastomers (TM, ET, TCF)	576
5.22.8	U-Elastomers (AFMU, EU, AU)	577
5.22.9	Polyphosphazenes (PNF, FZ, PZ)	578
5.22.10	Other Rubbers	578

6	Additives, Fillers, and Fibers	579
6.1	Additives	579
6.1.1	Slip and Anti-blocking Agents, Release Agents	579
6.1.2	Stabilizers	581
6.1.3	Static Inhibitors, Antistatic Agents	583
6.1.4	Flame Retardants	584
6.1.5	Colorants	586
6.1.6	Additives for Laser Labeling	590
6.1.7	Impact Modifiers and Plasticizers	590
6.1.8	Bonding Agents	590
6.1.9	Blowing Agents and Kickers	591
6.1.10	Nucleating Agents	593
6.1.11	Anti-bacterial Agents, Fungicides	594
6.2	Fillers	594
6.2.1	Inorganic Fillers	597
6.2.2	Nano-Fillers	602
	6.2.2.1 Fillers for Magnetic, Thermal, and Electrical Properties	604
6.3	Fibers	605
6.3.1	Reinforcing Fibers	606
	6.3.1.1 Synthetic, Inorganic Fibers, Glass Fibers (GF)	608
	6.3.1.2 Natural, Organic Reinforcing Fibers	612
	6.3.1.3 Synthetic, Organic Reinforcing Fibers, Carbon Fibers (CF), Aramid Fibers (AF), and Others	613
6.3.2	Fibers, Yarns, Bristles, Tapes	620
7	Material Properties	625
7.1	Processing Characteristics and Tolerances	626
7.2	Overview of Mechanical, Thermal, and General Electrical Properties	635
7.3	Electrical Characteristics	644
7.4	Optical Characteristics	645
7.5	Resistance to Environmental Influences	647
	7.5.1 Water, Humidity	647
	7.5.2 Chemical Resistance	649
	7.5.3 Stress Cracking Resistance	652
	7.5.4 Environmental Influences	653
	7.5.5 Migration and Permeation	655
	7.5.6 Flammability of Plastic Materials	658
7.6	Friction and Wear Behavior	660
Index		665

1

Common Acronyms in Plastics Technology

The plastics industry typically categorizes plastic materials by their chemical family and assigns material acronyms with respect to this family. While this is common practice, it does not reflect reality in the plastics industry, because the materials are sold under their trade names, each with a very specific property spectrum. In fact, the trade name is the only criterion for identification (similar to an order number). Standards defining the properties of specific material classes, such as are common practice for metals, have been introduced for thermosetting materials only. The materials within one family typically exhibit a wide range of properties.

However, in order to structure our knowledge of these materials, it is necessary to categorize them in a logical and comprehensible way.

We will introduce the common method of assigning acronyms in this book. Here, a compromise needs to be struck between an unambiguous classification that follows strict rules and the popular notations commonly used. Although there are several standards regarding plastic material notations, they are inconsistent and contradictory, sometimes even within the same standard.

Table I summarizes the acronyms of the plastic materials covered in this book, preferably considering the chemical composition of the polymers and avoiding additional specifications that relate to physical properties or processing technologies. However, in light of the fact that notations such as “A” for amorphous or “B” for block copolymers are often used in the literature, they are used here at times as well. We discourage using them though because they lack general validity and often cause contradictions.

Table I contains bold listings, indicating that they are standardized. They are based on suggestions made in connection with the plastics data base CAMPUS. Here, the current ISO-standards are reflected; however, exceptions are permitted as long as they are widely used. This approach allowed for CAMPUS to define a list of so-called base polymers that covers almost the entire plastic materials market. This list is routinely reviewed and expanded when necessary.

Table I A provides the acronyms for plastics and rubbers, while Table I B (page 9) provides acronyms for *plasticizers*.

1.1 Table I: Alphabetical List of Plastics Acronyms, Chemical Notation

A: Plastics and Rubbers

Acronym	Chemical notation	Page #
*	Pyrrone	501
*	Polycyclone	502
*	Polyphenylene (polyarylene)	501
*	Polytriazine	493
ABS	Acrylonitrile-butadiene-styrene copolymer	376
ACM	Acrylate rubber (AEM, ANM)	573
ACS	Acrylonitrile-chlorinated polyethylene-styrene	376
AECM	Acrylic ester-ethylene rubber	572
AEM	Acrylate ethylene polymethylene rubber	573
AES	Acrylonitrile ethylene propylene diene styrene copolymer	376
AFMU	Nitroso rubber	577
AMMA	Acrylonitrile methyl methacrylate	415
APE-CS	see ACS	
ASA	Acrylonitrile styrene acrylic ester copolymer	376
AU	Polyester urethane rubber	577
BIIR	Bromobutyl rubber	570
BR	Butadiene rubber	569
CA	Cellulose acetate	520
CAB	Cellulose acetobutyrate	520
CAP	Cellulose acetopropionate	520
CF	Cresol formaldehyde	538, 557
CH	Hydrated cellulose, cellulose film	520
CIIR	Chlorobutyl rubber	570
CM	Chlorinated polyethylene rubber	573
CMC	Carboxymethyl cellulose	520
CN	Cellulose nitrate, celluloid	520
CO	Epichlorohydrin rubber	574
COC	Cyclic polyolefin copolymers	348
COP	COC copolymer	358
CP	Cellulose propionate	520
CR	Chloroprene rubber	569
CSF	Casein formaldehyde, artificial horn	548
CSM	Chlorosulfonated polyethylene rubber	573
CTA	Cellulose triacetate	520

* There are no known acronyms for these plastic materials.

Acronym	Chemical notation	Page #
E/P	Ethylene propylene copolymer	348
EAM	Ethylene vinyl acetate rubber	572
EAMA	Ethylene acrylic acid ester maleic acid anhydride copolymer	348
EB	Ethylene butene	348
EBA	Ethylene butyl acrylate	348
EC	Ethyl cellulose	520
ECB	Ethylene copolymer bitumen blend	348
ECO	Epichlorohydrin rubber	574
ECTFE	Ethylene chlorotrifluoroethylene	407
EEA	Ethylene ethyl acrylate copolymer	348
EIM	Ionomer copolymer	348
EMA	Ethylene methacrylic acid ester copolymer	348
EP	Epoxy resin	538
EP(D)M	see EPDM	572
EPDM	Ethylene propylene diene rubber	572
EPM	Ethylene propylene rubber	572
ET	Polyethylene oxide tetrasulfide rubber	577
ETER	Epichlorohydrin ethylene oxide rubber (terpolymer)	574
ETFE	Ethylene tetrafluoroethylene copolymer	408
EU	Polyether urethane rubber	577
EVAC	Ethylene vinyl acetate copolymer	348
EVAL	Ethylene vinyl alcohol, old acronym EVOH	348
FEP	Polyfluoroethylene propylene	408
FF	Furan formaldehyde	538
FFKM	Perfluoro rubber	574
FKM	Fluoro rubber	573
FPM	Propylene tetrafluoroethylene rubber	574
FVMQ	Fluorosilicone rubber	575
HCR	Hydrocarbon resin	564
HNBR	Hydrated NBR rubber	571
ICP	Intrinsically conductive polymers	527
IIR	Butyl rubber (CIIR, BIIR)	570
IR	Isoprene rubber	569
LCP	Liquid crystal polymer	497
LSR	Liquid silicone rubber	576
MABS	Methyl methacrylate acrylonitrile butadiene styrene	411
MBS	Methacrylate butadiene styrene	411
MC	Methylcellulose (cellulose derivate)	520
MF	Melamine formaldehyde	538
MFA	Tetrafluoroethylene perfluoromethyl vinyl ether copolymer	410
MFQ	Methylfluoro silicone rubber	575

Acronym	Chemical notation	Page #
MMAEML	Methyl methacrylate-exo-methylene lactone	418
MPF	Melamine phenolic formaldehyde	538
MPQ	Methylphenylene silicone rubber	575
MQ	Polydimethyl silicone rubber	575
MS	see PMS	
MUF	Melamine urea formaldehyde	538
MUPF	Melamine urea phenolic formaldehyde	538
NBR	Acrylonitrile butadiene rubber	570
NCR	Acrylonitrile chloroprene rubber	570
NR	Natural rubber	568
PA	Polyamide (other notations see Section 5.8)	430
PA 11	Polyamide from aminoundecanoic acid	430
PA 12	Polyamide from dodecanoic acid	430
PA 46	Polyamide from polytetramethylene adipic acid	430
PA 6	Polyamide from ϵ-caprolactam	430
PA 610	Polyamide from hexamethylene diamine sebacic acid	430
PA 612	Polyamide from hexamethylene diamine dodecanoic acid	430
PA 66	Polyamide from Hexamethylene diamine adipic acid	430
PA 69	Polyamide from hexamethylene diamine azelaic acid	430
PAA	Polyacrylic acid ester	410
PAC	Polyacetylene	527
PAEK	Polyarylether ketone	483
PAI	Polyamide imide	494
PAN	Polyacrylonitrile	410
PANI	Polyaniline, polyphenylene amine	528
PAR	Polyarylate	472
PARI	Polyarylimide	494
PB	Polybutene	370
PBA	Polybutyl acrylate	410
PBI	Polybenzimidazole	493
PBMI	Polybismaleinimide	493
PBN	Polybutylene naphthalate	474
PBO	Poly(p-phenylene-2,6-benzobisoxazole)	619
PBT	Polybutylene terephthalate	470
PC	Polycarbonate (from bisphenol-A)	456
PCTFE	Polychlorotrifluoro ethylene	401
PDAP	Polydiallylphthalate resin	544
PDCPD	Polydicyclopentadiene	374

■ 2.1 Economic Significance of Plastics

Plastics in general have gained significant technological and economic importance alongside metals and ceramics. Globally, plastics represent a larger production volume today than steel or aluminum, thanks to the considerable growth of this material class (Fig. 2.1).

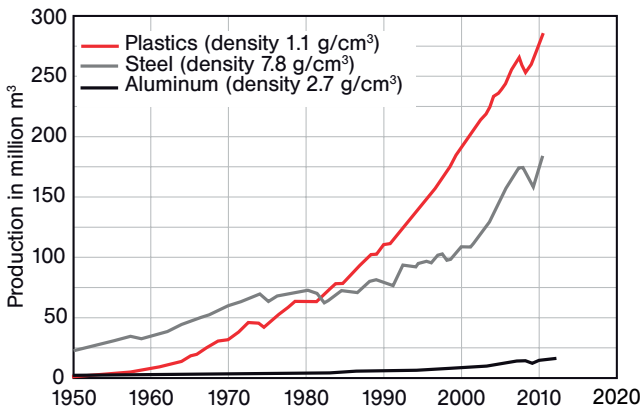


Figure 2.1 Production volume of various materials. Source: Plastics Europe, World Steel Association, The International Aluminium Association

Figure 2.2 provides an overview of the fast-paced growth in plastics production in different global regions between 1990 and 2011. Undoubtedly, we have entered the “age of plastics” in the 21st century. This material class is an integral foundation for technological development and an indicator of the economic growth in an industrial society.

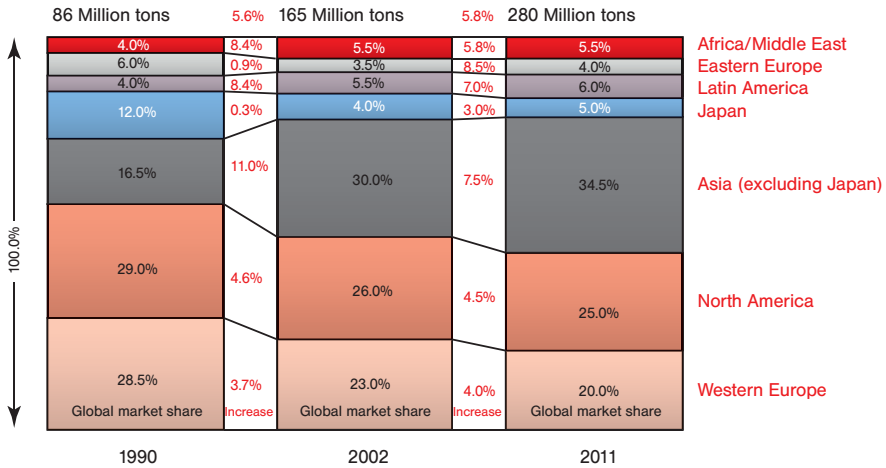


Figure 2.2 Global plastic production since 1990. Source: Plastics Europe

There is a clear correlation between plastic production and the economic and technological performance of a region.

Analyzing the main application areas for plastics in Europe in 2012 (Fig. 2.3) exemplifies the variety of plastic utilization. The “Other” applications, totaling 26% in Figure 2.3 include applications in agriculture, furniture, home appliances, leisure, sport, medicine, and machine construction. Although medical applications have been increasing significantly, their overall share of the plastics market is still only 1%. Plastics have gained entrance into all sectors of industrial production. That their application is profitable is not necessarily a result of their specific properties, such as their potential for lightweight construction or their good insulation properties, but the ability to use economic processing technologies for the manufacture of plastic parts and components. For example, injection molding allows for the manufacture of highly complex components within cycle times ranging from a few seconds to several minutes. The majority of the costs of such manufacturing technologies can be attributed to the depreciation of machine and molds and the cost for raw materials and energy. However, with increasing number of units produced, even highly sophisticated manufacturing equipment becomes profitable quickly.

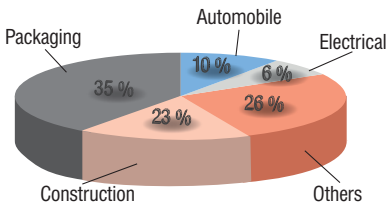


Figure 2.3 Main fields of application for plastics in Europe (2012)
Source: Plastics Europe

The industry branches involved in, and working with, plastics can be distinguished in three categories:

- Plastic production,
- Plastic manufacturing, and
- Plastic machine building industry.

The plastics industry significantly contributes to the world economy in general. For example, it employs almost 900,000 people in the US, and about 1.5 million in the EU countries. Furthermore, there are more than 16,000 plastics industry facilities in the US, in contrast to 60,000 in the EU countries. In the US, \$380 billion are created in shipments every year, compared to \$400 billion in the 27 European countries.

■ 2.2 Classification of Plastics

Polymers are organic or semi-organic materials with high molecular mass (molecular weight), *i.e.*, they are composed of very large molecules (macromolecules), which significantly determine the distinct characteristics of these materials. Figure 2.4 reflects the classification of plastic materials in the general field of material science. Here, distinguishing characteristics are chemical structure, type of polymerization, and the processing and service properties.

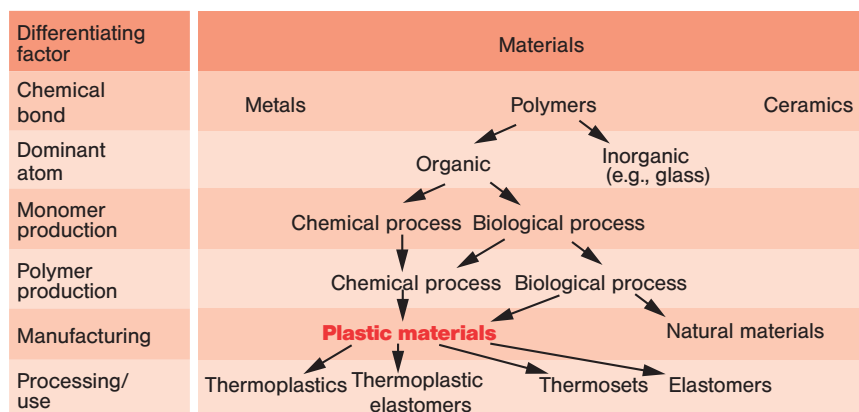


Figure 2.4 Classification of plastic materials in the general field of material science

In this book, the focus will be on thermoplastic materials, reflecting their economic importance. However, many statements made for thermoplastics are valid for all polymeric materials. A clear definition of the terminology used is missing in

many texts, *e.g.*, the terms plastic and polymer are often used synonymously. In our view, the term *polymer* is applicable to all materials with a macromolecular structure, whereas the term *plastics* only describes polymers that are modified with additives to meet the requirements of industrial processing technologies, such as processing aids, stabilizers, pigments, fillers, and others.

Despite this clear definition we were not always able to strictly adhere to this terminology. One reason for this shortcoming is the fact that even in the language of science and in economic statistics the differentiation is not consistent. Even in material standards the term polymer is often used when in fact they cover plastic materials. In these cases, it is not an option to change the term *polymer* to *plastics*, because that would make it impossible to retrieve the standard.

The following general statements can be made for plastic materials:

- The variety of plastic material classes and types is unparalleled by any other material class. Plastics represent an extremely large span of property profiles, and the slogan of the early days of plastic material development that euphorically declared them “**tailored materials**” has become reality. In almost every area of modern life plastic materials have established themselves as manufacturing materials of choice or as materials with specific functionalities.
- Their complex chemical and morphological structures together with their wide variety in terms of composition and modifiability result in highly complex **material behaviors** that strongly determine service and processing conditions. Examples of properties to be considered include their visco- and entropy elasticity, non-Newtonian flow, complex aging characteristics, semi-crystallinity, liquid crystallinity, orientation- and modification-dependent anisotropy, stress cracking, and many others. A variety of test procedures is necessary to comprehensively describe plastic properties and to provide meaningful characteristic values (single-point data) or property functions (multiple-point data) (see Chapter 3).
- Plastics technology provides a large number of different **processes** for the compounding, processing, and post-processing of plastic materials. The molding and shaping processes play a dominant role because they offer highly productive and energy efficient material utilization within a minimal number of process steps. In some cases, material shaping and conversion (*e.g.*, tempering, vulcanization) happen simultaneously during processing. The properties of the final product are significantly influenced by the processing conditions. Therefore, process optimization and quality control have to be emphasized appropriately in plastics manufacturing operations (see Chapter 4).
- It is not possible to efficiently **design** plastic components without considering the constraints introduced by material properties and manufacturing processes. This fact, together with the high degree of material and geometry specialization of many manufacturing technologies, requires the consideration of the close interdependence of design, material, and process decisions.

