

Contents

| | | |
|----------|---|-----------|
| 1 | Introduction | 3 |
| 1.1 | Deformation Processes | 3 |
| 1.2 | Material Removal Processes | 5 |
| 1.3 | Phase Change Processes | 7 |
| 1.4 | Salient Features of Manufacturing Processes and the Boundary Element Method | 8 |
| 2 | Problems Involving Large Strains and Rotations | 15 |
| 2.1 | Continuum Mechanics Fundamentals | 15 |
| 2.1.1 | Kinematics in Cartesian Coordinates | 15 |
| 2.1.2 | Kinetics in Cartesian Coordinates | 19 |
| 2.1.3 | Kinematics and Kinetics in General Curvilinear Coordinates | 24 |
| 2.1.4 | Objective Rates of Tensors | 28 |
| 2.2 | Boundary Element Formulations | 34 |
| 2.2.1 | Constitutive Assumptions | 35 |
| 2.2.2 | Three-Dimensional BEM Formulation for Velocities | 36 |
| 2.2.3 | Stress Rates and Velocity Gradients on the Boundary | 42 |
| 2.2.4 | Internal Stress Rates and Velocity Gradients | 43 |
| 2.2.5 | Plane Strain | 46 |
| 2.2.6 | Plane Stress | 46 |
| 2.2.7 | Axisymmetric Problems | 47 |
| 2.2.8 | Derivative Boundary Integral Equations (DBEM) for Plane Strain Problems | 55 |
| 2.2.9 | Derivative Boundary Integral Equations (DBEM) for Plane Stress Problems | 57 |
| 2.2.10 | Sharp Corners for Planar Problems | 58 |
| 2.3 | Finite Element Formulations | 59 |
| 2.3.1 | A Three-Dimensional FEM in an Updated Lagrangian Formulation | 60 |

| | | |
|----------|--|------------|
| 2.4 | Numerical Implementation and Results | 63 |
| 2.4.1 | Viscoplastic Constitutive Models | 63 |
| 2.4.2 | Planar Problems | 66 |
| 2.4.3 | Axisymmetric Problems | 75 |
| 3 | Thermal Problems | 86 |
| 3.1 | Steady-State Conduction | 86 |
| 3.1.1 | Direct Formulation | 86 |
| 3.1.2 | Alternative Complex Variable Approach | 88 |
| 3.1.3 | A Derivative BEM (DBEM) Formulation | 90 |
| 3.2 | Steady-State Conduction–Convection | 94 |
| 3.2.1 | Formulation | 94 |
| 3.2.2 | Numerical Implementation | 98 |
| 3.2.3 | Evaluation of Singular Integrals | 102 |
| 3.2.4 | Numerical Results and Verification | 103 |
| 3.3 | Transient Conduction with Moving Boundaries and Phase Changes | 131 |
| 3.3.1 | Formulation | 131 |
| 3.4 | Transient Conduction–Convection | 137 |
| 3.4.1 | Formulation | 137 |
| 3.4.2 | Numerical Implementation | 140 |
| 3.4.2.1 | Discretization | 140 |
| 3.4.2.2 | Integration of Kernels in Time and Space | 142 |
| 3.4.3 | Example Problems and Numerical Results | 145 |
| 3.5 | Thermal Stresses and Thermomechanical Aspects | 151 |
| 3.5.1 | Constitutive Laws | 152 |
| 3.5.2 | Stationary Thermoplasticity in Nonhomogeneous Media | 156 |
| 3.5.2.1 | Special Case for Homogeneous Media | 164 |
| 3.5.3 | Nonstationary Thermoelasticity | 168 |
| 3.5.3.1 | Numerical Implementation | 171 |
| 3.5.4 | Nonstationary Thermoplasticity | 179 |
| 4 | Design Sensitivities and Optimization | 184 |
| 4.1 | Design Sensitivity Coefficients (DSCs) | 184 |
| 4.1.1 | The Finite Difference Approach (FDA) | 185 |
| 4.1.2 | The Adjoint Structure Approach (ASA) | 185 |
| 4.1.3 | The Direct Differentiation Approach (DDA) | 185 |
| 4.1.4 | Linear Elasticity | 186 |
| 4.1.5 | Nonlinear Problems in Solid Mechanics | 186 |
| 4.2 | DBEM Sensitivity Formulation | 187 |
| 4.2.1 | Boundary Integral Equations for Sensitivities | 188 |

