Contents

Preface xv

Chapter 1. Introduction to Heat Transfer During the Forming of Organic Matrix Composites 1
Didier DELAUNAY

1.1. Introduction. 1
1.2. Examples of injection of short fiber reinforced composites 2
1.2.1. Heat transfer during the filling phase 2
1.2.2. Heat transfer during part consolidation 18
1.3. Injection on continuous fiber reinforcements 22
1.4. Conclusion: toward a controlled processing. 24
1.5. Bibliography 25

Chapter 2. Experimental Determination and Modeling of Thermophysical Properties 29
Nicolas BOYARD and Didier DELAUNAY

2.1. Measurement of specific volume and shrinkage 29
2.1.1. Thermoplastic PvT diagram. 30
2.1.2. Specific volume of thermosetting polymers 36
2.2. Determination of specific heat capacity of resin and composites 40
2.3. Thermal conductivity: a tricky task.... 43
2.3.1. A first assessment of experimental data. 44
2.3.2. Overview of the main characterization techniques to measure the thermal conductivity of polymers and associated composites 46
2.3.3. Modeling of the thermal conductivity of composites 57

2.4. Conclusions 69
2.5. Bibliography 70

Chapter 3. Experimental Determination and Modeling of Transformation Kinetics 77
Nicolas BOYARD, Jean-Luc BAILLEUL and M'hamed BOUTAOUS

3.1. Introduction 78
3.2. What are the most suitable devices to analyze a reaction rate? 79
3.2.1. Conventional methods 79
3.2.2. Original methods 86
3.2.3. A first assessment of the current characterization methods 86
3.3. Modeling of the cure kinetics of thermosetting resins 88
3.3.1. Mechanistic models: complexity versus accuracy 89
3.3.2. Description of the kinetics with empirical models: the engineer approach 91
3.3.3. Modeling of the diffusion induced by vitrification 97
3.4. Overall crystallization kinetics of semi-crystalline thermoplastics 98
3.4.1. Most popular crystallization kinetics models for process simulations 100
3.4.2. Systems of differential equations 102
3.4.3. Measurements of crystallization kinetics and associated parameters 104
3.4.4. Models for specific crystallization phenomena and geometries 107
3.5. Concluding remarks 109
3.6. Bibliography 111

Chapter 4. Phase Change Kinetics within Process Conditions and Coupling with Heat Transfer 121
M'hamed BOUTAOUS, Matthieu ZINET, Nicolas BOYARD and Jean-Luc BAILLEUL

4.1. Introduction 121
4.2. Flow-induced crystallization: experimental observations 124
4.2.1. Relevant experimental techniques 124
4.2.2. Effect of flow on crystallization kinetics 125
4.2.3. Flow effect on crystalline morphology 131
4.2.4. Flow effect on crystalline growth rate 134

4.2.5. Effect of flow on rheological properties 134
4.2.6. Summary of experimental observations and guidelines for modeling 136
4.3. Flow-induced crystallization: modeling 138
4.3.1. Overall kinetics modeling 138
4.3.2. Explicit nucleation and growth modeling 139
4.3.3. Role of viscoelasticity 140
4.4. Effect of the composite components 143
4.4.1. Effect of nucleating agents 143
4.4.2. Effect of fibers 144
4.5. Concluding remarks 147
4.6. Bibliography 149

Chapter 5. From the Characterization and Modeling of Cure-Dependent Properties of Composite Materials to the Simulation of Residual Stresses 157
Yasir NAWAB and Frédéric JACQUEMIN

5.1. Introduction 157
5.2. Origin of residual stress 157
5.2.1. Mechanical levels of residual stress 158
5.2.2. Parameters contributing to the formation of residual stress 159
5.2.3. Problems generated by residual stress 161
5.3. Determination of composite properties 161
5.3.1. Modeling the mechanical properties of composites 162
5.3.2. Experimental determination of thermomechanical properties of composite 164
5.4. Modeling of residual stress 167
5.4.1. Linear approach or classical theory of laminates 168
5.4.2. Nonlinear approach 168
5.4.3. Minimization of energy approach 169
5.4.4. Application 170
5.5. Conclusion 171
5.6. Bibliography 172

Chapter 6. Heat Transfer in Composite Materials and Porous Media: Multiple-Scale Aspects and Effective Properties 175
Michel QUINTARD