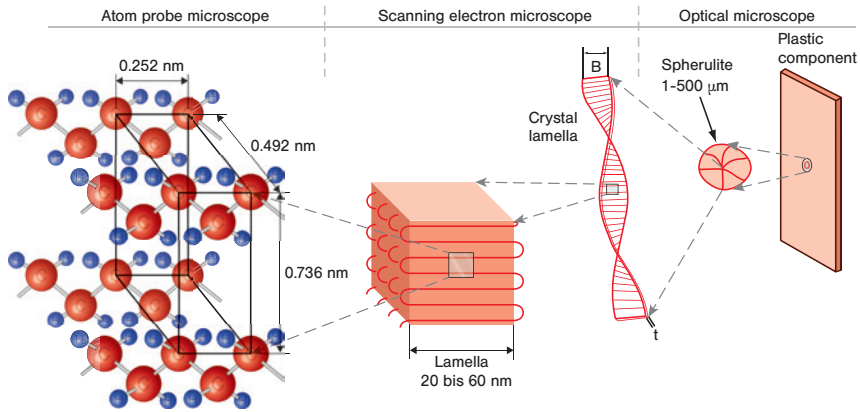


Figure 2.12 Morphology of a semi-crystalline thermoplastic material

Figure 2.13 shows the dynamic shear modulus as a function of temperature for a PE-HD, the most common semi-crystalline plastic material. This curve presents data measured at one test frequency. The figure clearly shows two distinct transitions: one at about $-110\text{ }^{\circ}\text{C}$, the *glass transition temperature*, and one near $140\text{ }^{\circ}\text{C}$, the *melting temperature*. Above the *melting temperature*, the shear modulus is negligible and the material will flow. Crystalline arrangement begins to develop as the temperature decreases below the melting point. Between the melting and glass transition temperatures, the material behaves as a leathery solid. Once the temperature decreases below the glass transition temperature, the amorphous regions between the crystalline structures vitrify, resulting in stiff and often also brittle material behavior.

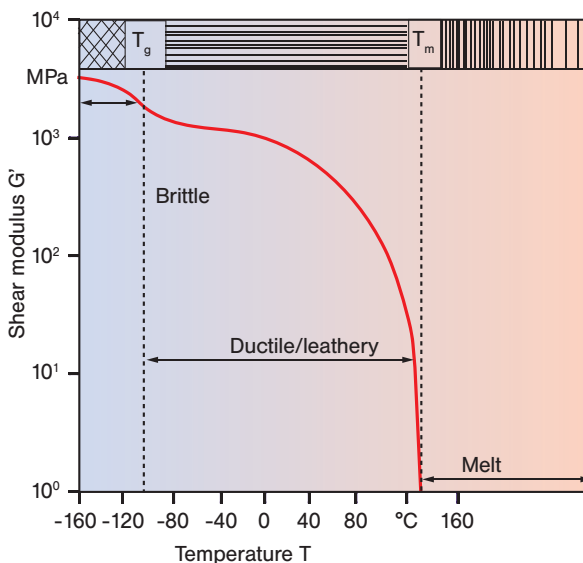


Figure 2.13

Shear modulus of PE-HD as a function of temperature

During processing of plastic materials, inhomogeneous crystal nucleation or differential cooling rates in the material may create locally different crystalline structures, *e.g.*, the fine spherulitic surface layers in injection molded components. This in turn results in anisotropic material properties. The particular characteristics of the molecular structure of semi-crystalline plastics have been tailored in various ways in order to create desired properties:

- Stretching or shearing of macromolecules are used to create molecular rearrangement and the formation of new oriented, crystalline structures, respectively. This results in a significant increase in stability and stiffness, in particular in a desired direction. Examples of such crystalline structures are the fibrils and shish-kebab structures shown in Figure 2.14. A number of processing variations are common in the chemical fiber industry and in plastic engineering, including fiber stretching, biaxial film stretching, and injection- and compression molding stretching. These manipulations result in anisotropic structures with unidirectional or orthogonal orientation.
- Highly homogeneous and fine-grained crystallite structures are obtained by controlling the cooling conditions and/or adding finely dispersed nucleating agents. These structures are advantageous in particular for dimensionally stable and wear resistant components.

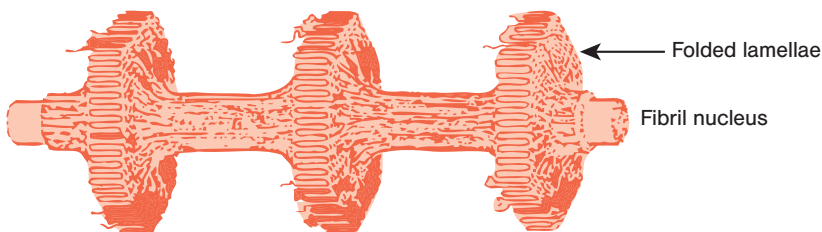


Figure 2.14 Shish-kebab structure

Under common solidification conditions, some polymers are not able to crystallize because of their specific molecular configuration. However, stretching facilitates a partial crystallization by aligning and denser packing of molecular segments (*elongation-induced crystallization*). This type of structure formation requires a certain level of micro-Brownian molecular mobility, because crystallites can form only by molecular rearrangement during stretching. Elongation-induced crystallization is often seen with rubbers (*e.g.*, NR, IR, IIR, CR). However, the corresponding increase in hardness is not necessarily a welcome side effect in rubber applications.

Crystalline structures in polymers represent the state of highest molecular order in terms of dense molecular aggregation and the corresponding stronger intermolecular forces. Yet, they are still imperfect results of a “frozen” crystallization imbalance so that an increase in temperature will cause melting over a varying

3

Material Properties and Testing Methods

In this chapter we will introduce the characteristic properties of plastics and the testing methods required to determine them. It is our goal to develop and improve a general understanding of this group of materials. Our descriptions will be general and qualitative and the diagrams displaying material characteristics are meant to help gain insight into the behavior of this group of materials. Some tables and figures provide a comparison of selected plastics; however, these comparisons are also only means to foster a general understanding.

It should be noted that plastics are almost always modified by functional or other additives. The properties of commercially available plastic materials may vary from the “average values” provided here. Before selecting a specific plastic material, it is recommended to verify properties through the manufacturer. Another highly recommended source of material property information is CAMPUS, a free database provided by 30 plastic material producers. This database contains material data for materials under their respective tradenames. Both space and timeliness are prohibitive factors for a printed work to provide the plethora of information available. More detailed information regarding the CAMPUS database and free downloads can be found at www.CAMPUSplastics.com.

Figure 3.1 compares the stress/strain diagrams of unfilled PBT grades to exemplify the wide variation of plastic characteristics (data according to CAMPUS). Large differences in property profiles can be found even within one plastic class.



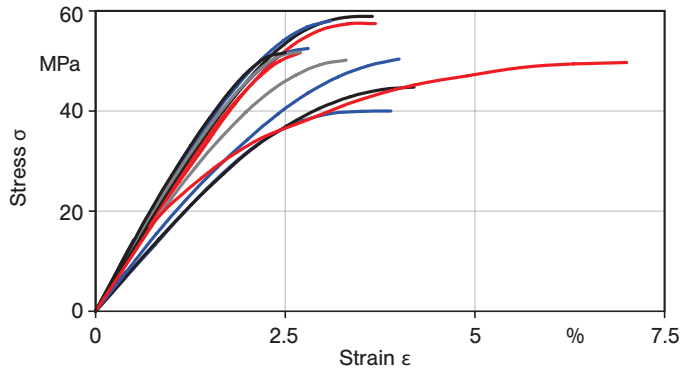


Figure 3.1 Range of stress-strain diagrams for PBT at 23 °C

■ 3.1 Significance of Characteristic Values

Material characteristics are the determining factors during all phases of development and design. They affect the initial, conceptual design steps, material selection, and dimensioning of molded components. In order to meet these requirements, material characteristics have to be

- comparable,
- meaningful, and
- determined by a rational process.

Databases and material data sheets provide up to 200 different characteristics of a product. This large amount of information makes it difficult if not impossible to gain and maintain a comprehensive overview.

In order to select meaningful characteristics here, we refer to a globally respected source: ISO 10350: “Plastics – Acquisition and presentation of comparable single-point data, molding materials” (see Table 3.1). The reference to this standard will also determine the order in which we will describe specific characteristics in this chapter. Another important standard is ISO 11403: “Plastics – Acquisition and presentation of comparable multipoint data, mechanical properties” (see Table 3.2).

Table 3.1 CAMPUS Characteristic Data Catalog According to ISO 10350

Property	Symbol	ISO-(IEC)-standard	Specimen (in mm)	Unit	Notes
Rheological characteristics					
Melt volume rate	MVR	1133	Compound	cm ³ /10 min	
Mold shrinkage <i>parallel</i>	S _{Mp}	294-4 (thermoplastics) 2577 (thermosets)	60 · 60 · 2	%	See ISO 294-3, thermoplastics and ISO 10724-2, thermosets
Mold shrinkage <i>normal</i>	S _{Mn}				
Mechanical characteristics, 23 °C					
Tensile modulus	E _t	527-1/2	ISO 3167 (multi-purpose specimen)	MPa	Elongation 0.05 to 0.25%
Yield stress	σ _y			MPa	
Yield strain	ε _y			%	After yield
Nominal strain at break	ε _{IB}			%	For specimens without σ _y up to ε = 50%
Stress at 50% strain	σ ₅₀			MPa	For specimen without yield
Stress at break	σ _B			MPa	For specimen without yield
Strain at break	ε _B			%	Elongation 0.5%
Tensile creep modulus: 1 h	E _{tc} 1	899-1		MPa	
Tensile creep modulus: 1000 h	E _{tc} 10 ³			MPa	
Charpy impact strength, unnotched at + 23 °C	a _{CU} + 23	179/1eU	80 · 10 · 4 (general purpose specimen)	kJ/m ²	
at - 30 °C	a _{CU} - 30				
Charpy impact strength, notched at + 23 °C	a _{CA} + 23	179/1eA		kJ/m ²	
at - 30 °C	a _{CA} - 30				
Tensile impact strength at + 23 °C	a _t 1	8256/1	80 · 10 · 4 (multi-purpose specimen) with double V-notch	kJ/m ²	When Charpy impact strength cannot be determined



Table 3.1 CAMPUS Characteristic Data Catalog According to ISO 10350 (continued)

Property	Symbol	ISO-(IEC)-standard	Specimen (in mm)	Unit	Notes
Puncture impact properties at + 23 and – 30 °C	F_M	6603-2	60 · 60 · 2	N	
Max. force at + 23 and – 30 °C	W_P			J	
Thermal characteristics					
Melting temperature	T_m	11357-1 and -3	Material	°C	Temperature increase 10 K/min
Glass transition temperature	T_g	11357-1 and -2			
Temperature of deflection under load at 1.8 MPa	$T_f 1.8$	75-1/2	80 · 10 · 4 (multi-purpose specimen)	°C	Select 1.8 MPa and a second load level
at 0.45 MPa	$T_f 0.45$				
at 8.0 MPa	$T_f 8.0$				
Vicat softening temperature	$T_v 50/50$	306	$\geq 10 \cdot 10 \cdot 4$ (multi-purpose specimen)	°C	Temperature increase 10 K/min, load increase 50 N
Coefficient of linear thermal expansion, parallel Normal	α_p	11359-1/2	Center of 80 · 10 · 4 (multi-purpose specimen)	E-6/K	Increase in elongation between 23 and 55 °C
Burning behavior, 1.5 mm thickness	α_h B50/-1.5 B500/1.5	60695-11-10	125 · 13 · 1.5 $\geq 150 \cdot 150 \cdot 1.5$	Class	Classes for B50: V-0, V-1, V-2, HB Classes for B500: 5VA, 5VB, N
-/- mm thickness	B50/-/- B500/-/-	60695-11-10/-20	125 · 13 · 1.5 $\geq 150 \cdot 150 \cdot 1.5$		
Oxygen index	OI23	4589-1/2	80 · 10 · 4 (multi-purpose specimen)	%	Method A: Ignition at upper surface

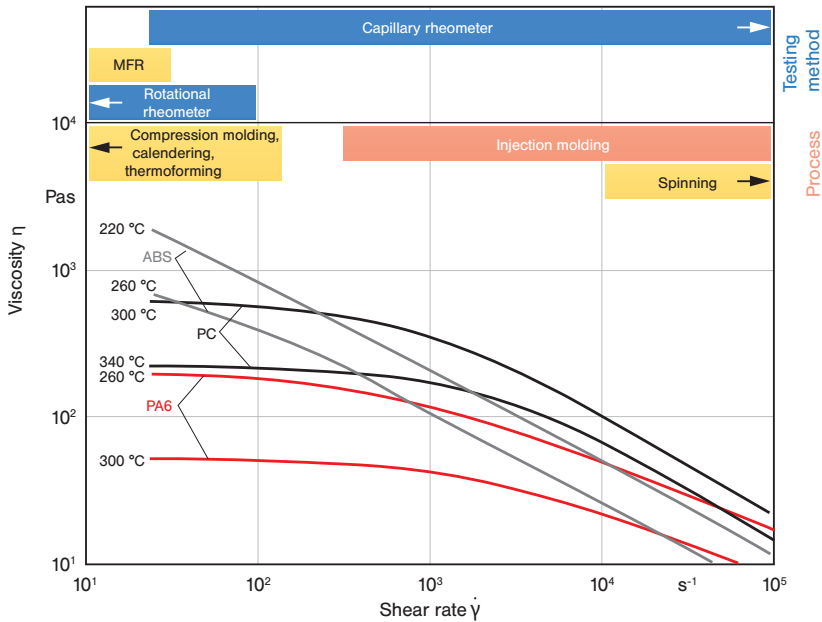


Figure 3.2 Melt viscosity of selected thermoplastics at normal upper and lower permissible melt temperature, respectively

Temperature also influences viscosity: with decreasing temperature the viscosity will increase. Figure 3.2 also shows the shear rate ranges encountered in different processing technologies and identifies the testing methods used for their determination. Figure 3.3 shows the order of magnitude of possible variations in the viscosity curves for ABS at constant temperature. Flow path calculations based on these viscosity curves resulted in variations of up to 30%. This example shows that caution is warranted when operating with averaged values for rheological data. They should be used exclusively for comparisons between material classes – never as the basis for design or dimensioning.

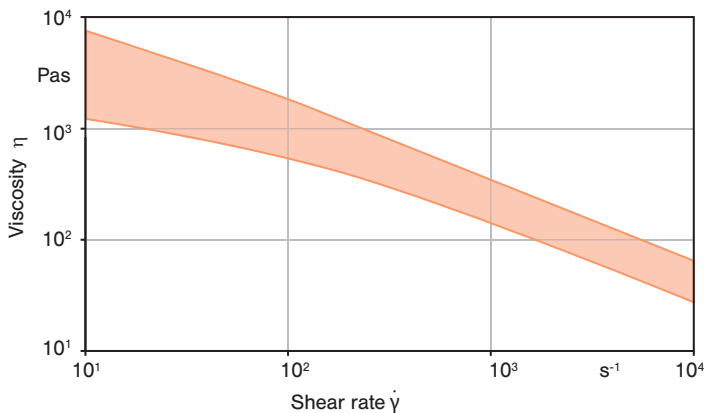


Figure 3.3
Viscosity curve range for ABS at 240 °C

Figure 3.4 shows the two most commonly used rheometer designs and their areas of application. Rotational rheometers, such as the depicted cone-plate system, facilitate measurements at low shear rates. These typically complex measurements allow for the fundamental analysis of rheological phenomena, such as principal stress differences and the derivation of rheological models, because they detect changes on the molecular level. Shear viscosity, which is a processing relevant parameter, is typically measured using capillary rheometers. It is determined at constant temperature by measuring the material exiting a capillary at a specific pressure.

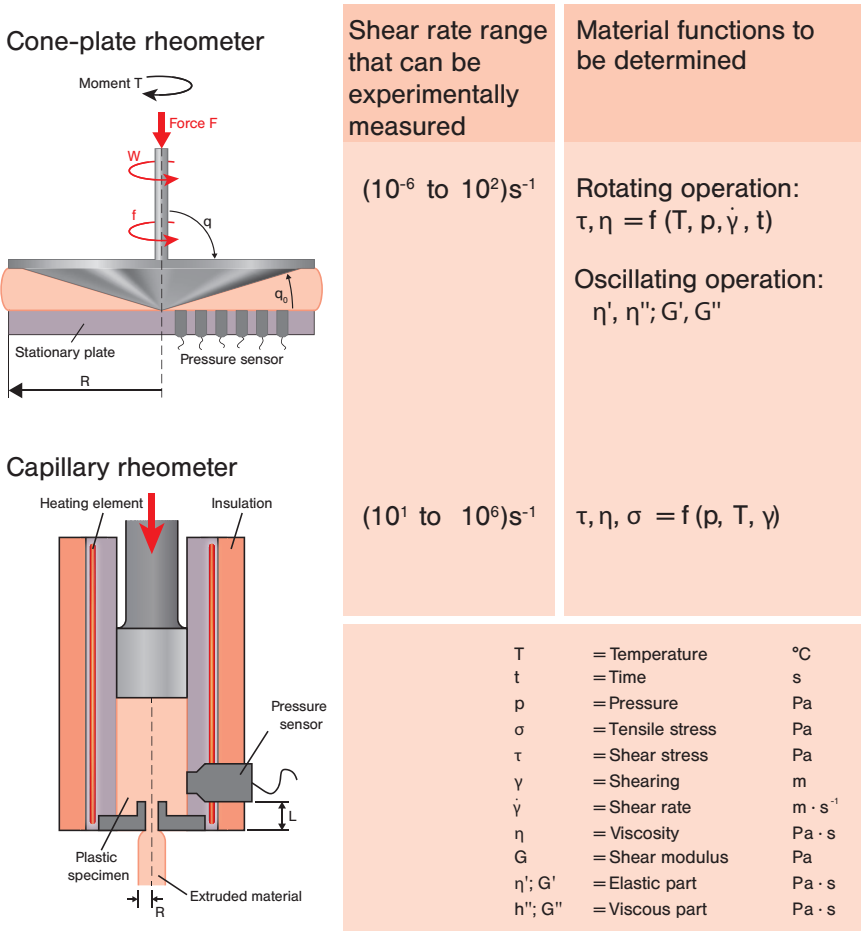


Figure 3.4 Rheometer types

Online- and inline rheometers help monitor both injection molding and extrusion processes. While in the past partial flows were sampled from the volume flow (bypass principle), today viscosity is measured directly in the main volume flow. In order to do this, pressure and temperature sensors are placed along the flow length that allow to calculate the viscosity taking into consideration the time of contact with the flow front, the pressure drop, and the geometric dimensions of the cavity. However, this approach is possible only at the shear rate predetermined by the process.