| | | |
|----------|--|------------|
| 4.2.2 | Boundary Condition Sensitivities | 190 |
| 4.2.3 | Sensitivities of Inelastic Constitutive Model Equations | 191 |
| 4.2.4 | Kinematic and Geometric Sensitivities | 192 |
| 4.2.5 | Stress Rates and Velocity Gradient Sensitivities on the Boundary | 194 |
| 4.2.6 | Sensitivities of Integral Equations at an Internal Point | 195 |
| 4.2.7 | Stress Rate Sensitivities at an Internal Point | 197 |
| 4.2.8 | Sensitivities of Corner and Compatibility Equations | 197 |
| 4.2.9 | Special Cases—Small-Strain Elasto-viscoplasticity and Linear Elasticity | 198 |
| 4.2.10 | Leibnitz Rule, Calculation of Geometric Sensitivities, and Related Issues | 199 |
| 4.3 | Numerical Implementation | 205 |
| 4.3.1 | Discretization of Equations | 205 |
| 4.3.2 | Solution Strategy | 206 |
| 4.4 | Numerical Results for Sample Problems | 209 |
| 4.4.1 | One-Dimensional Problems | 209 |
| 4.4.2 | A 2D Problem—Simple Shearing Motion | 218 |
| 4.4.3 | Axisymmetric Problems | 222 |
| 4.5 | Design Optimization | 227 |
| 4.6 | Optimization of Plates with Cutouts | 231 |
| 4.6.1 | Parametrization of Cutout Boundary | 231 |
| 4.6.2 | Objective Functions and Constraints | 231 |
| 4.6.3 | Elastic Shape Optimization | 232 |
| 4.6.4 | Elasto-viscoplastic Shape Optimization | 235 |
| 5 | Planar Forming Processes | 250 |
| 5.1 | Introduction | 250 |
| 5.2 | Interface Conditions in Planar Forming Problems | 252 |
| 5.2.1 | General Equations | 253 |
| 5.2.2 | Follower Load | 255 |
| 5.2.3 | Sheet Forming | 255 |
| 5.2.4 | Extrusion | 256 |
| 5.2.5 | Slab Rolling | 256 |
| 5.3 | Numerical Implementation for Planar Cases | 257 |
| 5.3.1 | Objective Stress Rates for Problems Involving Large Shear Strains | 258 |
| 5.3.1.1 | Relationship with the Dienes Rate | 259 |
| 5.3.1.2 | Relationship with Rolph and Bathe's Model | 259 |
| 5.3.1.3 | Elastoplasticity with Finite Rotations | 260 |
| 5.3.1.4 | Solution Strategy | 261 |

| | | |
|----------|---|------------|
| 5.4 | Applications to Forming Problems | 264 |
| 5.4.1 | Plane Strain Extrusion | 265 |
| 5.4.1.1 | Numerical Results for Plane Strain Extrusion | 266 |
| 5.4.2 | Profile Rolling of Gears | 270 |
| 5.4.2.1 | Numerical Results for Profile Rolling | 274 |
| 5.4.3 | Plane Strain Slab Rolling | 279 |
| 5.4.3.1 | Numerical Results for Slab Rolling | 281 |
| 5.4.4 | Plane Strain Sheet Forming | 286 |
| 5.4.4.1 | Numerical Results for Plane Strain Sheet Forming | 287 |
| 5.5 | Concurrent Preform and Process Design for Formed Products | 290 |
| 5.5.1 | The Concept of Reverse Forming | 292 |
| 5.5.2 | Integrated Design Algorithm | 294 |
| 5.5.2.1 | Step 1: Reverse Forming along Minimum Plastic Work Path | 294 |
| 5.5.2.2 | Step 2: Feasibility Check for the Forward Forming Step | 295 |
| 5.5.2.3 | Step 3: Analysis of a Feasible Forward Forming Step | 296 |
| 5.5.2.4 | Step 4: Design Sensitivities of the Forward Forming Step | 297 |
| 5.5.2.5 | Step 5: Optimization of the Forward Forming Step | 298 |
| 5.5.2.6 | Issues Relating to Concurrent Product and Process Design | 301 |
| 6 | Axisymmetric Forming Processes | 306 |
| 6.1 | Introduction | 306 |
| 6.2 | Interface Conditions for Axisymmetric Forming Problems | 307 |
| 6.2.1 | Axisymmetric Ring Compression | 308 |
| 6.2.2 | Axisymmetric Extrusion | 309 |
| 6.3 | Numerical Implementation for Axisymmetric Cases | 311 |
| 6.4 | Applications to Axisymmetric Forming | 317 |
| 6.4.1 | Axisymmetric Upsetting and Ring Compression | 317 |
| 6.4.2 | Axisymmetric Extrusion | 321 |
| 6.5 | Design Sensitivity and Optimization Issues | 325 |
| 7 | Solidification Processes | 327 |
| 7.1 | Introduction | 327 |
| 7.2 | Direct Analysis of Solidification | 329 |
| 7.2.1 | Governing Differential Equations | 329 |
| 7.2.2 | Integral Formulation | 331 |

