Contents

1. Overview 1
Horst Loch
1.1 Introduction 1
1.2 Systematics and Boundary Conditions of This Book 3
1.3 Some Important 3D Continuum Equations 6
References 15

2. Melting and Fining 17
2.1 Modeling of the Melting Process in Industrial Glass Furnaces
Ruud G.C. Beerkens 17
2.1.1 Application of Process Simulation Models for Glass Furnaces 18
2.1.2 Modeling of Heat Transfer and Convection Flows in Glass-Melting Tanks 23
2.1.3 Sand-Grain Dissolution, Behavior of Gas Bubbles in Glass Melts, and Glass-Quality Index 47
2.1.4 Models for Evaporation and Superstructure Refractory Attack by Vapors 61
2.1.5 Dynamic Modeling 71
2.1.6 Concluding Remarks 72
2.2 Mathematical Modeling of Batch Melting in Glass Tanks
Wolf S. Kuhn 73
2.2.1 Motivation and Requirements on Batch Modeling 74
2.2.2 Survey of Batch Melting 76
2.2.3 Theoretical Basis of Batch Modeling 93
2.2.4 Key Values and Non-Dimensional Numbers 105
2.2.5 Batch Models 110
2.3 High-Frequency Melting of Glass in Crucibles
Frank-Thomas Lentes 126
2.3.1 Basics of Electrodynamics 126
2.3.2 Mathematical Formulation of the Simulation Model 129
2.3.3 Simulation Results 134
2.3.4 Conclusion and Outlook 136

2.4 Model-Based Glass Melter Control
Ton Backx 137
2.4.1 Model Concepts 138
2.4.2 Model-Predictive Control 142
2.4.3 Extensions of the MPC Technology 148
2.4.4 Application of MPC in the Glass Industry 150
References 155

3. Homogenizing and Conditioning 165
3.1 The Intensity of Mixing Processes
Henry Eisermann, Ulrich Lange, Horst Loch, Günter Weidmann 165
3.1.1 Description and Quantification of Mixing Processes . . . 165
3.1.2 Flows and Particle Paths in Stirrers 169
3.1.3 Statistics of Residence Time and Dispersion 173
3.1.4 Deformation of Infinitesimal Test Bodies Along Particle Paths 176
3.1.5 Deformation Statistics 187
3.1.6 Example: a Simple Paddle Stirrer 189
3.1.7 Outlook 192
3.2 Instabilities and Stabilization of Glass Pipe Flows
Ulrich Lange, Horst Loch 193
3.2.1 Stationary Temperature and Pressure Profiles in the Pipe 193
3.2.2 A Stability Phenomenon 197
3.2.3 Appendix: Derivation of Several Equations 205
3.3 Shape Optimization of Flanges
Norbert Siedow, Horst Loch, Sandro Manservisi 208
3.3.1 General Shape Optimization: Continuously Varying Thicknesses and Contours 209
3.3.2 Finite-Dimensional Shape Optimization: the 3-Ring/Spoke Flange 230
References 237

4. Shaping at Low Viscosities 239
4.1 Heat Transfer Between Glass and Mold During Hot Forming
Matthias Brinkmann, Norbert Siedow 239
4.1.1 Heat Transfer Coefficient Between Glass and Mold 241
4.1.2 Physics and Mathematics of the Heat Transfer 245
4.1.3 Sample Computations 252
4.1.4 Radiative Contributions to the Heat Transfer 255
4.1.5 Laboratory Experiments 259
4.2 Remote Spectral Temperature Profile Sensing
Matthias Brinkmann, Norbert Siedow, Thomas Korb 262
4.2.1 Thermal Radiation in Hot Glass 263

4.2.2 The Inverse Problem of Spectral Temperature Sensing ... 266
4.2.3 Sample Computations ... 273
4.2.4 Laboratory Experiment ... 275
4.2.5 Spectral Imaging of Hot Glass ... 279
4.3 Heat Transfer During Casting Experiments
Matthias Brinkmann, Thomas Korb ... 286
4.3.1 Experimental Set-Up ... 287
4.3.2 Comparison Between "Exact" Modeling and Measurement ... 289
4.3.3 Alternative Modeling Using the Active Thermal Conductivity ... 290
4.4 Thin-Layer Flows of Glass
Ulrich Lange ... 293
4.4.1 Example of a Thin-Layer Model ... 294
4.4.2 Simplified Energy Balance ... 298
4.4.3 Validation of the Model ... 300
4.4.4 Fiber- and Tube-Drawing Models ... 302
4.4.5 More Comprehensive Thin-Layer Flow Models ... 305
4.5 Pressing of Drinking-Glass Stems
Günter Weidmann, Kurt Holtberg, Henry Eisermann ... 306
4.5.1 Model 1: Finite-Element Modeling ... 309
4.5.2 Model 2: Analytical Modeling ... 310
4.5.3 Comparison of Model 1 and Model 2 ... 316
4.6 The Use of Remeshing Methods in Pressing Simulations
Ulrich Lange ... 317
4.6.1 Some Technical Aspects of the Method ... 319
4.6.2 Example: Pressing of a Tumbler ... 320
4.6.3 Example: Pressing of an "Axisymmetric TV Screen" ... 321
4.7 Chill Ripples in Pressing and Casting Processes
Ulrich Lange ... 326
4.7.1 A Simple Casting Process ... 328
4.7.2 A Model for Kluge's Experimental Set-Up ... 330
References ... 335