Figure 3.5 shows the flow curves of different plastics with Fig. 3.5 a) showing the viscosity curves of polyolefins with different flow behaviors. The easy flowing grades exhibit lower viscosities. Many plastics contain additives, such as flow promoters or color pigments, which affect processing behavior as well as product properties (*e.g.*, color). As seen in Fig. 3.5 b), the addition of white pigments (TiO_2) increases the viscosity of the compound [1]. The data also indicate that this effect is more pronounced for particles with larger diameters. The increase in viscosity caused by the addition of fillers is also dependent on the viscosity of the plastic itself: the lower the viscosity, the higher the increase in viscosity. This is further illustrated in Fig. 3.5 c) in the case of an easy flowing PE-LD [1]. The viscosity of plastic grades that are offered by the manufacturer already compounded with color pigments typically matches that of the base (uncolored) grade. For master batches however, the processing conditions have to be adjusted accordingly by the processor. Figure 3.5 d) illustrates the effect of fillers with even larger particles, such as fibers or the copper platelets shown here, as a function of temperature [2]. At high temperatures the filler content has less influence than at lower temperatures.

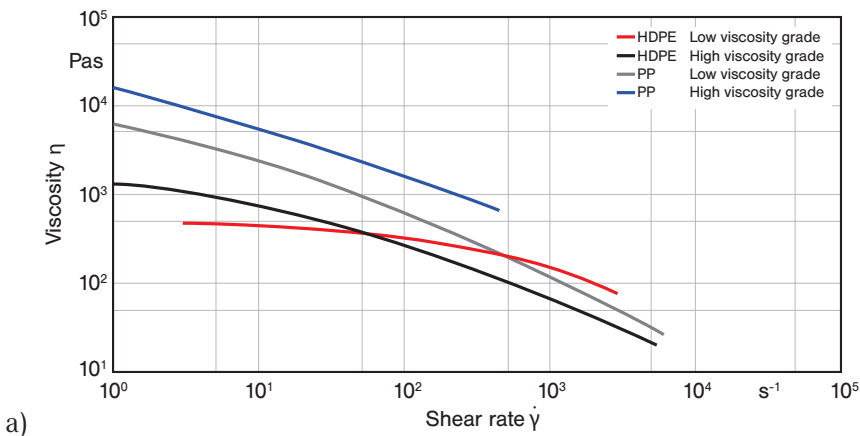


Figure 3.5 Flow curves of selected plastics

This model can be used over a wide range of shear rates because it also covers the shear rate-independent behavior at low shear rates. In its more complex variation, the model may also be used to represent the second Newtonian plateau. At high shear rates the completely stretched molecular chains also exhibit shear-independent behavior. Given the fact that this case is not relevant in industrial practice, simulation uses the model in the form presented in Eq. 3.2.

Cross Model

Another model that is able to represent the transition from zero shear to shear thinning viscosity is the Cross model:

$$\eta(\dot{\gamma}) = \frac{\eta_0}{1 + \left[\frac{\eta_0}{\tau} \dot{\gamma} \right]^{1-n}} \quad (3.3)$$

where η_0 is zero shear viscosity, τ describes the transition to the shear thinning region, and n is the flow exponent. Both models are used interchangeably in common simulation programs.

Temperature Dependency

The fact that viscosity is dependent on temperature is taken into consideration by two different approaches. For semi-crystalline plastics at high processing temperatures ($T > T_g + 100^\circ\text{C}$), the Arrhenius approach is used:

$$a_T(T) = \exp\left(\frac{E_0}{R} \left(\frac{1}{T} - \frac{1}{T_0}\right)\right) \quad (3.4)$$

where E_0 is the activation energy, R is the universal gas constant, and T_0 is the reference temperature. For amorphous thermoplastics and lower temperature ranges between processing temperature and T_g , the Williams-Landel-Ferry (WLF) equation is used:

$$a_T(T) = \exp\left(\frac{-C_1(T - T_0)}{C_2 + T - T_0}\right) \quad (3.5)$$

where C_1 and C_2 are material constants and T_0 is the reference temperature. In both models, the shift factors are multiplied with the respective values of the zero shear viscosity. Both models also recognize the pressure dependency of the viscosity, a factor that is the particular focus of scientific research. However, because there are only few experimental characteristic data available, the pressure shift factor is typically not considered.

3.2.1.3 Melt Volume Flow Rate (MVR) and Melt Mass Flow Rate (MFR)

The melt volume flow rate (MVR) is used as a comparative index for the flow behavior of a melt; however, it is not suitable for its calculation. It is defined as the volume of melt exiting a capillary with defined dimensions within 10 minutes ($\text{cm}^3/10 \text{ min}$) under given temperature and pressure conditions (Fig. 3.7). Also commonly used is the melt mass flow rate, also called melt flow index, which is determined under the same conditions, but measured in $\text{g}/10 \text{ min}$. The respective values can be easily converted using the melt density. When comparing such data, it is important to make sure they were determined under the same conditions, *i. e.*, under the same temperature and pressure.

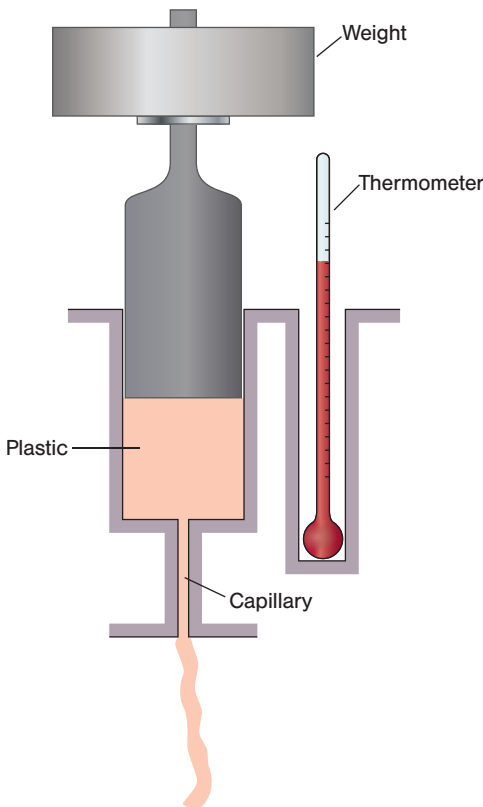


Figure 3.7
Schematic of melt volume flow measurement (flow indexer)

3.2.2 Solidification Behavior

3.2.2.1 Sealing Time

In industrial practice, the time until a molded component is solidified is determined by weight. Here, a series of tests is used to determine the duration of holding time after which the component weight no longer increases. It is not easy to

haze number is a measure for haze. It is the ratio of scattered light reflected by the specimen at an angle of 80° to the axis of the incident ray to the almost perpendicularly impinging primary light. According to another definition (ASTM D 1003) haze is the portion of light transmitted by the specimen that deviates from the direction of incident light by more than 2.5° .

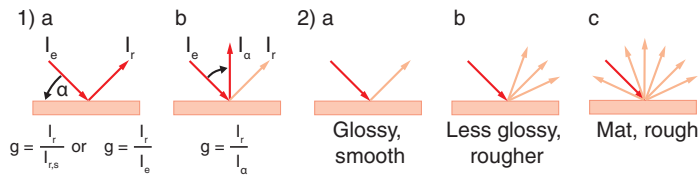


Figure 3.72 Left: Schematic illustration of different gloss measurement methods on plastic surfaces (1a and b); right: different types of surface reflection (2a: directed, 2b: dispersed, and 2c: diffused)

3.6.3 Color

3.6.3.1 Fundamentals

Color is a visual impression of a surface gained by an observer. In order to understand why a surface appears colored, the concepts of light, color, and complementary color have to be explained.

Visible light is comprised of electromagnetic waves with wavelengths ranging from 400 nm to 800 nm, and it is only a small region in the overall spectrum of electromagnetic waves. Every wavelength in this “visible region” corresponds to a specific color. “White light” is the composition of all wavelengths in the visible range.

Two colors are called complementary when their combination results in white light. A color circle can be used to determine the respective complimentary color. The color circle is filled with all possible color transitions.

When “white light” impinges on a colored surface, certain wavelengths are absorbed by the surface and free and/or bonding electrons in the pigments are excited so that the surface appears in its complementary color. The coloring effect of pigments is based on this phenomenon.

3.6.3.2 Colorimetry

Objective measuring methods are required to characterize color, *e.g.*, in quality control. For this purpose, the CIE-Lab system (Commission international de l'éclairage) is globally accepted. The intensity of the reflected light is recorded as a function of wavelength in so-called radiance curves. The colors are arranged in a



horizontal plane similar to the color circle (with the only difference that we now know that the circle is in fact a quasi-elliptical), see Fig. 3.73. Here, all colors are represented in their maximum saturation. The additional z-axis represents the color intensity, shown in Figure 3.74. The perceivable color is defined by the coordinates L, a, and b.

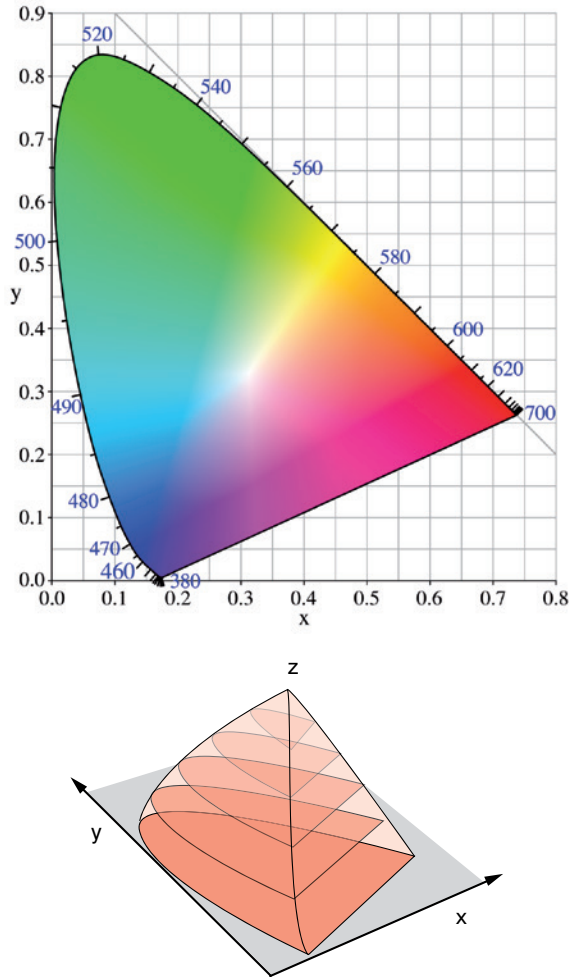


Figure 3.73 Above: CIE-standard chromaticity table; below: three-dimensional illustration of intensity

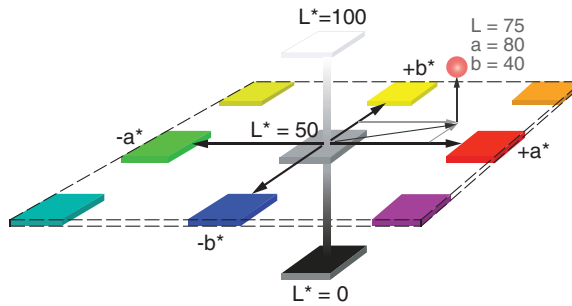


Figure 3.74 CIE-Lab system for color characterization

According to the theory of complementary colors, green ($a = -127$) and red ($a = +127$) are opposite each other on the a^* -axis. The b^* -axis represents the complementary colors blue ($b = -127$) and yellow ($b = +127$). The L^* -axis is perpendicular to this plane and represents color intensity. Black ($L = 0$) and white ($L = 100$) are the terminal points, with shades of gray as intermediate values. If the a -component equals 0, only colors ranging from blue to yellow can be represented with intensities ranging from white to black. Analogously, colors from red to green are represented when the b -component equals 0.

3.6.4 Index of Refraction, Birefringence

When light passes from one medium into another, *e. g.*, from air into a plastic material, it is refracted. The degree of light refraction is characterized by the relative index of refraction of medium 2 with respect to medium 1.

$$n_{21} = \frac{\sin \alpha}{\sin \beta} = \frac{c_1}{c_2} \quad (3.27)$$

where α and β are the angles that a light ray will form in the first and second medium with the axis of incidence, and c_1 and c_2 are the respective rates of propagation of light in these media. In general, indices of refraction refer to vacuum as the first medium. The speed of light c_0 in a vacuum is higher than in any other medium. Assuming the speed of light in a medium is c , and the index of refraction with respect to vacuum is n , we can calculate for light passing from a vacuum into a medium:

$$n = \frac{\sin \alpha}{\sin \beta} = \frac{c_1}{c_2} \quad (3.28)$$

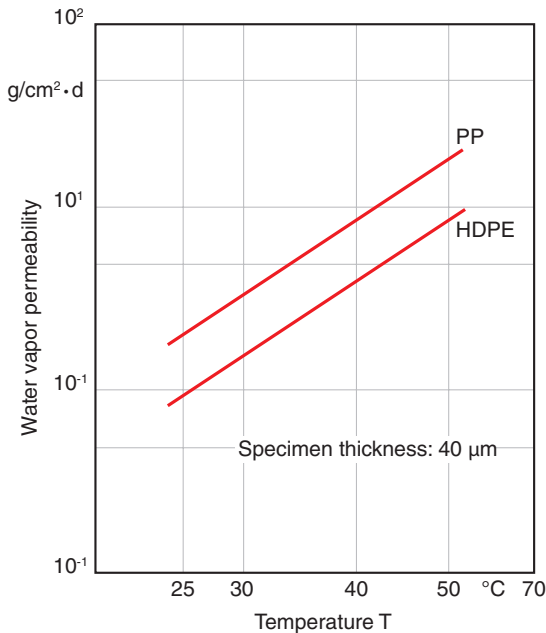


Figure 3.91
Water vapor permeability as a function of temperature

3.7.7.2 Gas Permeability

The gas permeability q is defined as the gas volume (reduced to standard conditions) that permeates through 1 m^2 of a plastic film within 24 h at a specified temperature and pressure differential:

$$q \text{ in } \left[\frac{\text{cm}^3}{\text{m}^2 \cdot 24\text{h} \cdot \text{bar}} \right] \quad (\text{ISO 2556})$$

Again, the specimen thickness has to be specified. The permeability coefficient Q for gases is the permeability in relation to specimen thickness and pressure differential:

$$Q \text{ in } \left[\frac{\text{cm}^3(\text{NTP})}{\text{cm} \cdot \text{s} \cdot \text{mbar}} \right]$$

Permeability characteristics increase sharply with increasing temperature (Fig. 3.92) and depend strongly both on the measurement conditions and the kind and condition of the tested film. Published permeability values therefore offer only a qualitative standard of comparison. In critical applications, measurements of the actual product are required. Sometimes, different units are used for permeability values and permeability coefficients, see Table 3.10.

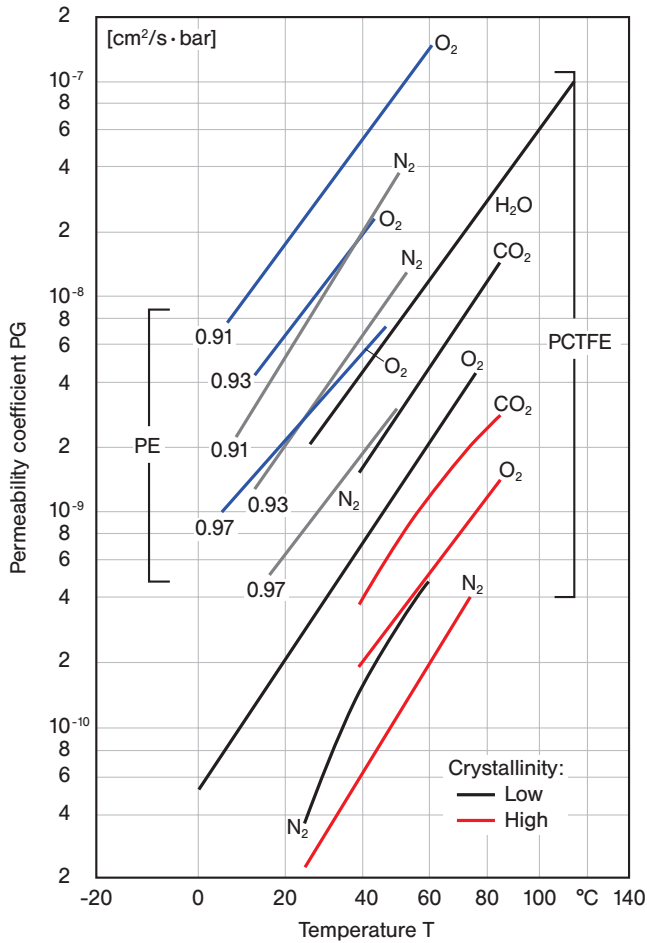


Figure 3.92 Permeability coefficients for selected PE and PCTFE as a function of temperature

Table 3.10 Conversion Table for the Permeability Characteristics of Gases and Water Vapor

Parameter	Recommended unit	Conversion factor
Permeability coefficient	$1 \frac{\text{cm}^3 \cdot 100 \mu\text{m}}{\text{m}^2 \cdot \text{d} \cdot \text{bar}} \triangleq$	$10^{-2} \frac{\text{cm}^3 \cdot 100 \mu\text{m}}{\text{dm}^2 \cdot \text{d} \cdot \text{bar}}$
		$10^{-9} \frac{\text{cm}^2}{\text{d} \cdot \text{mbar}}$
		$1.5 \cdot 10^{-14} \frac{\text{cm}^2}{\text{s} \cdot \text{Torr}}$
		$1.2 \cdot 10^{-11} \frac{\text{cm}^2}{\text{s} \cdot \text{bar}}$
		$10^{-11} \frac{\text{cm}^2}{\text{d} \cdot \text{Pa}}$
Gas permeability	$1 \frac{\text{cm}^3}{\text{m}^2 \cdot \text{d} \cdot \text{bar}} \triangleq$	$1.2 \cdot 10^{-9} \frac{\text{cm}}{\text{s} \cdot \text{bar}}$
		$12 \cdot 10^{-6} \frac{\text{cm}^3}{\text{m}^2 \cdot \text{s} \cdot \text{bar}}$
		$10^{-4} \frac{\text{cm}}{\text{d} \cdot \text{bar}}$
		$10^{-9} \frac{\text{cm}}{\text{d} \cdot \text{Pa}}$
		$1.3 \cdot 10^{-7} \frac{\text{cm}}{\text{d} \cdot \text{Torr}}$
Water vapor permeability	$1 \frac{\text{g}}{\text{m}^2 \cdot \text{d}} \triangleq$	$12 \cdot 10^{-6} \frac{\text{g}}{\text{m}^2 \cdot \text{s}}$
		$12 \frac{\mu\text{g}}{\text{m}^2 \cdot \text{s}}$

Figure 3.93 provides an example for gas permeability showing the oxygen permeation of films; Fig. 3.94 shows the effect of temperature on gas permeability.