6.1. Introduction 175
6.2. Effective thermal conductivity 177
6.2.1. Background on upscaling methods 178

6.2.2. A simple example: continuous thermal conductivity 179
6.2.3. Effective thermal conductivity: properties and bounds. 181
6.3. Local-equilibrium model and thermal dispersion. 184
6.4. Local equilibrium versus local non-equilibrium models 187
6.4.1. The two-equation model. 187
6.4.2. Further discussion 189
6.5. Various extensions 192
6.5.1. Effect of homogeneous and heterogeneous thermal sources 193
6.5.2. Interfacial thermal resistance 194
6.6. Conclusions. 195
6.7. Bibliography 196

Chapter 7. Thermal Optimization of Forming Processes 203
Vincent SOBOTKA

7.1. Context of optimization. 203
7.2. Heat transfer: optimization lever 204
7.3. Definition of the optimization criterion 206
7.4. Problem modeling 207
7.4.1. Spatial scale 207
7.4.2. Time scale: process steps 207
7.4.3. Multi-physical aspects 207
7.5. Numerical optimization methods 208
7.5.1. The adjoint problem 210
7.5.2. Practical setting of the method 211
7.6. Example of process optimization: determination of optimal heat flux setpoint. 211
7.6.1. Experimental setup and constraint 212
7.6.2. Instrumentation of the mold and the preform 214
7.6.3. Thermal modeling 215
7.6.4. Experimental data from a composite part molding 218
7.6.5. Estimation of the thermal contact resistances 219
7.6.6. Determination of the optimal setpoint. 220
7.7. Optimal design of molds 222
7.7.1. OSOTO project 222
7.7.2. The considered thermoplastic part 222
7.7.3. General methodology 223
7.7.4. Conformal cooling approach 223

7.7.5. Heat transfer model in the process 224
7.7.6. Objective function 226
7.7.7. Minimization of the functional J 227
7.7.8. Cooling channel design 228
7.8. Conclusions and outlook 231
7.9. Bibliography 232

Chapter 8. Modeling of Thermoplastic Welding 235
Gilles REGNIER and Steven LE CORRE

8.1. Introduction. 235
8.1.1. Polymer welding processes 235
8.1.2. Healing mechanisms of polymer interfaces 237
8.2. Physics of thermoplastic welding 237
8.2.1. Intimate contact at interface. 237
8.2.2. Macromolecular diffusion. 241
8.3. Linear viscoelasticity to quantify the macromolecular diffusion 246
8.4. Application to continuous welding of composite tape. 248
8.4.1. Process description 248
8.4.2. Influence of processing conditions on interfacial strength 249
8.4.3. Modeling of macromolecular diffusion 249
8.4.4. Modeling of thermal aging 251
8.4.5. Thermal modeling of the process 253
8.4.6. Weldability prediction 254
8.5. Application to ultrasonic welding. 255
8.5.1. Process description and time scale separation 255
8.5.2. Process modeling: necessity of a time homogenization framework. 256
8.5.3. Numerical multi-physical model 257
8.5.4. Ultrasonic welding with energy directors: process analysis and optimization 259
8.6. Conclusion 262
8.7. Acknowledgments. 263
8.8. Bibliography 263

Chapter 9. Multiphysics for Simulation of Forming Processes 269
Luisa SILVA, Patrice LAURE, Thierry COUPEZ and Hugues DIGONNET

9.1. Introduction. 269
9.2. Multiscale, multiphysics and multidomain modeling 270
9.2.1. Flow equations 271

9.2.2. Thermal-rheological-kinetical coupling 273
9.2.3. Orientation and structure development during processing 275
9.3. Advanced numerical techniques and macroscale simulations. 278
9.3.1. Implicit boundaries 280
9.3.2. Immersed subdomains and regularization 281
9.3.3. Multiphase flow and thermokinetical numerical resolution 282
9.3.4. Composite forming simulation illustrations 283
9.3.5. Parallel mesh adaptation and high-performance computing 286
9.4. Determination of equivalent properties and microscale simulations 289
9.4.1. Generation of representative numerical samples 289
9.4.2. Permeability of a composite 291
9.4.3. Stiffness tensor determination 294
9.5. Conclusions. 294
9.6. Bibliography 296

Chapter 10. Thermal Instrumentation for the Control of Manufacturing Processes of Organic Matrix Composite Materials 301
Jean-Christophe BATSALE and Christophe PRADERE