| | | |
|----------|--|------------|
| 7.2.3 | Numerical Implementation | 332 |
| 7.2.4 | Evaluation of Integrals | 334 |
| 7.2.5 | Modeling of Corners | 335 |
| 7.2.6 | Matrix Formulation | 335 |
| 7.3 | An Inverse (Design) Solidification Problem | 337 |
| 7.3.1 | The Problem | 337 |
| 7.3.2 | Future Information and Spatial Regularization Methods | 338 |
| 7.3.3 | Calculation of the Sensitivity Coefficients | 340 |
| 7.4 | Numerical Examples | 342 |
| 7.4.1 | Dimensionless Parameters | 342 |
| 7.4.2 | The Direct Problem | 342 |
| 7.4.3 | The Design Problem | 346 |
| 8 | Machining Processes | 354 |
| 8.1 | Introduction | 354 |
| 8.2 | Boundary Element Formulation | 358 |
| 8.2.1 | Numerical Implementation | 360 |
| 8.2.2 | Verification of the Conduction–Convection Algorithm | 363 |
| 8.3 | Modeling of Machining Processes | 364 |
| 8.3.1 | Mathematical Formulation | 365 |
| 8.3.1.1 | Within the Workpiece | 366 |
| 8.3.1.2 | Within the Chip | 367 |
| 8.3.1.3 | Within the Tool | 368 |
| 8.3.1.4 | Matching Boundary Conditions | 369 |
| 8.3.2 | Matching Scheme | 370 |
| 8.4 | Results from BEM Analyses | 374 |
| 8.5 | BEM Sensitivity Formulation | 380 |
| 8.6 | Sensitivities of Machining Processes | 389 |
| 8.6.1 | Matching Boundary Conditions for Sensitivity Calculations | 390 |
| 8.6.2 | Matching Scheme for the Sensitivity Problem | 392 |
| 8.7 | Results from BEM Sensitivity Analysis | 394 |
| 8.8 | Discussion and Conclusion | 405 |
| 9 | Integral Equations for Ceramic Grinding Processes | 409 |
| 9.1 | Introduction | 409 |
| 9.2 | Background of Strength Degradation in Ceramic Grinding | 412 |
| 9.3 | Indentation Fracture Mechanics Model for Monolithic Ceramics | 414 |
| 9.3.1 | An Integral Equation Formulation for Grinding of Monolithic Ceramics | 415 |
| 9.3.2 | Numerical Solution Procedure | 422 |

| | | |
|-------|--|-----|
| 9.4 | Determination of Effective Elastic Properties | 425 |
| 9.4.1 | Numerical Results for Monolithic Ceramics | 426 |
| 9.5 | Grinding of Ceramic Composites | 442 |
| 9.5.1 | Fundamental Fields due to Point Loads and Point Dislocations | 446 |
| 9.5.2 | An Integral Equation Formulation for General Crack–Anticrack Systems | 452 |
| 9.5.3 | Numerical Results for Grinding of Ceramic Composites | 460 |
| 9.6 | Micro-Scale Features in Macro-Scale Problems | 469 |
| 9.6.1 | Micro-Scale Fundamental Solutions | 474 |
| 9.6.2 | Micro–Macro BEM Formulation | 481 |
| 9.6.3 | Numerical Implementation for Hybrid Micro–Macro BEM | 484 |
| 9.6.4 | Numerical Results for Hybrid Micro–Macro BEM | 485 |
| | Index | 503 |