4.1.1 Mixing Processes

The properties of the finished product in almost all polymer processes depend in part on how well the material was mixed, and all processing methods include a mixing step of the base materials. For example, an integral part of a screw extruder is a mixing zone. In fact, most twin screw extruders are primarily used as mixing devices. Hence, a better understanding of the mixing process helps to optimize processing conditions and increase part quality.

The process of polymer blending or mixing is accomplished by distributing or dispersing a minor or secondary component within a major component serving as a matrix. The major component can be thought of as the continuous phase and the minor components as distributed or dispersed phases in the form of droplets, filaments, or agglomerates. When creating a polymer blend, one must always keep in mind that the blend will probably be re-melted in subsequent processing or shaping processes. Coalescence may compromise the finely dispersed structure created during compounding by causing phase separation. To avoid this problem, compatibilizers, which are macromolecules used to ensure compatibility in the boundary layers between the two phases, are common.

We distinguish between three general categories of polymer blends (for examples see Table 4.1):

- Homogeneous mixtures of compatible polymers,
- Single-phase mixtures of partly incompatible polymers, and
- Multi-phase mixtures of incompatible polymers.

The mixing process itself is defined by three fundamental mechanisms:

- Distributive mixing,
- Dispersive mixing, and
- Coalescence.

Table 4.1 Common Polymer Blends

Blends of compatible plastic materials	Natural rubber and polybutadiene Polyamides (<i>e.g.</i> , PA 6 and PA 66) Polyphenylene ether and polystyrene
Blends of partially incompatible plastic materials	Polyethylene and polyisobutene Polyethylene and polypropylene (<5% PE in PP) Polycarbonate and polyethylene terephthalate
Blends of incompatible plastic materials	Polystyrene and polyethylene Polyamide and polystyrene Polypropylene and polystyrene

Distributive or laminar mixing of compatible materials describes the distribution of a component A in a matrix B. This distribution is achieved by imposing large strains on the material. This increases the interfacial area between the two or more phases and decreases the local dimensions, or striation thicknesses, of the secondary phases. Imposing large strains on the blend is not always sufficient to achieve a homogeneous mixture. The type of mixing device and the initial orientation and position of the two or more fluid components play a significant role in the quality of the mixture.

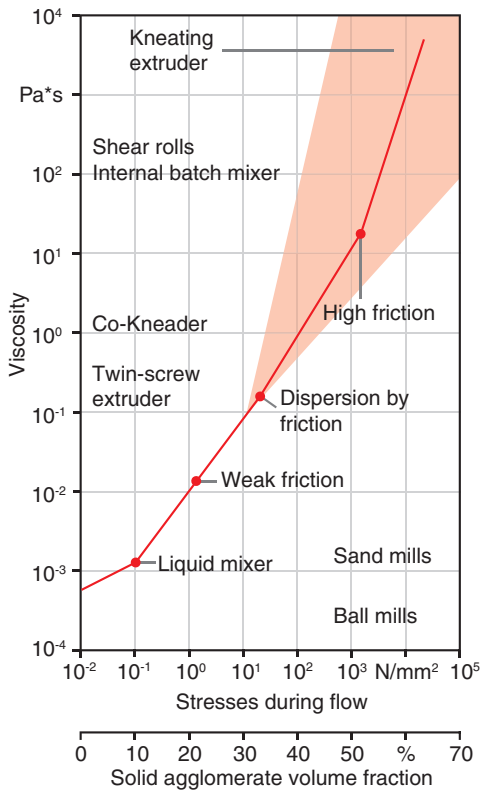


Figure 4.1

Use of dispersive mixing equipment depending on compound viscosity and volume fraction of solid agglomerates

Dispersive mixing in polymer processing involves breaking a secondary immiscible fluid or an agglomerate of solid particles and dispersing them throughout the matrix. Here, the imposed strain is not as important as the imposed stress which causes the system to break up. Hence, the type of flow inside a mixer plays a significant role on the break-up of solid particle clumps or fluid droplets when dispersing them throughout the matrix. The most common example of dispersive mixing of particulate solid agglomerates is the dispersion and mixing of carbon black into a rubber compound. Figure 4.1 relates the viscosity of the compound to the volume fraction of the solid agglomerates and the type of mixing device. When breaking

up a polymer melt within a matrix, *i. e.*, when compounding a polymer blend, the droplets inside the incompatible matrix tend to stay or become spherical because of the natural tendency of the drop to maintain the lowest possible surface-to-volume ratio. However, the flow field within the mixer applies a stress on the droplets, causing them to deform. If this stress is high enough, it will eventually cause the drops to elongate and finally break up. This phenomenon of dispersion and distribution continues to repeat itself until the stresses caused by the flow field can no longer overcome the surface tension of the ever smaller droplets that are formed.

The dispersion of solid agglomerates or melt droplets is most effectively achieved by stretching or elongational flow. Hence, devices that stretch the melt, instead of shearing it, lead to more effective mixers while significantly lowering energy consumption.

Coalescence describes the coming together of single drops, *e. g.*, by collision in the flow field. In essence, it is the opposite of dispersion. Depending on filler content and surface tension, coalescence may predominate dispersion. In this case, mixing will cause a coarsening of the blend morphology.

4.1.1.1 Mixing Devices

We generally distinguish between two categories of mixers:

- Discontinuous mixers and
- Continuous mixers.

Rotating Solid Particulate Mixers

The different designs have varying types of mixing drums and thus rely on different kinds of mixing mechanism. There are simple roll drums, drum hoop mixers, tumbling mixers (for larger volumes), double conical mixers, and V-mixers. They are used as pre-mixers for free flowing materials and additives to be further processed on screw kneaders, extruders, or injection molding machines. They are also used to post-mix and homogenize charges of final compounds and for subsequent drying operations.

Solid Particulate Mixers with Rotating Elements

This mixer type comes in a wide variety of designs. The internal impeller speeds range from less than 2 m/s to speeds up to 50 m/s. As the speed increases, so does the energy input and dispersion of the mixed components. However, that also makes the mixing process less gentle. These types of mixers can be discontinuous (Fig. 4.2) or continuous (Fig. 4.3). In continuous systems, the mixing impellers also impose a conveying action on the particulates or mixture.



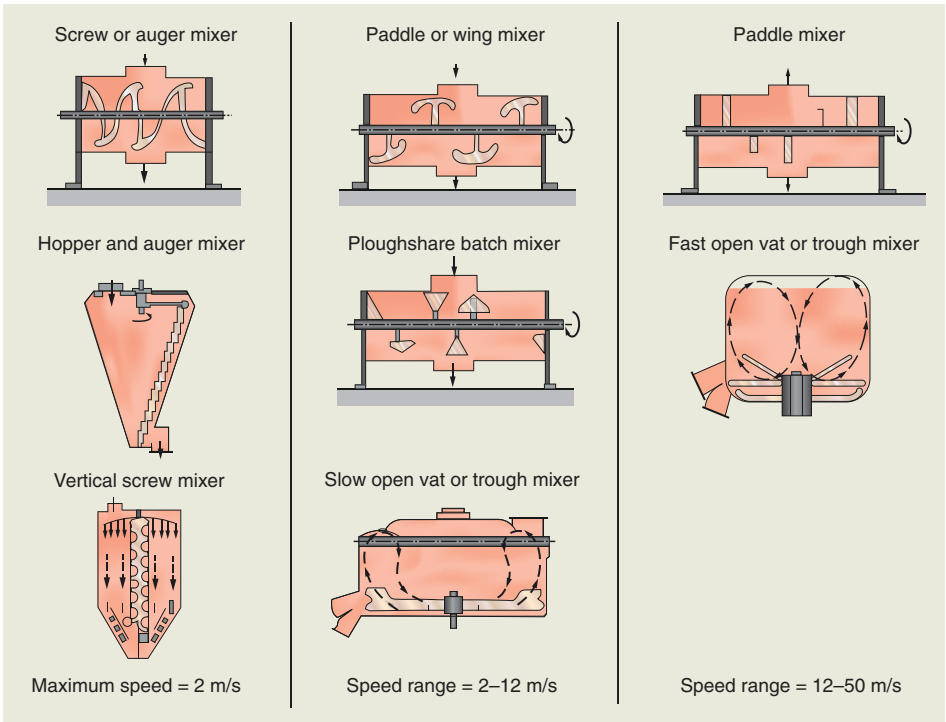


Figure 4.2 Solid particulate (discontinuous) batch mixing devices

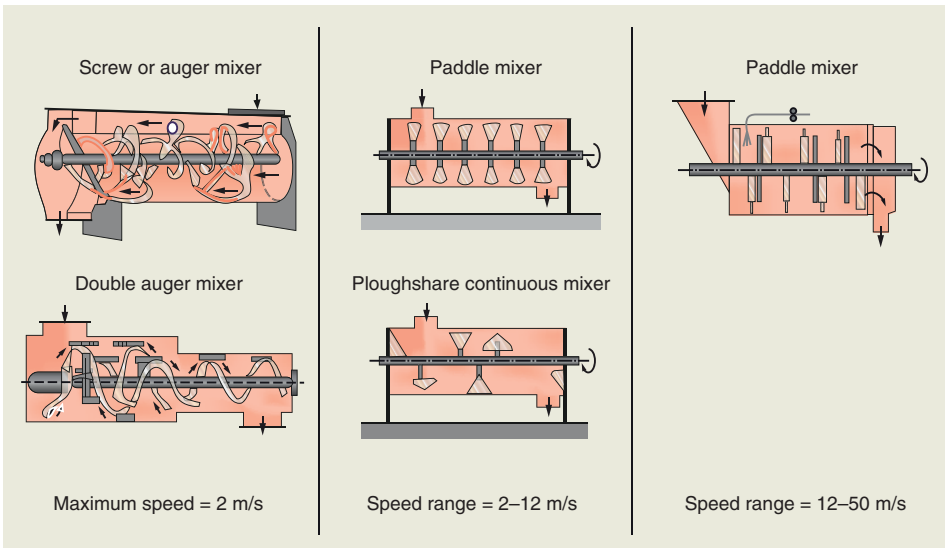


Figure 4.3 Solid particulate continuous mixing devices

products and thus improve product properties by introducing molecular and/or crystallite orientation in the direction of drawing. It is also possible to proceed with thermoforming operations immediately after the manufacture of plastic sheets or films, thus eliminating a heating process.

■ 4.12 Plastic Joining

4.12.1 Plastic Welding

Plastic welding is defined as the joining of thermoplastic materials under heat and pressure (either with or without filler materials). The joining surfaces are heated to a temperature above the melt temperature and then joined under pressure to ensure a homogeneous joint. In general, only thermoplastics and thermoplastic elastomers can be welded because thermosets and crosslinked elastomers are not fusible and cannot flow. However, a material can still be welded if the crosslink density is not too high, *e.g.*, semi-crystalline crosslinked polyethylene. In this case, the bond is formed through crystallization across the joining area. Joining partners belonging to different plastic material types can only be welded if they have a certain chemical compatibility and if their melting temperatures are within a certain range.

When assessing the quality of welded joints, both leak tightness (pipes, containers, bags, packaging) and weld strength have to be considered. While leak tightness is typically determined using practical tests with welded components, test specimens are used to determine short- and long-term welding factors (quality factors). These factors provide the ratio of weld strength to strength of the parent material, and they range between 0.3 and 1. Weld quality factors always have to be listed together with the test procedure that was used to determine them because these procedures significantly influence the values of the factors. Common testing procedures are tensile, bending, flexural bending, flexural impact, tensile impact, and creep rupture tests, *e.g.*, of pipe joints under internal pressure. A welded joint may introduce a notch effect into the component. The heat introduced locally into the weld seam creates local changes in residual stresses which significantly affect the service life of a welded joint and may require testing of the long-term properties of a welded component. The quality of a welded joint is also affected by material and processing properties (residual stresses, crystallization, orientation) of the joining partners.

The different welding processes are categorized according to their type of external heat input (Fig. 4.119).



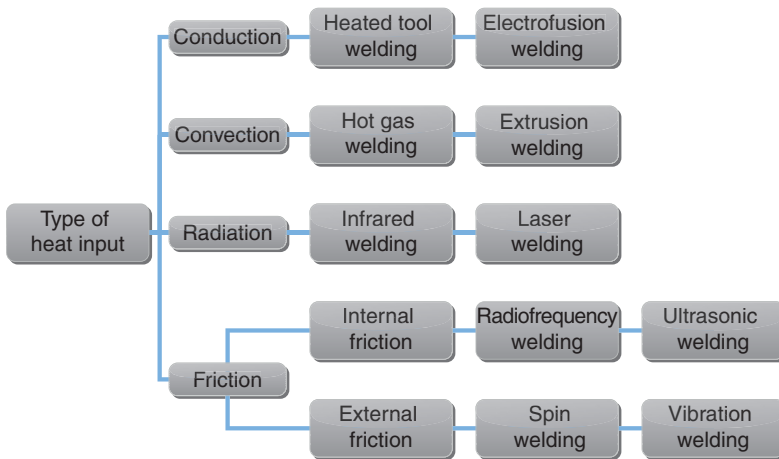


Figure 4.119 Welding of thermoplastics

4.12.1.1 Heated Tool Welding with Contact Heating

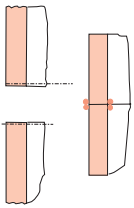
The joining areas are brought into direct contact with the metal hot plates (electrically heated to 180–300 °C, in special cases up to 550 °C) and are heated up under light pressure until a bulge of plastic molten material has been formed. After quick removal of the heated tool(s), the joining surfaces are pressed together with a pressure of 0.1 to 2 N/mm² so that molten material is pushed out of the joining area. The heating elements (typically made from Al-alloys) match the joining area and for temperatures up to 260 °C are coated with a PTFE anti-stick layer. To prevent scaling, they are either nickel or silver plated. When different materials are to be joined, the surface temperatures of the heated tools are adjusted to match the different melting temperatures of the plastic joining partners. The difference in surface temperature of the heated tools should not exceed 5 K.

Heated tool welding equipment that can be used both on the shop floor and on-site allow for high quality welded joints. Here, the parts to be joined are clamped and guided, the heat reflectors are automatically swiveled, and the sequence of operations, heat reflector temperature, and contact pressure are controlled. Polyolefin semi-finished products in particular are manufactured this way:

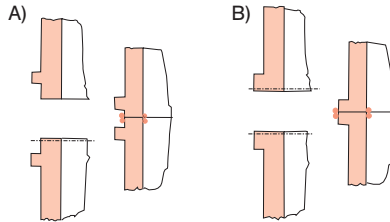
- Welding and edge bending of plastic sheets using heated swords with lengths up to 2 m,
- Butt welding of pipes with diameters up to 1,400 mm,
- Welding of pipe fittings using heated tools that heat interior and exterior surfaces to be welded,
- Welding of components into sheets or pipes (Y-pipes),
- Mitered joints, *e. g.*, of PVC window frames,
- Joining of injection molded parts, *e. g.*, to form hollow parts and intake manifolds.

Heating muffles and mandrels are used to form and heat internal and external pipes for welded sleeves in a single operation. Figure 4.120 shows examples of typical joint designs.

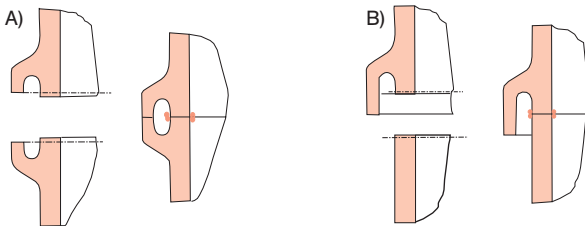
1) Simple butt weld



2) Modified butt weld



3) Joint design for hidden butt welds



4) Butt welds for external attachments

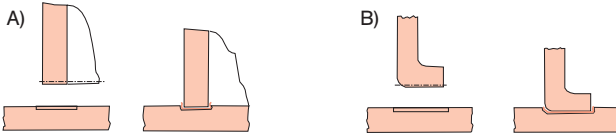


Figure 4.120

Joint design for heated tool welding

Socket welding with arc welding fittings is a special variation of heated tool welding. During injection molding, lost heating coils are internally imbedded in the socket and electrically heated. The plastic material's thermal expansion creates the welding pressure.

Lap joints of flexible sealing membranes for roofing and landfill applications are manufactured continuously by guiding the membranes over heated wedges and subsequently joining them using pressure rollers.