10.1. Introduction 301
10.2. Methods based on contact measurement 302
10.2.1. Temperature sensors and fluxmeters 302
10.2.2. Heat flux estimation 304
10.2.3. Thermal probes for thermophysical property measurement in static conditions 308
10.3. Contactless heating 311
10.3.1. Photothermal methods with monosensors (under microscale characterization) 312
10.3.2. Thermal non-destructive evaluation: cracks or delamination detection in composite samples 313
10.3.3. Screening of chemical processes and microfluidic experiments 317
10.3.4. Principles for the factory global monitoring, example of conveyor belt parameter estimation 323
10.3.5. In a near future: the Big Data related to multiscale process survey 325

10.4. Conclusion 326
10.5. Bibliography 326

Chapter 11. Sensors for Heat Flux Measurement 333
Fabien CARA and Vincent SOBOTKA

11.1. Motivations: heat flux sensor 333
11.2. Principle of heat flux sensors. 335
11.2.1. Gradient heat flux sensor. 335
11.2.2. Inertial heat flux sensor 338
11.2.3. Inverse heat flux sensor 338
11.3. Main characteristics of HFS 340
11.3.1. Invasiveness 340
11.3.2. Time constant 340
11.3.3. Calibration 343
11.4. Type, positioning and use of heat flux sensors 344
11.4.1. Commercial sensors 345
11.4.2. Positioning of heat flux sensors. 347
11.4.3. Price 348
11.5. Advantages and limitations of HFS compared to other *in situ* monitoring techniques 349
11.5.1. Advantages 349
11.5.2. Limitation and care in using HFS. 349
11.6. Examples 349
11.6.1. Compression molding 350
11.6.2. Resin transfer molding flow front detection 352
11.6.3. Resin transfer molding: influence of mold temperature 353
11.6.4. Internal temperature prediction during infusion 354
11.6.5. Glass mat transfer, internal temperature monitoring 355
11.7. Conclusions 356
11.8. HFS suppliers. 356
11.9. Bibliography 357

Chapter 12. Thermal Radiative Properties of Polymers and Associated Composites 359
Benoit ROUSSEAU

12.1. Introduction 359
12.2. Fundamental requisites concerning thermal radiation 361
12.2.1. Spectral range of thermal radiation. 361

12.2.2. Radiant energy, radiant flux, radiative flux density and radiative intensity . . . 363
12.2.3. Blackbody spectral emissive power . . . 366
12.2.4. Radiative properties at interfaces . . . 368
12.2.5. Radiative properties of semi-transparent slabs . . . 372
12.3. Prediction of the radiative properties of homogeneous semi-transparent slabs: case of the isotactic polypropylene . . . 373
12.3.1. Intrinsic optical properties for a homogeneous, isotropic and non-magnetic medium . . . 374
12.3.2. Prediction of the radiative properties of polypropylene slabs at 20°C . . . 376
12.4. Radiative properties of polymer composites with fiber structures . . . 378
12.4.1. Normal spectral absorptance of Roving TWINTEX® . . . 378
12.4.2. Normal spectral absorptance of sheet of PEEK with carbon fibers . . . 380
12.5. Conclusion . . . 381
12.6. Bibliography . . . 381

Chapter 13. Infrared Radiation Applied to Polymer Processes . . . 385
Yannick LE MAOULT and Fabrice SCHMIDT

13.1. Introduction . . . 386
13.1.1. Why use infrared heating for polymers? . . . 386
13.1.2. Application of radiative transfers in polymer processing . . . 386
13.2. Infrared radiation characteristics . . . 388
13.2.1. Radiative properties (basis and main definitions) . . . 389
13.2.2. Infrared emitters: characterization . . . 393
13.2.3. Infrared camera measurements . . . 397
13.3. Modeling of infrared radiation . . . 403
13.3.1. Opaque medium: surface to surface methods . . . 403
13.3.2. Semi-transparent medium . . . 405
13.3.3. Ray tracing method . . . 407
13.4. Polymer processing applications . . . 409
13.4.1. Optimization of preform temperature for the ISBM process . . . 409
13.4.2. Optimal infrared composite curing . . . 415
13.5. Future work . . . 419

13.6. Acknowledgements 420
13.7. Bibliography 420

List of Authors 425

Index 427