5. Reshaping at High Viscosities ... 339
5.1 Temperature-Dependent Elasticity in Reshaping Simulations
Thoralf Johansson, Ulrich Fotheringham ... 339
5.1.1 Model ... 339
5.1.2 Simulation Results ... 341
5.2 Sagging and Pressing of Glass Sheets
Thoralf Johansson ... 343
5.2.1 Model and Boundary Conditions ... 344
5.2.2 Results of the Model Computations ... 345

5.3 Calibration of Glass Tubes
Thoralf Johansson 349
5.3.1 Model Description 349
5.3.2 Results of the Model Computations 350

6. Thermal Treatment 359
6.1 Verification of Relaxation Models
Peter Thomas, Clemens Kunisch 359
6.1.1 Mathematical Models 359
6.1.2 Experiments in the Lehr 362
6.1.3 Simulation 363
6.1.4 Measuring Stress and Compaction 363
6.1.5 Results 363
6.2 Stresses and Crack Growth in Continuously Formed Slabs
Clemens Kunisch 367
6.2.1 Cooling a Continuous Strip 369
6.2.2 Crack Growth 370
6.2.3 Modified Temperature Program in Order to Avoid Cracking 371
6.2.4 Cutting the Strip into Slabs 372
6.3 Thermal Tempering of Drinking Glasses
Volker Seibert, Andreas Bensberg 374
6.3.1 Principles of Thermal Tempering 375
6.3.2 Results for Spatially Inhomogeneous Quenching 376
6.3.3 Realization of a Quenching Process 378

7. Post-Processing by Laser Cutting 381
Kurt Nattermann, Christoph Hermanns
7.1 Rough Estimation of Process Parameters 381
7.1.1 Stress Levels 381
7.1.2 Laser-Beam Profiling 382
7.1.3 Selection of Laser 384
7.2 Numerical Analysis of Cutting Processes 385
7.2.1 Calculation of Temperature Distributions 386
7.2.2 Calculation of Stress Distributions 391
7.2.3 Condition for Cut Elongation 396
7.2.4 Calculation of Stress Intensities for Laser Cutting 399
7.3 Practical Realization 404
7.4 Appendix: Fundamentals of Fracture Mechanics 408
7.4.1 Fracture Mechanics for Brittle Solids 408
7.4.2 FEA Calculation of Stress-Intensity Factors 410
7.4.3 Prediction of the Crack Path 411

8. Glass Products Under Mechanical and Thermal Loads 413
8.1 Strength Optimization of Airbag Igniters
Kurt Nattermann, Harald Krümmel, Ludwig Frank 413
8.1.1 FEA for Axial-Symmetric Models 413
8.1.2 FEA of 3D Models 420
8.1.3 Pull-Out Tests 423
8.1.4 Push-Out Tests 432
8.1.5 Pressure Tests 435
8.1.6 Appendix: Statistical Procedure 437
8.2 Stiffness and Weight Optimization of a Reticle Stage for Optical Lithography
Volker Seibert 438
8.2.1 Requirements for a $(9 \times 9)''$ Reticle Stage 439
8.2.2 Design of a Prototype 440
8.2.3 FEM Optimization Without Additional Masses 442
8.2.4 FEM Analysis With Additional Masses 444
References 446

9. Simulation and Test of the Spinning Process Applied to Platinum Metals 449
Seth Nzahumunyurwa, Hans-Jürgen Hoffmann, Hans Oechsner, Joachim Disam
9.1 Necessity to Shape Materials 449
9.2 Qualitative Description of the Spinning Process 449
9.3 Essential Assumptions for the Modeling of the Spinning Process 451
9.4 General Relations for the Model of the Spinning Process 453
9.5 Approximations 455
9.5.1 First Approximation: Quasi-Homogeneous Deformation 455
9.5.2 Second Approximation: Linearly Decreasing Deformation 458
9.6 A Practical Example for the First and Second Approximations 460
9.7 Experimental Observations and Discussion 464
References 465

List of Contributors 467

Sources of Figures and Tables 471

Index 473