4.12.1.2 Heated Tool Welding with Non-Contact Heating

The processes have been developed in particular for films in the packaging industry. The overlapping films are placed between two tools with either one or both tools being heated. *Heat sealing* processes use constant heating at 150 to 250 °C. The heated tools are covered with PTFE-coated glass fiber fabrics and transfer heat through the film into the weld area. Weld seam quality is optimized by varying welding time and pressure. The fact that the welded seam does not cool while un-

5

Plastic Materials

■ 5.1 General Remarks

Comparisons between different plastic materials will be based on characteristics provided in Table 3.1 in Section 3.1 (see also CAMPUS database or ISO 10350). For example, in general, no values for impact strength will be provided, because these values typically do not contribute significant information to either part design or a part's load bearing capacity, see also Section 3.3.3. As a general rule of thumb it can be assumed that parts made from resin types with a lower modulus of elasticity and a higher elongation at yield (elongation at break) will be more ductile (tougher) under excessive loads.

Unless particularly noted, specific property values are given for generic unmodified material classes. Because in general there will be no data provided for specific trade names, the property values given should be considered an indicating range. Specific material types may vary widely from these ranges, particularly regarding classifications such as “resistant” or “non-resistant” to environmental conditions.

■ 5.2 Polyolefins (PO), Polyolefin Derivatives and Copolymers

Polyolefins are polymers built from hydrocarbons with a double bond and the general chemical structure C_nH_{2n} (ethene, propene, butene-1, isobutene). They include polyethylene, polypropylene, polybutene-1, polyisobutene, poly-4-methylpentene as well as their respective copolymers. Today, the available homo- and copolymeric resins based on ethylene and propylene provide an extraordinarily broad range of properties.

The polyolefin architecture is determined in particular by the catalysts used, with *metallocene catalysts* gaining increasing importance. Polymeric resins made with

metallocene catalysts provide a narrow molecular weight distribution and their polymerization allows for a particular sequence and order of their monomer building blocks. In addition, it is possible to incorporate building blocks into the polyolefin structure that could not be incorporated previously by copolymerization.

5.2.1 Polyethylene Standard Homo- and Copolymers (PE-LD, PE-HD, PE-HD-HMW, PE-HD-UHMW, and PE-LLD)

Polyethylenes (PE) are semi-crystalline thermoplastic materials. Their structure, molecular weight, crystallinity, and thus their properties depend to a high degree on the polymerization method used and on possible chain branching options (see Section 2.3). The relative molecular weight and its distribution can be influenced by high thermal or mechanical stresses, which is typically avoided. The degree of crystallinity is determined by the structure of the polymer and the processing conditions. For industrial applications, ISO 1133 categorizes polyethylenes by their different densities, which depend on the respective degree of crystallinity of each specific PE grade. ISO 1872 is used internationally and specifies PE resins mainly by “density” and “melt flow rate (MFR)”; in addition, it uses a system of abbreviations indicating application, processing method, additives, fillers, and reinforcements. However, the characterization by these designations is inadequate in describing the properties and application ranges for the numerous PE grades available and is therefore rarely used in practice.

5.2.1.1 Polymerization, Chemical Constitution

In general, polyethylenes are produced either by high-pressure processes in the presence of radicals (radical polymerization) or by medium- and low-pressure processes with the help of catalyst systems (anionic polymerization). In addition, polyethylenes are classified as suspension-, solution-, gas phase-, or mass polymerization grades depending on their state. High-pressure processes are used for highly branched homopolymers (PE-LD), while medium- and low-pressure processes are used to synthesize linear homo- and copolymers (PE-HD, PE-MD, PE-LLD).

High-pressure process: PE-LD (LD = low density) is synthesized by a *high pressure process* from ethylene ($\text{CH}_2=\text{CH}_2$) under a pressure of 1,000 to 3,000 bar at 150 to 275 °C with 0.05 to 0.1% oxygen or peroxides as catalysts; synthesis occurs either discontinuously in stirrer vessels or continuously in pipe reactors. The result is a highly branched PE with side chains of different lengths. Its crystallinity ranges from 40 to 50%, its density from 0.915–0.935 g/cm³, and it has a molecular weight average up to 600,000 g/mol. With the help of high-performance catalyst systems, PE-LD synthesis equipment can also produce linear low density PE (PE-LLD).

Medium- and low-pressure process: PE-HD (HD = high density) is synthesized by either a *medium-pressure* (Phillips method) or a *low-pressure process* (Ziegler method), both of which are suspension processes. The Phillips method uses pressures from 30 to 40 bar, temperatures from 85 to 180 °C, and chromium oxide or aluminum oxide as catalysts. The molecular weights obtained are approx. 50,000 g/mol. The *Ziegler method* uses pressures from 1 to 50 bar, temperatures from 20 to 150 °C, and titanium halides, titanium esters, or aluminum alkyls as catalysts, obtaining molecular weights ranging from 200,000–400,000 g/mol. PE-HD is almost unbranched and therefore has a higher degree of crystallinity (60–80%) and higher densities (0.94–0.97 g/cm³) than PE-LD.

PE-HD-HMW (HMW = high molecular weight) with a density of 0.942–0.954 g/cm³ and PE-HD-UHMW (UHMW = ultra-high molecular weight) with a density of 0.93–0.94 g/cm³ offer high molecular weights together with their high densities. These resins are produced with special catalysts in a low-pressure process. The average molecular weight ranges from 200–500 kg/mol for PE-HD, from 500–1,000 kg/mol for PE-HD-HMW, and from 3,000–6,000 kg/mol for PE-HD-UHMW.

PE-LLD (LLD = linear low density) is polymerized with high-efficiency catalysts (metal complexes) in four different processes: a *low-pressure process* in the gas phase, in solution, in suspension, or in a *modified high-pressure process*. Copolymerization of ethylene with 1-olefins, such as butene-1 or hexene-1, creates short side chains. Compared to linear PE-HD, PE-LLD contains a higher ratio of comonomers. The higher molecular weight and the low number of side chains lead to improved properties of these resins.

PE-VLD (VLD = very low density) with a density of 0.905–0.915 g/cm³ and PE-ULD (ULD = ultra low density) with a density of 0.890–0.905 g/cm³ exhibit such a high degree of branching caused by their increased comonomer content that their densities decrease below 0.915 g/cm³.

PE-(M) (*polyethylene produced with metallocene catalysts*) exhibits a narrow molecular weight distribution and can be produced in a broad range of densities. Although PE-MLLD (M) is of the same composition as “regular” PE-LLD, it shows a different sequence statistic. Transition metal compounds activated by methyl aluminoxanes are used as catalysts, typically with Ti- or Zr-centers linked with cyclopentadienyl residues.

The densities of PE-(M) grades range from

- PE-MLLD: 0.915–0.930 g/cm³
- PE-MMD: 0.930–0.940 g/cm³ (medium density)
- PE-MHD: 0.940–0.995 g/cm³

In addition, it is possible to produce PE-MVLD with densities from 0.863–0.885 g/cm³ (polyolefin-elastomers) and 0.866–0.915 g/cm³ (polyolefin-thermoplastics).



5.17.3.2 Rigid Foams (PUR-R)

Rigid foams exhibit relatively high resistance to deformation under compression load. Their most important properties are their very low thermal conductivity caused by the insulating gases in the *closed cells* and their ability to form solid composites with almost any flexible or rigid skin layer. *Rigid foam blocks* are manufactured either continuously or in batch processes as semi-finished products and subsequently cut to measure depending on application. They range in density from 30–90 kg/m³ and are used for various insulation applications, automotive interiors, and others.

Comparison of properties, see Table 5.48.

Foamed panels with protective outer skins are produced either continuously on double belt lines or discontinuously. The outer skins can be either flexible or rigid. Examples of carrier materials include Kraft paper, aluminum, particle or plaster boards, coiled steel or beaded sheet metal, and coated glass fiber mats. Areas of application are: building/construction as roofing insulation, sheet rock and plaster boards, sandwich elements for industrial buildings and cooling facilities. The core density of the foams ranges from 30–40 kg/m³. Foams are introduced into hollow parts or hollow spaces as liquid reaction mixtures and fill these spaces after foaming. With densities from 30–60 kg/m³ they serve as thermal insulators in cooling appliances of all sorts, for hot water boilers and district heating pipes. *In situ* foams for roofing and wall insulation, window- and door installation, and sealing is produced directly on site by mobile foaming machines or by pressure vessels from single- or two-component foam systems. Densities are ≈ 30 kg/m³; spray foams for roof sealing purposes have densities up to 55 kg/m³.

5.17.3.3 Integral Foams (PUR-I)

While flexible and rigid foams are fundamentally different in their chemical structure (highly crosslinked/little crosslinked), *integral foams* represent a *variation in production technology*: they are available both as rigid and as flexible *molded foams* only. The liquid, highly reactive mixture is injected into a closed mold, in which foam generation and mold temperature control are used to produce parts with cellular cores and solid skins. The transition from core to skin is not abrupt but rather continuous (see Fig. 5.20). This technique of foaming highly reactive PUR systems with particularly short holding times is generally called *reaction injection molding (RIM)*; it is used to produce both large parts as well as parts with minimum dimensions and with flow length-to-wall thickness ratios of up to 1 : 1000.

Flexible integral foams with densities from 200 to 1100 kg/m³ are used for exterior body parts, bicycle seats, shoe soles, and others.

Rigid integral foams with comparable densities are used for technical parts, in construction, furniture, and sport- and leisure products of various designs and purposes.



Glass fiber reinforced integral foams (R-RIM) with densities from 1.0–1.4 g/cm³ are used for automotive body parts and housings.

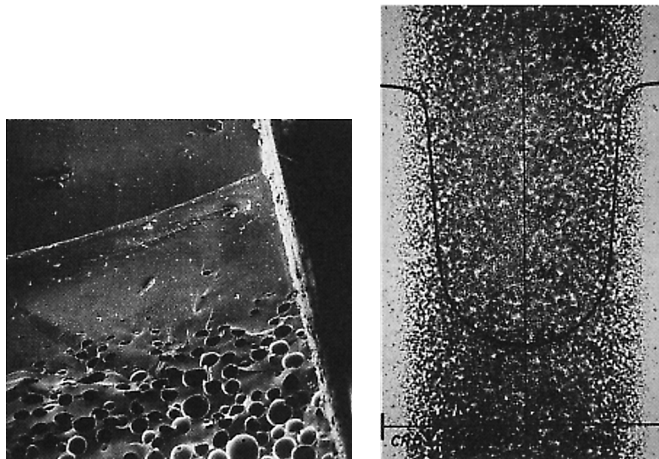


Figure 5.20 Integral foams
 Left: Foam structure
 Right: Density transition across specimen section

PUR-RIM is used to produce stiff, laminar parts, *e.g.*, automotive interior side panels. Long fibers, fabrics, non-woven material, or fiber mats, for which bio-renewable materials such as flax, sisal, or coir (coconut fibers) are increasingly used, are sprayed or impregnated with the PUR mixture and laid into the mold where they are compression molded.

Table 5.49 provides an overview of the properties of various integral foam systems, while Table 5.50 shows the dependency of certain properties on density and provides an example of flexible integral foam properties in automotive applications.

R-RIM parts (with 20–25% wollastonite reinforcement) can be coated in-line, *e.g.*, for exterior automotive panels. The plastic parts are connected to the car body prior to electro-immersion coating. Shrinkage is 0.8 or 0.57%, respectively, for temperature loads of 2 times 45 min at 200 °C. These systems are also suitable for thin-wall technology: automotive door sills with 2 mm thickness and a length of 2 m.

Table 5.49 Property Comparison for PUR Flexible Integral Foam, R-RIM

PUR-System	Filler	Filler content	Density	Shore-hardness	Flexural modulus of elasticity	Tensile strength	Elongation at break	Application, see below
		wt.-%	g/cm ³		MPa	MPa	%	
Flexible		0	1.05–1.10	D 66	500–760	26–33	135–150	A
	Glass flakes	20	1.20	D 75	1550	31	30	A
	Mica	22	1.25	D 75	1720	30	25	A
	Glass fibers, average fiber length 180 µm	15	1.20	D 68	950	31	140	A
		20	1.24	D 70	1400	28	130	A
25		1.30	D 71	1700	27	120	A	
Shoe soles		0	0.55–0.60	A 55–60		8–10	550–460	B
		0	0.60	A 60		25	600	C
Rigid	Glass mat 225 g/cm ²	30	0.25		250	5.8 ¹⁾	2.3	D
	300 g/cm ²	20	0.48		900	25 ¹⁾	2.2	E
	600 g/cm ²	20	1,0		3500	110 ¹⁾	2.2	F
	1800 g/cm ²	32	1.4		650	170 ¹⁾	2.8	G
S-RIM ²⁾		25	1,05		4200	70	1.9	H
LFI ³⁾		25–30	0.7–1.0		4500–6000	54–68	2.2–1.8	H

¹⁾ Flexural strength; ²⁾ Structural RIM; ³⁾ Long fiber injection.

A Car panels	E Automotive roof frames, -columns-/door-/seat-/trunk liners, rear window shelf
B Integral shoe soles	F Car dashboard frame, consoles, seat frame, seat-back, spare tire and engine cover
C Shoe soles	G Automotive seat shells and frames, bumper beams
D Automotive roof linings	H Sun roof

Table 5.50 Property Comparison of Flexible PUR Integral Foam in Automotive Applications (RIM)

Property	Unit	Application (see below)						
		A		B	C	D		
		Core	Skin				GF 22	
Density	g/cm ³	0.120–0.175		0.7	0.95–1.08	1.0–1.1	1.22	
Tensile strength	MPa	0.27–0.50		1.7–3.5	5.7	14–31	17–28	23
Flexural modulus	MPa				17	75–720	40–350	1300
Elongation at break	%	220–125		220–120	230	220–140	> 300–230	130
Shore hardness					A 75	D 39–69	D 33–57	D 67

Application: Type A: Motorcycle seats, interior automotive safety equipment
 Type B: Bumper skins, door protection strips
 Type C: Bumpers, truck splash boards, external automotive body parts
 Type D: Car body parts

■ 5.19 Thermoplastic Elastomers (TPE)

Acronyms, see Table 5.56.

Table 5.56 Overview of Thermoplastic Elastomers

Acronym	Chemical description
TPE	Thermoplastic elastomers
TPA	Polyamide TPE
TPA-EE	TPA, soft segments with ether- and ester bonds
TPA-ES	TPA with polyester soft segments
TPA-ET	TPA with polyether soft segments
TPC	Copolyester TPE
TPC-EE	TPC, soft segments with ether- and ester bonds
TPC-ES	TPC with polyester soft segments
TPC-ET	TPC with polyether soft segments
TPO	Olefin TPE
TPO-(EPDM+PP)	Ethylene/propylene/diene + polypropylene
TPO-(EVAC+PVDC)	Ethylene/vinyl acetate + polyvinylidene chloride
TPS	Styrene TPE
TPS-SBS	Styrene/butadiene block copolymer
TPS-SIS	Styrene/isoprene block copolymer
TPS-SEBS	Styrene/ethene/butene/styrene block copolymer
TPS-SEPS	Styrene/ethene/propene/styrene block copolymer
TPU	Urethane TPE
TPU-ARES	Aromatic rigid segments, polyester soft segments
TPU-ARET	Aromatic rigid segments, polyether soft segments
TPU-AREE	Aromatic rigid segments, soft segments with ether and ester bonds
TPU-ARCE	Aromatic rigid segments, polycarbonate soft segments
TPU-ARCL	Aromatic rigid segments, polycaprolactone soft segments
TPU-ALES	Aliphatic rigid segments, polyester soft segments
TPU-ALET	Aliphatic rigid segments, polyether soft segments
TPV	TPE with crosslinked rubber
TPV-(EPDM-X+PP)	Highly crosslinked EPDM + PP
TPV-(NBR-X+PP)	Highly crosslinked acrylonitrile/butadiene
TPV-(NR-X+PP)	Highly crosslinked natural rubber + PP
TPV-(ENR-X+PP)	Highly crosslinked epoxidized natural rubber + PP
TPV-(PBA-X+PP)	Crosslinked polybutylacrylate + PP
TPZ	Other TPEs
TPZ-(NBR+PVC)	Acrylonitrile/butadiene rubber + polyvinyl chloride

5.19.1 Physical Constitution

TPEs combine the elastomeric properties of crosslinked elastomers with those of rubbers (see Section 5.22) with the advantage of thermoplastic processability.

Their composition allows the classification in two groups:

Polymer blends consist of a “rigid” thermoplastic polymer matrix, into which either non-crosslinked or crosslinked elastomer particles are incorporated as a “flexible phase”. Examples are thermoplastic polyolefin elastomers (TPO or TPV) that consist of PP with up to 65% of incorporated ethylene-propylene-[diene] rubber (EP[D]M).

Graft- or copolymer molecules contain thermoplastic sequences A and elastomeric sequences B. Both components A and B are incompatible and demulsify locally so that the rigid A sequences form physical crosslinking points in the continuous matrix of flexible B sequences. An example is styrene block copolymer TPS, in which blocks of polystyrene (S) and butadiene (B) alternate: SSSSSSSS-BBBBBBBB-SSSSSSSS.

At service temperature, the flexible B sequences are above their glass transition temperature (freezing point); however, the rigid A sequences are below their glass transition temperature (for amorphous polymers) or their melt temperature (for semi-crystalline polymers). Above their transformation temperature, the A sequences soften so that TPEs can be processed like thermoplastics.

5.19.2 Chemical Constitution, Properties, Applications

Compared to rubbers, TPEs offer the following advantages: being suitable for thermoplastic processing and therefore also for recycling, weldability, transparency for some grades, colorability. An important area of application is therefore rigid-flexible combinations in 2-component injection molding (see Section 4.3.5.4) and in coextrusion (see Section 4.2.3.9). Table 5.56 provides an overview of acronyms and chemical designations, while Table 5.57 provides a comparison of properties.



Table 5.57 Property Comparison of Thermoplastic Elastomers (TPE)

TPE	Type	Density g/cm ³	Shore hardness		Service temperature °C			Glass transition temperature T _g °C	Resistance against ¹⁾				
			A	D	max. short-term	max. con- tinuous	min. con- tinuous		Wear	Oil	Acid	Alkali	Aging
TPA	PA6	1.0–1.2	> 65	< 75	85	-60	80	2	1	2	2	2	2
TPA	PA12	1.1–1.3	> 85	< 85	150	-65	160/220	2	1	3	4	4	2
TPC ²⁾		0.9–1.0	> 50	< 70	115	-50	160	4	4	2	1	2	2
TPO	EVAC-PVDC		> 55	< 80	100	-40							
TPO	PP-EPDM-X	0.94–1.0	> 35	< 75	145	-50	160	3	3	1	1	1	1
TPV	PP-NBR-X		> 45	< 70	110	-40	160						
TPS	SBS	0.9–1.1	> 27	< 50	90	-40	95	2	4	2	2	2	2
TPS	SEBS		> 10	< 75	150	-50							
TPU	AREE	1.1–1.3	> 65	< 80	120	-50	130–200	1	1	3	4	4	1

¹⁾ 1 = excellent, 2 = good, 3 = adequate, 4 = poor

²⁾ see also Table 5.30

5.19.2.6 Polyolefin Blends with Crosslinked Rubber (TPV)

These TPEs are crosslinked with flexible rubber segments. They exhibit increased elasticity and resistance. Oil-resistant and foamable grades are available. Applications: door- and window seals, air intake manifolds in automotive applications.

5.19.2.7 Other TPEs, TPZs

This category includes TPEs based on PVC with NBR [TPZ-(NBR + PVC)] or PBA [TPZ-(PBA + PVC)]. They are used for extruded seals. TPEs with crosslinked NBR are considered TPVs.

■ 5.20 Thermosets, Curable Resins, Formaldehyde Molding Resins (PF, RF, CF, XF, FF, MF, UF, MUF, MUPF), Other Resins (UP, VE (PHA), EP, PDAP, SI)

Thermosets is a general term describing polymeric materials consisting of close-meshed, spatially crosslinked macromolecules. In general, these materials are rigid and behave as elastics up to their degradation temperature so that they cannot be processed like thermoplastics. Molding and forming occurs either at the same time or prior to chemical crosslinking (curing).

Raw materials for thermosets are reaction resins (curable resins), which will react either at room temperature after the addition of curing agents or at elevated temperatures without curing agents. Curing can also be initiated by electron- or UV radiation.

Curable molding compounds are resins that can be processed by compression, transfer molding, extrusion, or (for special resins) by injection molding under simultaneous formation of macromolecules (crosslinking). They are filled and reinforced (some to a high degree). Delivery forms: dust-free grounds, pellets, free-flowing rods, and granules.

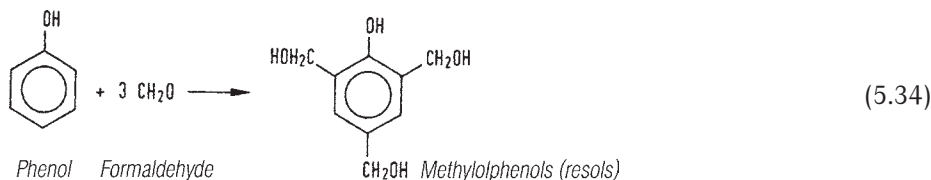
Prepregs (pre-impregnated) are laminar or tape-like materials, into which reinforcement in the form of mats, fabrics, or rovings can be incorporated (possible orientation from anisotropic to uniaxial).

5.20.1 Chemical Constitution

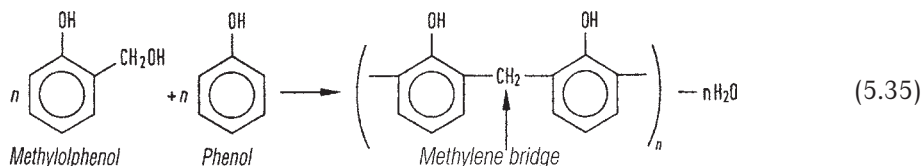
5.20.1.1 Formaldehyde Molding Resins (PF, RF, CF, XF, FF, MF, UF, MUF, MUPF)

The polycondensation of formaldehyde resins will be exemplified by phenol formaldehyde (PF). It begins with fundamental reactions (see Eq. 5.34 to 5.36), which involve the formation of various cross-linkages during curing:

Addition to phenol alcohols:

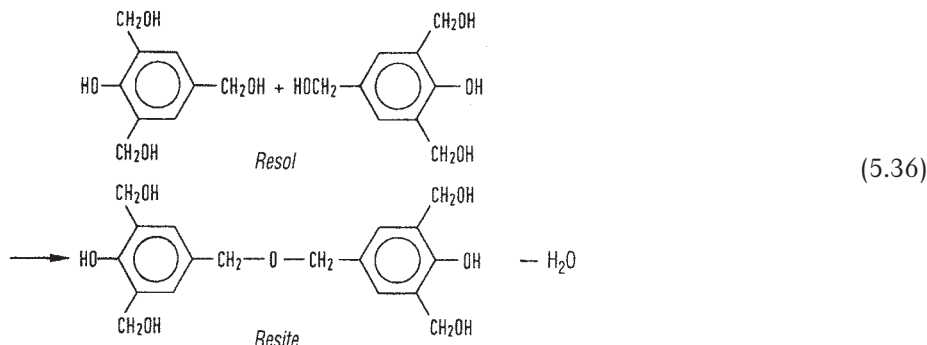


Condensation under elimination of water:



The condensation is performed step-wise to facilitate the escape of volatile reaction products. In stage “A” (resol), the reaction product is still soluble and can be melted. In stage “B” (resistol), the product can only be swelled and softens only at elevated temperatures, while in stage “C” (resite) complete crosslinking has occurred (Eq. 5.36). The product is insoluble and cannot be melted. The manufacturing of molded parts can be based on stage A resins, though mostly it is based on stage B resins.

Condensation with further elimination of water:



ISO 1043-4 classifies different flame retardant groups by code numbers, see Table 6.3. This identification is particularly important for components that are molded from recycled material and must not contain halogen-based flame retardants.

Table 6.3 ISO 1043-4 Codes for Flame Retardants

Code No.	Flame retardant
10–29	Halogen compounds (chlorine, bromine, fluorine)
30–39	Nitrogen compounds
40–49	Organic phosphorus compounds
50–59	Inorganic phosphorus compounds
60–69	Metal oxides, metal hydroxides, metal salts
70–74	Boron compounds and zinc compounds
75–79	Silicon compounds
80–89	Graphite, among others
90–99	Not assigned

6.1.5 Colorants

Colorants for plastics are comprised of specially compounded *insoluble pigments* and of plastic-*soluble dyes*. Figure 6.1 demonstrates the significance of pigments for the coloring of plastics compared to dyes. Pigments are classified as organic or inorganic depending on their chemical constitution. In contrast to pigments for special effects (see below), absorbing pigments reflect only the colors they do not absorb (subtractive color) so that the color impression is created by the complementary color.

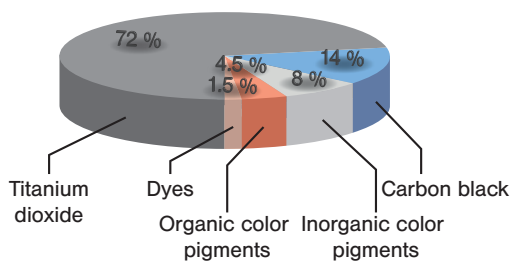


Figure 6.1

Proportions of different colorants in current applications

Because of their irregular form and light absorption, absorbing pigments exhibit only one color (independent of sight angle) and no gloss.

Inorganic pigments (Table 6.4) include metal oxides, sulfides, chromates, and carbon blacks (the latter are categorized as inorganic despite their chemical constitution).

Table 6.4 Inorganic Pigments

Pigment	Chemical family	Temp. resistance in PE-HD, °C	Chemical formula
White	Lithopone (zinc sulfide + barium sulfate)	300	ZnS • BaSO ₄
	Titanium dioxide (rutile-, anatase modification)	300	TiO ₂
	Zinc oxide		ZnO
Black	Carbon blacks		
	Iron oxide black	240	Fe ₃ O ₄ , (Fe,Mn) ₂ O ₃
	Spinel black	300	Cu(Cr,Fe) ₂ O ₄ , Cu(Cr,Mn) ₂ O ₄ , (Fe,Co)Fe ₂ O ₄
Yellow/orange	Cadmium yellow ¹⁾	300	CdS, (Cd,Zn)S
	Chrome yellow ¹⁾	260/290	PbCrO ₄ , Pb(Cr,S)O ₄
	Chrome rutile yellow	300	(Ti,Sb,Cr)O ₂ , (Ti,Nb,Cr)O ₂ , (Ti,W,Cr)O ₂
	Iron oxide yellow	220/260	α-FeO(OH), χ-FeO(OH)
	Nickel rutile yellow	300	(Ti,Sb,Ni)O ₂ , (Ti,Nb,Ni)O ₂
	Bismuth vanadate/ molybdate	280	BiVO ₄ Bi ₂ MoO ₆
	Zinc ferrite		ZnFe ₂ O ₄
Brown	Chrome iron brown	300	(Fe,Cr) ₂ O ₃
	Iron oxide(manganese-) brown	260/300	(Fe,Mn) ₂ O ₃
	Rutile brown		(Ti,Mn,Sb)O ₂ , (Ti,Mn,Cr,Sb)O ₂
	Zinc ferrite brown	260	ZnFe ₂ O ₄
Red	Cadmium red/orange ¹⁾	300	Cd(S,Se) (Cd,Hg)S
	Iron oxide red	300 (1200)	α-Fe ₂ O ₃
	Molybdate red	260/300	Pb(Cr,Mo,S)O ₄
Green/blue	Chrome oxide green	300	Cr ₂ O ₃
	Cobalt (spinel) green	300	(Co,Ni,Zn) ₂ (Ti,Al)O ₄
	Cobalt blue	300	CoAl ₂ O ₄ , Co(Al,Cr)O ₄
	Ultramarine blue	300	Na ₈ (Al ₆ Si ₆ O ₂₄)S _x
Metallic	Aluminum	300	Al
	Copper	260	Cu/Zn alloys

¹⁾ Should be avoided because of Cd, Cr, or Hg content or only pigments with low soluble content should be used.

Azo- and polycyclic pigments among others represent the most significant families of *organic pigments*. All azo-pigments are characterized by their common azo-group (-N=N-), which is responsible for the selective absorption of light. Because the



entire molecular structure determines the specific color of an azo-pigment, they cover a wide color spectrum, ranging from yellow, orange, brown, and red to violet. Some azo-pigments contain carcinogenic amine components and may therefore not be used for plastic coloration applications. Polycyclic pigments also cover a wide color spectrum, ranging from orange, brown, red, violet, and blue to green. Important representatives of polycyclic pigments include quinacridones (red) and phthalocyanines (blue/green).

Polyol dyes are used to color PUR foams. Here, chromophores (constituents of a dye with excitable electrons such as conjugated double bonds) are chemically bound to polymer chains with terminal hydroxyl groups that react with isocyanate. The results are homogeneously colored polyurethanes (foams, rigid and rubber-elastic components; the latter can also be manufactured with transparent coloration).

The following properties determine application and processing conditions of pigments: light and weather fastness, heat and chemical resistance. Other undesirable issues to be considered are warpage caused by pigments and migration of pigments to the surface of manufactured components. Pigments may also considerably affect flow, curing, and electrical properties. Compatibility with the plastic is another important criterion for the selection of suitable pigments. The coloration created by pigments is determined by particle size and distribution in the plastic. The smaller the particles, the more vivid the color. Inorganic pigments generally exhibit higher light fastness and better temperature resistance with low migration tendency. Organic pigments offer more luminous colors.

Several plastics yellow under UV exposure and are therefore not light/color fast as such. This results in a darkening, in particular of lighter colors.

Pigments are available in powder form; however, they are difficult to disperse in plastic materials. Therefore, plastics are often colored using pigment pastes with binders and/or plasticizers. These are available either as pelletized masterbatches or in liquid plastics.

Over the past decades, the colorant market has seen continuous increase in products that provide special optical effects in addition to coloring plastics. These products include metal and pearlescent pigments, fluorescent colorants, and last but not least optical brighteners.

Pigments for Special Effects

Pigments that provide metal and pearlescent effects are “special effect” pigments.

Metal pigments consist of small aluminum, bronze, or gold platelets that reflect light like mirrors. Pearlescent pigments are based on silicon or aluminum oxide platelets with thin (few nanometers thick) titanium or iron oxide layers. TiO₂-pearlescent pigments are often used. Pearlescent pigments partially reflect light directly at the smooth surface of the pigment, while another part of the



7

Material Properties

This chapter provides comparisons of the most important properties of plastic materials in table format. When possible, tables and charts referring to specific classes of plastic materials were placed in the respective chapter.

Because material names and properties have already been discussed in the previous chapters, this chapter will not offer additional explanations.



7.1 Processing Characteristics and Tolerances

Table 7.1 Processing-Relevant Characteristics for Selected Plastic Materials (Injection Molding)

Plastic material	Processing temperature °C	Pre-drying °C/h	Mold temperature °C	Shrinkage %	Length of flow path ¹⁾ at 2 mm wall thickness
PE-LD	160-220	-	20-60	1.5-5.0	550-600
PE-HD	180-250	-	10-60	1.5-3.0	200-600
EVAC	130-240	-	10-50	0.8-2.2	320
PP	200-270	-	20-90	1.3-2.5	250-700
PB	220-290	-	10-60	1.5-2.6	300-800
PIB	150-250	-	50-80	1.5-3.0	
PMP	280-310	-	ca. 70		
PS	170-280	-	10-60	0.4-0.7	200-500 -
SAN	200-260	85/2-4 -	50-80	0.4-0.7	200-500
SB	190-280	70-80/2 ²⁾	10-80	0.4-0.7	320 -
ABS	200-275	70-80/2-4	50-90	0.4-0.7	
ASA	220-260		50-85	0.4-0.7	
PVC-U	170-210	-	20-60	0.4-0.8	160-250
PVC-P	160-190	-	20-60	0.7-3.0	150-500
PMMA	190-270	70-100/2-6	40-90	0.3-0.8	200-500
POM	180-230	110/2 ²⁾	60-120	1.5-2.5	500
PA 6	240-290	80/8-15 ²⁾	40-120	0.8-2.5	400-600
PA 66	260-300	80/8-15 ²⁾	40-120	0.8-2.5	810
PA 610	220-260	80/8-15	40-120	0.8-2.0	-
PA 11	200-250	70-80/4-6	40-80	1.0-2.0	-
PA 12	190-270	100/4 ²⁾	20-100	1.0-2.0	200-500
PA 6-3-T	250-320	80-90/10	70-90	0.5-0.6	-
PC	270-320	110-120/4	80-120	0.6-0.8	150-220
PET	260-300	120/4 ²⁾	130-150 20 ³⁾	1.2-2.0 0.2 ³⁾	200-500
PBT	230-280	120/2 ²⁾	40-80	1.0-2.2	250-600
PPE + PS	240-300	100/2	40-110	0.5-0.8	260
PSU	340-390	120/5 -	100-160	0.6-0.8	-
PPS	320-380	160/5	20-200	ca. 0.2	-
PES	320-390		100-190	0.2-0.5	-
PVDF	250-270	-	90-100	3-6	-
PTFE	320-360	-	200-230	3.5-6.0	-
PFA	380-400	-	95-230	3.5-5.5	80-120

Table 7.1 Processing-Relevant Characteristics for Selected Plastic Materials (Injection Molding) (continued)

Plastic material	Processing temperature	Pre-drying	Mold temperature	Shrinkage	Length of flow path ¹⁾ at 2 mm wall thickness
	°C	°C/h	°C	%	
PEEK	350–390	150/3	120–150	ca. 1 –	–
PAI	330–380	180/8	ca. 230	0.4–0.7	–
PEI	340–425	150/4	65–175	ca. 1	–
PEK	360–420	150/3	120–160		–
CA	180–220	80/2–4	40–80	0.4–0.7	350
CP	190–230	80/2–4	40–80	0.4–0.7	500
CAB	180–220	80/2–4	40–80	0.4–0.7	500
PF Type 31	60–80	–	170–190	1.2	–
MF Type 131	70–80	–	150–165	1.2–2	–
MF/PF	60–80	–	160–180	0.8–1.8	–
Type 180/82		–			–
UP Type 802	40–60	–	150–170	0.5–0.8	–
EP Type 891	ca. 70		160–170	0.2	
TPO	180–200	75/2 or 65/3	10–80	1.5–2.0	–
SBS	175–250	–	10–90	0.3–2.2	–
TPA	170–230	110/2–4 or 100/3–6	15–80	1.0–2.0	–
TPC	160–220				–
TPS	180–220				–
TPU	180–220	110/0.5 or 100/2	20–40	0.8–1.5	–

¹⁾ At average melt temperature, melt pressure, and injection mold wall temperature.

²⁾ Not necessary when delivered in pre-dried form. ³⁾ For amorphous grades

Additional Shrinkage Information

Plastic material	%	Plastic material	%
PP-GF 20	1.2–2.0	PBT-GF-30	0.5–1.5
PS-HI	0.4–0.7	PPE+PS-GF-30	0.2
SAN-GF 30	0.2–0.3	PSU-GF40	0.2–0.4
ABS-GF 30	0.1–0.3	PPS-GF-40	0.2
POM-GF 30	0.5–1.0	PES-GF-40	0.15
PA 6-GF 30	0.2–1.2	PEK	0.7–0.9
PA 66	0.2–1.2	PEK-GF-30	0.3–0.8
PET-A	0.2	PC-GF-30	0.2–0.4
PET-GF-30	0.2–2.0		

Index

Symbols

1,4-cyclohexane dimethanol 464
3D printing 289

A

AA/BB polymers 430
AB polymers 430
ABS polymers 379
accelerators 592
accumulator head 220
acetate rayon 522
ACM 389
acrylamide 358
acrylate elastomers 573
acrylic acid 359, 542
acrylic acid esters 348, 410
acrylonitrile 565
additive manufacturing 289
additives 579
adhesion bonding 634
adhesive bonding 318, 634
adhesive films 319
adhesive joining 317
adiabatic extruder 203
adipic acid 430
AF 409
AFP 283
aggregation 27
aldehydes 559
algae 143
aliphatic polyesters 483
aliphatic polyketone 530
alkyd resins 560
alkyl sulfonic acid esters of carboxylic acid 393
all-electric injection molding machines 228
allyl derivatives 559
allyl esters 544
aluminum hydroxide 596, 600
aluminum nitride 596
aluminum silicate 596
aluminum trihydrate 600
amines 509, 543
aminocaproic acid 430
amino lauric acid 430
aminoplastic molding compounds 548, 554
aminoplastics 558
amorphous phase 29
amorphous polyamides 435
amorphous structures 27
amorphous thermoplastics 34
annealing 39
anti-bacterial agents 594
anti-blocking agents 579
antioxidants 581
antistatic agents 583
aqueous coatings 558
aramid 455
aramid fibers 617
arc resistance 121
aromatic polyesters 456
aromatic polyether ketones 483
aromatic polyethers 480
aromatic polyimides 487
aromatic polysulfides 475
aromatic polysulfones 475
aromatic units 25
Arrhenius approach 59
artificial horn 526
ASA 380
asbestos 607
aspect ratio 269
assembly injection molding 236
atactic 19
ATL 283
auger mixer 182

auto-ignition temperature 152
automated fiber placement 283
automated tape layup 283
azo crosslinking 347
azodicarboxylic acid diamide 592
azo-pigments 587

B

bacteria 143
ball indentation hardness 75
Barfilex-technology 212
barrier films 658
barrier screws 201
batch production 266
bending 298
bending strength 73
bending stress 73
bend test 72
biaxial stretching 208
binder jetting 295
biodegradable plastics 519
bioplastics 519
biopolymers 24, 519
bi-polymer 40
Bird-Carreau-Yasuda model 58
birefringence 129, 131
bis-(isocyanatomethyl)-norbornane 508
bisphenol A 456, 558
bisphenol A glycidyl ethers 542
blending 179
blister process 302
block-copolymers 40
block foams 512
blowing agents 510, 591
blowing die 213
blowing mandrel 219
blown film 209
BMC 270
BMC injection 233
bonding agents 590
break bending 299
Brenner process 324
bristles 620
bromiumbutyl rubber 570
bubble process 302
bulk modulus 88
bulk molding compounds 270, 545
butadiene 565
butadiene elastomers 569
butanediol 470, 537, 541

butene 355
butt welding 304
butyl acrylate copolymer 358
butyl elastomers 570

C

calcium carbonate 596, 598
calcium sulfate 596
calendering 214, 216
camphor 524
CAMPUS 45
capillary rheometer 54
caprolactam 430
carbon black 123, 597, 602
carbon fibers 613
carbon nano-fibers 603
carbon nano-tubes 603
carbon particles 603
carboxymethyl cellulose 525
Carreau model 58
cascade extruder 202
cascade injection molding 240, 250
casein formaldehyde 526
casein polymers 526
cast films 257
casting 257
castor oil 509
cast polyamides 455
Catalloy-catalysts 361
cell size control 510
celluloid 524
cellulose 25
cellulose acetobutyrate 523
cellulose derivatives 520
cellulose hydrate 525
cellulose nitrate 524
cellulose propionate 523
Celuka process 210
ceno-spheres 601
ceramics 596
ceramics injection molding 236
chain branches 21
chain extenders 509
chalk 596
charge transport 112
Charpy impact strength 78
chemical foaming 255
chemical resistance 139, 649
chemical structure 18
chemical vapor deposition 329

- chill roll 207
- chlorinated PE 348
- chlorinated PE elastomers 573
- chlorinated PVC 386
- chlorobutadiene 565
- chlorobutyl rubber 570
- chloroprene elastomers 569
- chlorosulfonated PE elastomers 573
- chromaticity table 131
- chromatography 173
- CIE-Lab system 127
- citric acid esters 393
- clamping force 223
- clarifiers 593
- classification 15
- cleaning pellets 234
- CLIP 295
- closed cells 515
- coalescence 179, 181
- coat hanger die 208
- coating 193, 322
- coatings 214
- coefficient of diffusion 137, 647
- coefficient of friction 155
- coefficient of thermal expansion 105
- coefficient of wear 156
- coextrusion 212
- coextrusion adaptor 213
- coextrusion blow molding 220
- co-kneader 183
- cold cast systems 518
- cold curing 543
- cold foam 513
- cold pelletizing systems 193
- cold plasma 321
- cold thermoforming 300
- colorants 586
- colorimetry 127
- color variable pigments 589
- comonomers 397
- comparative tracking index 120
- compatibility 628
- composite films 214
- composite materials 268
- compostability 519
- compounding 178
- compression mold 285
- compression molding 284
- compression resin transfer molding 278
- compression test 74
- conductive plastics 123, 644
- conductive polymer coatings 323
- conductive thermoplastic compounds 527
- cone-plate rheometer 54
- configuration 18, 19
- conformation 19, 27
- conical hopper mixers 183
- constitution 18, 21
- contact adhesives 318
- continuous fiber-reinforced composites 269
- continuous liquid interphase process 295
- cooling time 223, 231
- COP 359
- copolyamides 450, 535
- copolyesters 535
- copolyester TPE 532
- copolymers 40
- core compression process 232
- corner warpage 67
- corona treatment 321
- cotton 520, 612
- counter rotating extruders 204
- counter-valve process 250
- crack formation 140
- crankshaft polymers 498
- crash simulation 75
- creep 29
- creep modulus 80
- creep resistance 83
- creep test 79
- creep-time diagram 79
- creep-time lines 79
- resol resins 557
- critical strain 83
- crosslinked elastomers 35
- crosslinked PE 346
- crosslinking 26, 334
- crosslinking agents 509
- Cross model 59
- C-RTM 278
- crystal growth 29
- crystalline phase 29
- crystalline superlattices 29
- crystallinity 21, 38
- crystallite melting temperature 91
- crystallization 29, 38
- CTI 120
- curable molding compounds 538
- curing 26
- curing time 285
- cutting 332, 333
- cyclic polybutylene terephthalates 471

cyclooctene 565
cycloolefin copolymers 358
cyclopentane 510

D

DEA 164
decorating 324
de-flashing 331, 332
deformation 29
degassing extruder 201
degassing screws 230
dehumidified air dryers 196
density 89
density distribution 255
design 16
di-2-ethylhexyl phthalate 522
diallyl phthalate molding compounds 551, 556
diallyl phthalate resins 544, 564
dibutyl phthalate 522
dicarboxylic acid 535
dicarboxylic acid ester 535
dicyclopentadiene 359, 369, 541
dicyclopentadiene resins 564
dielectric constant 121
dielectric displacement 112
dielectric dissipation factor 121, 165
dielectric properties 117
dielectric spectroscopy 164
dielectric strength 117
diethyl phthalate 522
differential calorimetry 166
differential shrinkage 65
differential thermal analysis 166
diffusion 137
diffusion bonding 317, 634
digital light processing 294
dihydroxydiphenyl sulfide 462
dihydroxypolytetrahydrofuran 535
diisocyanates 508, 537
diisopropyl phthalate 522
dilatometry 168
dimethyl glycol phthalate 522
dimethyl phthalate 522
diphenyl carbonate 457
direct tooling 297
discontinuous fiber composites 269
dispersion adhesives 318
dispersive mixing 179, 180
displacement orientation 112
distributive mixing 179

D-LFT process 274
DMA 163
DOD 462
dodecane dicarboxylic acid 462
double bonds 26
dough molding compounds 545
draft angle 133
drapability 284
drape forming 299
drilling 332
dryers 194
drying parameters 195
dry-offset printing 325
DSC 166
DTA 166
dyes 586
dynamic behavior 84

E

ebonite 565
edge bending 304
ejection 225
ejection shrinkage 63
elastomers 26, 565
electrical characteristics 49, 644
electrical conductivity 115
electrical field strength 112
electrical insulation properties 113
electrically conductive fillers 605
electrically conductive polymers 527
electrical properties 111, 637-639
electrolytic corrosion 121
electromagnetic interference 116
electromagnetic shielding 116
electron beam crosslinking 347
electro-plating 630
electrostatic behavior 123
electrostatic charges 335
electrostatic discharge 111, 123
electrostatic fluidized bed coating 324
electrostatic powder spray process 324
elongational flow 181
elongational viscosity 58
elongation-induced crystallization 31
embossing 326
EMI 116
emulsifiers 510
emulsion polymerization 385
energy-elastic zone 28
entanglements 24

- enthalpy 98
 - entropy elasticity 24
 - entropy-elastic zone 28
 - environmental influences 133, 647
 - environmental stress cracking 140
 - EPDM 367
 - epichlorohydrin 558
 - epichlorohydrin elastomers 574
 - epoxidized products 393
 - epoxy resins 542, 551, 556, 558, 563
 - ESC 140
 - ESD 123
 - esters of aliphatic dicarboxylic acids 393
 - ethyl acrylate copolymer 358
 - ethyl cellulose 525
 - ethylene/acrylic acid acrylate 355
 - ethylene acrylic ester elastomers 572
 - ethylene bitumen blends 360
 - ethylene chlorotrifluoroethylene 407
 - ethylene copolymers 348
 - ethylene glycol 464
 - ethylene-meth(acrylic acid) copolymers 358
 - ethylene-propylene (diene) copolymers 367
 - ethylene propylene (diene) elastomers 572
 - ethylene-propylene rubbers 536
 - ethylene tetrafluoroethylene 408
 - ethylene vinyl acetate copolymer 355
 - ethylene vinyl acetate elastomers 572
 - exo-methylene lactones 418
 - expandable graphite 585
 - expanded graphite 603
 - extender 392
 - extrusion 197
 - extrusion blow molding 219
 - extrusion die 205
 - extrusion-injection 231
 - extrusion molding 288
 - extrusion screw 198
 - extrusion welding 307
- F**
- fabric molding 243
 - fabric prepregs 545
 - FAR 153
 - far-field welding 311
 - fatigue curves 85
 - fatigue tests 84
 - FDM 293
 - Federal Aviation Regulations 153
 - Federal Motor Vehicle Safety Standards 302
153
 - feeding zone 200
 - fiber fineness 624
 - fiber length 42
 - fiber-reinforced plastics 268
 - fibers 211, 579, 605, 620
 - fiber spray-up molding 275
 - fibrides 341
 - fibroids 362
 - fibrils 621
 - fields of application 14
 - filament winding 279
 - filler orientation 67
 - fillers 579, 594
 - filling foams 513
 - film gates 252
 - film tapes 621
 - finishing 630
 - flame oxidation 320
 - flame propagation 151
 - flame retardants 584
 - flame spraying 324
 - flammability 658
 - flash 286
 - flat films 207
 - flat yarns 621
 - flax 612
 - flexibilizers 590
 - flexible foam blocks 264
 - flexible foams 512
 - flexo-printing 324
 - flexural impact test 77
 - flexural stress 72
 - FLM 293
 - flocking 326
 - flooring 214
 - flow behavior 52
 - flow curve 52
 - flow length 626
 - flow line 252
 - fluid injection technology 240
 - fluorescent colorants 589
 - fluorination 329
 - fluoro copolymers 407
 - fluoro elastomers 407, 573
 - fluoro phosphazene elastomers 578
 - fluoro polymers 401
 - fluoro silicone elastomers 576
 - fluoroterpolymer 409
 - FMV SS 153

foam blocks 515
foamed profiles 210
foaming 254
foam injection molding 242
foam stabilizers 510, 582
formaldehyde resins 539
fracture behavior 82
free jet formation 231
friction 154, 660
friction coefficient 660, 663
friction welding 309
fuel tanks 220
functional polymers 498
fungicides 594
furan resins 559
furfuryl alcohol 559
fused deposition modeling 293
fused filament fabrication 293
fused layer modeling 293

G

gas injection technology 241
gas permeability 147, 151, 655–657
gas-phase polymerization processes 361
gate designs 252
gate marks 250
glass 596
glass fibers 608
glass mat reinforced thermoplastics 273
glass transition range 27
glass transition temperature 27, 30, 91
glassy state 27
global plastic production 14
gloss 126
gloss measurement 127
glucose remnant 520
GMT 273
graft-copolymer 40
grafting 341
granulated molding compounds 544
granulators 193
gravure printing 325
green parts 236
grooved-barrel extruder 200
gun cotton 524

H

HALS 582
hand lamination 275

hardness measurement 74
hard rubber 565
haze 126
HDT 94
heat capacity 98
heat conductivity 171
heat distortion temperature 94
heated tool welding 304, 305
heat sealing 305
heat-shrink tubing 298
heat stabilizers 582
heat treatment 334
heat value 100, 152
heavy tow fibers 614
hemp 612
heteroatoms 18
hexa curing agent 557
hexamethylene diamine 430
hexamethylene tetramine 557
hexanediol 537
hexene 355
high-energy radiation 142
high frequency welding 630
high impact resistant PS 379
high-pressure machines 262
high-pressure process 338
high-pressure RTM 278
high-speed extruder 203
hinges 299
hollow chamber profiles 206
hot air dryers 195
hot cast systems 518
hot disk method 171
hot-embossing films 326
hot foam 513
hot gas welding 306
hot melt adhesives 318
hot melt process 215
hot plate pelletizing 191
hot plate welding 630
hot runner 249, 250
hot stamping 630
HP-RTM 278
humidity 647
hydrated NBR elastomers 571
hydrocarbon resins 564
hydrogen bridge bonds 438
hydrolysis 138
hydroxyethyl cellulose 525

- I**
- ignitability 151
 - ignition temperature 152
 - i-hexane 510
 - IMD 243
 - imidazo derivatives 510
 - impact behavior 75
 - impact modifiers 590
 - impact test 77
 - implant induction welding 314
 - impregnation 279
 - impulse welding 306
 - incandescent wire cutting 333
 - indentation test 74
 - index of refraction 645
 - infrared spectroscopy 163
 - inherent viscosity 173
 - injection blow molding 245
 - injection compression molding 232, 235, 271
 - injection molding 221
 - injection molding cycle 223, 231
 - injection molding machine 223
 - injection molding of elastomers 234
 - injection molding of thermosets 232
 - injection molds 248
 - in-line compounding 229
 - in-mold decoration 243
 - in-mold labeling 221, 325
 - in-mold lamination 243
 - in-mold skinning 256
 - inorganic fibers 608
 - inorganic fillers 597
 - in-plane draping 284
 - in situ foams 515
 - integral foam 255, 515
 - internal batch mixers 189
 - internal pressure creep tests 83
 - interval injection molding 239
 - intrinsically conductive polymers 527, 644, 645
 - intrinsic viscosity 23
 - intumescence 584
 - ion conductivity 165
 - ionomers 358, 359
 - ion viscosity 165
 - IR-spectrometer 163
 - isochronous stress-strain diagram 80
 - isocyanates 503, 508
 - isophthalic acid 464
 - isoprene 565
 - isoprene elastomers 569
 - isoprene styrene elastomers 571
 - isotropic melting temperature 497
 - izod impact strength 78
- J**
- joining 303
 - jute 612
- K**
- kaolin 593, 596, 600
 - keto-groups 483
 - ketones 559
 - kickers 591
 - kneading screw extruders 186
 - Knoop-hardness 75
 - K-value 387
- L**
- labeling 324
 - lactam 535
 - ladder polymers 500
 - laminated sheets 286
 - laminare insert molding 243
 - laminare painting process 243
 - laminates 214
 - laminating 286
 - lap joint welding 307
 - laser-flash analysis 171
 - laser labeling 325, 590
 - lasermicrojets 333
 - laser sintering 291
 - laser welding 315
 - lauro lactam 430
 - layered silica 603
 - layer laminare manufacturing 296
 - layer model 36
 - LCM 276
 - LCP 497
 - LFT 274
 - life-cycle analysis 520
 - light transmission 645
 - lignin 520
 - limiting oxygen index 152, 619
 - linear mass density 624
 - liquid composite molding 276
 - liquid crystalline polymers 32, 497
 - liquid silicone elastomers 576

- live feed injection molding 240
 - LOI 152
 - long fiber injection 267
 - long fiber-reinforced thermoplastics 274
 - longitudinal-wave modulus 88
 - long-term behavior 79
 - long-term temperature influence 97
 - loss factor 84, 85
 - lost core technology 244
 - low-pressure high-frequency mixer 262
 - low-pressure machines 260
 - low-pressure process 339
 - luminescent polymers 527
 - Lyocell 612
- M**
- machining 331, 333
 - macromolecules 15
 - magnetizable compounds 604
 - maleic acid 541
 - maleic anhydride 341
 - mandrel die 209
 - manual welding 307
 - manufacturing costs 17
 - Mark-Houwink Equation 23
 - mass polymerization 385
 - material extrusion 293
 - material jetting 295
 - mat laminates 562
 - matrix reinforcement 43
 - mats 609
 - Maxwell equation 112
 - mechanical characteristics 47
 - mechanical forming 300
 - mechanical properties 69, 635, 636
 - mechanical spectroscopy 163
 - medium-pressure process 339
 - melamine 585
 - melamine foams 558
 - melamine formaldehyde resins 558
 - melamine phenolic molding compounds 549
 - melamine polyester resin
 - molding compounds 550
 - melt chambers 249
 - melt filter 197, 204
 - melt flow index 60
 - melting heat 32
 - melting temperature 30
 - melt mass flow rate 60
 - melt pump 204, 211
 - melt spinning 362, 621
 - melt viscosity 53
 - melt volume flow rate 60
 - mesogenous 497
 - mesogens 32
 - mesomorphous 32, 497
 - mesophases 32
 - metal complex catalyst 339
 - metal injection molding 235
 - metallization 327
 - metallocene catalysts 337, 339, 358, 361, 375, 572
 - metal pigments 588
 - metal soaps 398
 - metering zone 200
 - methacrylate copolymer 358
 - methacrylic acid 411, 542
 - methyl cellulose 525
 - methylene methyl butyrolactone 418
 - methyl fluoro siloxane elastomers 576
 - methyl methacrylate 559, 562
 - methyl methacrylate copolymers 415
 - methyl phenyl siloxane elastomers 576
 - methyl phenyl vinyl siloxane elastomers 576
 - methyl vinyl siloxane elastomers 576
 - MFR 60
 - mica 596, 600
 - micro-balloons 601
 - microbial resistance 143
 - micro-Brownian molecular mobility 33
 - micro-fibers 624
 - micro-injection molding 236
 - micro-spheres 601
 - migration 144, 655
 - milling 332
 - mills 193
 - mixing 179
 - mixing devices 181
 - mixing elements 184
 - mixing head 259, 263
 - modulus of elasticity 71, 86
 - moisture 135
 - moisture test 139
 - mold 225
 - mold design 246
 - molded foams 513, 515
 - molded interconnect device 238
 - mold-free sintering 404
 - molds 246
 - mold standards 253

molecular mass 22
molecular mobility 33
molecular orientation 37
molecular weight 22
molecular weight distribution 22
monodisperse polymers 23
monofilaments 211, 620, 621
monomers 18
mono-sandwich process 238
montmorillonite 603
morphological structure 27
MuCell™ 242
multi-axial deformation 87
multi-cavity molds 251
multi-chamber kneader 190
multi-color injection molding 236
multi-component injection molding 236, 238
multifilaments 620
multi-layer composites 41
multi-layer extrusion 212
multi-layer films 214
multipoint data 46
MVR 60

N

nano-clay lacquers 323
nanocomposites 585
nano-fillers 602
nano-talcum 599
nano-tubes 603
nano-whisker 596
Natta catalysts 361, 375
natural fibers 519, 612
natural rubber 565, 568
near-field welding 311
needle valve gates 250
neopentyl glycol 561
Neopolen process 341
Newtonian behavior 52
nitrile-butadiene elastomers 570
nitrile-chloroprene elastomers 570
NMR-spectroscopy 163
nominal strain at break 70
non-crimp-fabrics 614
non-Newtonian flow 29
non-return valve 225
non-wovens 609
norbornene 358, 367, 374
novolacs 542, 557
nozzle 225

nucleating agents 31, 593
nucleation 29
number average 23

O

olefin TPE 532
oligomers 24
one-shot process 258, 505
open vat mixer 182
optical behavior 125
optical brighteners 589
optical characteristics 645
organically modified ceramics 323
organosols 398
organo(trichloro)silane 544
orientation polarization 112
orientations 298
ormocers 323
oscillating melts 240
outer fiber strain 72
overmolding 236, 242
oxidation induction time 167
oxidative aging 141
oxidative degradation 581
oxo-degradable plastics 519
oxygen bridge 541
oxygen permeability 150, 658

P

paddle mixer 182
PAI fibers 618
paintless film molding 243
para-phenylene diisocyanate 508
PA-RIM 455
parison 220
particle foam 256
parlylenes 501
pastes 272, 398
PBI fibers 618
PBO fibers 619
PC+ABS blends 462
PC+PBT blends 464
PC+PET blends 464
pearlescent effect 588
PE-C 348
pectin 520
pelletized molding compounds 544
pelletizers 191
pelletizing cylinder 187

- PE-(M) 339
pentane 510
percolation 123
perfluoroalkoxy 408
perfluoro elastomers 574
perfluoropropyl vinyl ether 408
permeability 145
permeability coefficient 148
permeation 144, 655
permittivity 112
peroxide crosslinking 347
peroxides 566
PET fibers 620
petroleum pitch 614
phenacrylate resins 562
phenolic resins 557
phenoplastic molding compounds 547, 551
phenyl acrylate resins 542
Phillips method 339
phosgene 457
phosphoric acid esters 393
photo-oxidation 342
phthalate plasticizers 393
physical foaming 255
physical vapor deposition 246
pigments 586, 602
pin-on-disk test 157
pin point gate 249
pipes 205
planetary gear extruder 203
planetary mixers 190
plasma polymerization 329
plasma treatment 321
plasticator 183
plastic composites 41
plasticized polyvinyl chloride 392
plasticizers 392, 590
plasticizing 224
plasticizing unit 228
plastigels 398
plasticols 398
plating 369
ploughshare mixer 182
plunger plasticizing unit 230
Poisson's ratio 86
polar filament winding 281
polarity 634
polishing 322
poly-2,6-diphenyl-phenyleneoxide 502
poly-4-methylpentene-1 373
polyacetal 419
polyacetals 25
polyacetylene 529
polyacrylates 410
polyacrylonitrile 410
polyacrylonitrile fibers 614, 622
polyaddition 24
polyadducts 24
polyalkylene ether diols 535
polyamide elastomers 454
polyamide fibers 622
polyamide imides 494, 618
polyamides 26, 430
polyamide TPE 532
polyamidoamines 543
polyamines 508, 543
polyanilines 530
polyaramide 617
polyaromates 500
polyarylates 472, 497
polyarylenes 501
poly(aryl)ether ketones 483
polyaryl ether sulfones 26, 478
polyaryl sulfides 26
polybenzimidazoles 493, 618
Poly(bis-maleinimide) 489
polybismaleinimides 493
polybrominated biphenyls 585
polybutene 370
polybutylene naphthalate 474
polybutylene terephthalate 470
polycarbonate 456
polycarbonate blends 462
polycarbonate copolymers 461
polycarbonate diol 537
polychlorotrifluoroethylene 406
polycondensation 26
polycycloacrylonitrile 502
polycyclobutadiene 502
polycyclone 500
polycyclones 502
polydicyclopentadiene 374
polydimethyl siloxane elastomers 575
polydispersity index 23
polyelectrolytes 18, 359
polyester 541
polyester carbonates 472, 497
polyester diol 537
polyester imide 491
polyesterimides 497
polyester plasticizers 393
polyester polyols 509

- polyester resins 550
- polyesters 26
- polyether 25
- polyether block amides 454
- polyether diol 537
- polyether imide 490
- polyetherimides 495
- polyether polyols 509
- polyethylene copolymers 338
- polyethylene dioxythiophene 530
- polyethylene fibers 619
- polyethylene glycol 454
- polyethylene homopolymers 338
- polyethylene naphthalates 474
- polyethylene oxide 483
- polyethylene terephthalate 464
- polyfluoroethylene propylene 408
- polyformaldehyde 419
- polyfuran 529
- polyglycols 483
- polyheterocyclenes 500
- polyhydroxybutyrate 526
- polyhydroxyethylene methacrylate 410
- polyhydroxyvalerate 526
- polyimidazopyrrolone 501
- polyimides 26, 487, 488
- polyimide sulfones 495
- polyisobutene 370, 372
- polyisocyanate 258, 503
- polyisophthalates 497
- polylactic acids 526
- polylactides 526
- polymer alloys 40
- polymer blends 40, 179
- polymerization 24
- polymethacrylate methylimide 497
- polymethacrylates 411
- polymethacrylimides 496
- polymethacrylmethylimide 416
- polymethylmethacrylate 411
- polymolecular material system 22
- poly(m-phenylene isophthalamides) 497
- polynorbornene 566
- polynorbornene elastomers 571
- polyocteneamer 565
- polyol 258, 505
- polyolefin elastomers 343, 536
- polyolefin fibers 623
- polyolefins 25, 337
- polyols 508
- polyoxymethylene 419
- polyoxymethylene blends 427
- polyoxypropylene diamine 509
- polyparaphenylene 529
- polypenteneamer 565
- polyperfluorotrimethyltriazine elastomer 578
- polyphenylene amine 530
- polyphenylene ethers 480
- polyphenylenes 501, 529
- polyphenylene sulfides 475
- polyphenylene terephthalamide 617
- polyphosphazenes 566, 578
- polyphthalamides 453
- poly-p-hydroxybenzoates 501
- poly-p-methylstyrene 375
- poly(p-phenylene phthalamides) 497
- polypropylene copolymers 366
- polypropylene glycol 454
- polypropylene homopolymers 360
- polypropylene oxide 483
- polypyrrole 529
- polypyrrones 501
- polysaccharides 525
- polysiloxane 18
- polystyrene blends 376
- polystyrene copolymers 376
- polystyrene elastomers 536
- polystyrene foams 384
- polystyrene homopolymers 375
- polystyrene sulfonates 530
- polysulfide elastomers 577
- polyterephthalate blends 472
- polyterephthalates 497
- polytetrafluoroethylene 404
- polytetrafluoroethylene fibers 623
- polytetrahydrofuran 454
- polythiophene 529
- polytriazines 493
- polytrimethylene terephthalate 472
- polyurethane elastomers 537
- polyurethane fibers 624
- polyurethane processing 257
- polyurethanes 503
- polyvinyl acetate 399
- polyvinyl alcohol 400
- polyvinyl alcohol fibers 623
- polyvinylbenzenes 375
- polyvinyl butyral 400
- polyvinyl carbazole 379, 400
- polyvinyl fluoride 406
- polyvinyl formal 400
- polyvinylidene chloride 399

- polyvinylidene fluoride 405
 - polyvinyl methyl ether 400
 - polyvinyl pyrrolidone 401
 - poly- α -methylstyrene 375
 - post-crystallization 39
 - post-curing 335
 - post-processing 630
 - post-shrinkage 63
 - powder bed fusion 291
 - powder coatings 323
 - powder extrusion 404
 - powder injection molding 235, 236
 - powder slash process 324
 - power law 23, 58
 - PP chlorinated 367
 - PP copolymers 367
 - PP-CR 361
 - PP+EPDM elastomer blends 368
 - PP foams 362
 - PP glass fiber reinforced 369
 - PP-R 361
 - pre-polymer process 258, 505
 - prepolymers 27
 - pregregging 282
 - pregreg layup 282
 - pregregs 538
 - pregreg tapes 545
 - press 284
 - pressure forming 301
 - primary plasticizer 392
 - printing 324, 630
 - processing characteristics 52, 626, 627
 - processing shrinkage 62
 - production volume 13
 - profiles 205
 - propylene glycol 541
 - propylene oxide elastomers 566, 575
 - propylene tetrafluoroethylene elastomers 574
 - prototype tooling 297
 - PS-E 384
 - PS-HI 379
 - PS particle foam 384
 - PS-S 375
 - PS-S(M) 375
 - pulse method 171
 - pultrusion 281
 - pulverizers 193
 - PUR rubber 518
 - PUR spraying 264
 - PUR systems 259
 - PUR waste 507
 - PVC-C 386
 - PVC-HI 389
 - PVC-(M) 385
 - PVC-P 392
 - PVC-(S) 385
 - PVC-U 385
 - pvT-diagram 61, 108, 109
 - pvT-measurement 170
 - pyrrones 500, 501
- R**
- radiance curve 127
 - radiation 142
 - radiation crosslinking 334
 - radio-frequency welding 313
 - raman spectroscopy 162
 - ram extrusion 404
 - ramie 612
 - ram kneader 189
 - rape seed oil 509
 - rapid prototyping 290
 - rapid tooling 297
 - reaction control 25
 - reaction injection molding 267, 515
 - reactive resins 269
 - recycling 197, 335
 - reflection 126
 - refraction 129
 - reinforced composites 42
 - reinforced reaction injection molding 267
 - reinforcing fibers 341, 606
 - relaxation 29
 - relaxation modulus 80
 - release agents 579
 - relief printing 324
 - renewable materials 519
 - residual stress 36, 331, 335
 - resilience 298
 - resin mats 272, 545
 - resin transfer molding 276, 277
 - resorcinol resins 557
 - restraining geometries 65
 - retardation 29
 - reverse-roll coater 214
 - rheological behavior 52
 - rheological characteristics 47
 - rheometer 54
 - rigid foams 515
 - RIM 267, 515
 - rivets 319

Rockwell-hardness 75
roll-embossing technology 212
rotary knife pelletizer 192
rotating extruders 204
rotational casting 257
rotational molding 341
roughness 133
roving eye 281
rovings 608
R-RIM 267
RTM 276
rubber 26, 35
rubber compounding 189
rubbing 329

S

sandwich injection molding 238
saturation values 135
scratch resistance 323
screen packs 204
screw 201
screw kneaders 185
screw mixer 182
screws 319
screw-type mixers 183
sealing time 60
secant modulus 71, 72
secondary plasticizer 392
secondary shaping 298
selective laser sintering 291
self-reinforcing polymers 32
semi-crystalline thermoplastics 29, 34
sequential coextrusion 221
sequential injection molding 250
sequential process 239
service temperature 640
service temperature range 90
shear 88
shear edge 285
shearing elements 184
shear modulus 28, 30
shear roll extruder 186
shear roll mixing 187
shear thinning 29
shear viscosity 52, 58
sheet 207
sheet lamination 296
sheet molding compounds 271, 545
shish-kebab structure 31
Shore hardness 74
short-fiber reinforced composites 270
short-term behavior 69
shot volume 228
shrinkage 61, 252, 626, 627
shrink-wrap films 298
shut-off nozzle 226
silane crosslinking 347
silica 398, 600, 602
silica gel 593
silicone 18
silicone elastomers 575
silicone molding compounds 557
silicone resin molding compounds 551
silicone resins 544
silicon tetrachloride 544
silo mixers 183
single-point data 46
single-screw compounder 183
single-screw extruder 198
sink marks 65
sintering 193
SiO_x coating 329
sisal 612
skin-pack process 302
slides 253
slip agents 579
slit die 208
small tow fibers 614
SMC 271
smoke formation 151
snap fits 319
S-N curve 424
softening behavior 94
softening temperature 28
soft rubber 565
solidification behavior 60
solid particulate mixers 181
solid PUR materials 518
solubility 634
solution viscosimetry 172
solvation 27
spacers 32, 498
specific enthalpy 99
specific heat capacity 98
specific volume 110
specific volume shrinkage 62
speed welding 307
Spheripol process 361
spherulites 29
spider leg mandrels 209
spinning processes 621

spin welding 310
spiral die 210
spray coating 325
spring-in effect 67
sprue bushing 248
sprue-gate 249
sprue types 248
S-RIM 276, 278
stabilizers 581
stacked molds 253
stamping 326, 332
staple fibers 609, 621
starters 592
static inhibitors 583
static mixers 188
steam sintering 341
steering 284
stereolithography 294
sterically hindered amines 582
stick-slip effect 155
stop-and-go-principle 266
strain at break 70
strainer 217
strands 608
stress at break 70
stress cracking resistance 139, 652
stress-strain diagrams 71
stretch blow molding 245
stretching 31, 207, 211
stripper rings 253
structural foam 255, 562
structural reaction injection molding 276, 278
structure 18
styrene 565
styrene butadiene elastomers 569
styrene mulch 384
styrene polymers 375
styrene TPE 532
submicron-talcum 599
sulfur 566
surface resistivity 113, 115
surface texture 132
surface treatment 319
surfactants 510
suspension polymerization 385
swelling 137
syndiotactic 19
synthetic elastomers 565
synthetic fibers 620, 622
synthetic leather 214

T

tacticity 19
tailored materials 16
talcum 593, 596, 599
tandem extruder 202
tandem machines 228
tapes 211, 620
tarps 214
tear propagation resistance 71
tempering 39
tensile-impact-strength 78
tensile impact test 77
tensile test 69
terephthalic acid 464
ter-polymers 40
terpolymers 376
textile glass fibers 609
textile wall paper 214
TGA 168
therimage process 325
thermal characteristics 48
thermal conductivity 100, 171
thermal diffusivity 104, 172
thermal effusivity 103
thermal expansion 105
thermal properties 90, 635, 636
thermal spraying 330
thermo-diffusion printing process 325
thermogravimetric analysis 167
thermoplastic elastomers 33, 35, 532
thermoplastic foam extrusion 210
thermoplastic olefin-elastomer 536
thermoplastic polyimides 494
thermoplastic starches 525
thermosets 26, 35, 538
thermosetting polyimides 488
thin-wall applications 366
thiocarbonyl difluoride
 copolymer elastomer 577
three-platen machine 227
three-platen molds 253
tie bars 225
titanium dioxide 602
TMA 168
TMC bisphenol 461
TM-DSC 167
tolerances 67
Tomasetti volatile indicator 138
torsion pendulum 164
TPS method 171

tracking index 120
transfer injection mold 289
transfer molding 288
transition zone 200
transmittance 125, 126
transparency 125
transparent plastic materials 645, 646
trans-polyoctenamer elastomers 571
tribological characteristics 157
tribological properties 158
trichloroethyl phosphate 522
triglycerides 560
triisocyanates 508
trimellitates 393
trough kneaders 189
trough mixer 182
TVI test 139
twin-conveyors 265
twine 621
twin-screw compounders 185, 186
twin-screw extruder 203
twin sheet process 302
two-component injection molding 237, 629
two-platen machines 228

U

UL 94 658-660
ultra-light polyethylene 355
ultrasonic welding 309, 311, 630
undercuts 253
underwater pelletizer 192
Underwriters' Laboratories 152
unsaturated polyester resins 541, 555, 559
urea resins 558
urethane elastomers 577
urethane TPE 532
UV light 142
UV stabilizers 582

V

VAC 355
vacuum assisted resin infusion 275
vacuum assisted resin transfer molding 277
vacuum thermoforming 301
vapor deposition 630
VARI 275
VA-RTM 277
vat photo-polymerization 294
VC 385

vertical screw mixer 182
vibration welding 311, 630
Vicat softening temperature 94
Vickers hardness 75
vinyl acetate 348
vinyl chloride 385
vinyl chloride copolymers 397
vinyl ester molding compounds 550
vinyl ester resins 542, 562
vinyl ester urethanes 542
vinyl polymers 385
virtual model 290
viscoelasticity 29
viscosity 52
viscosity average 23
viscosity models 58
viscosity number 172
viscosity ratio 172
voids 66
volume resistivity 113
vulcanization 26, 565
vulcanized fiber 525

W

wall thickness 219
warm curing 543
warp 252
warping 39, 66
water absorption 135, 647
water injection technology 241
water jet cutting 332, 333
water releasing compound 211
water ring pelletizer 192
water vapor diffusion resistance 151
water vapor permeability 145, 655-657
wear 660
wear coefficient 660, 663
wear rate 156
weathering 142, 653
weight average 23
weldability 633
welding 303
weld line 252
whiskers 602
Williams-Landel-Ferry equation 59
wing mixer 182
wire coating 206
wollastonite 596, 601
wood glue 318
wood plastics compounds 613

X

XPS 384

xylenol-formaldehyde resins 557

Y

YAG laser 315

yarns 620

yield strain 70

yield stress 70

Young's modulus 86

Z

Ziegler catalysts 361

Ziegler method 339