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Marcin Hojny

Modeling Steel Deformation in the Semi-Solid State

Second Edition

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*As far as the laws of mathematics refer to reality,
they are not certain, and as far as they are certain,
they do not refer to reality.*

Albert Einstein

Contents

1	Introduction	1
2	State of the Art	5
	References	20
3	Aim of the Study	29
4	Integration of Physical and Computer Simulation	31
4.1	Characteristics of the Integrated Modelling Concept	31
4.2	Hybrid Analytical-Numerical Model of Mushy Steel Deformation	36
4.2.1	Resistance Heating Model	40
4.3	“One Decision Software”—The DEFFEM Package	42
4.4	Stereoscopic Visual Representation Algorithm for the 3D Gemini Barco Projection System	45
4.5	Summary	53
	References	53
5	Spatial Solutions Based on the Smoothed Particle Method and the Finite Element Method—A Hybrid Approach	55
5.1	The Smoothed Particle Hydrodynamics (SPH) Method	55
5.1.1	Fluid Model	57
5.1.2	Thermal Model	59
5.2	Test Cases to Validate the Fluid Solver	60
5.2.1	Free Particles Fall	60
5.2.2	Structure Impact	64
5.3	Test Simulation of the Hybrid Solution	66
5.4	Summary	72
	References	73

6	Spatial Solutions Based on the Finite Element Method and the Monte Carlo Method—A Multi-scale Approach	75
6.1	Thermal Model	75
6.1.1	Discretization for Steady Heat Flow Cases	80
6.1.2	Discretization for Transient Heat Flow Cases	81
6.2	Solidification Model	82
6.3	Mechanical Model	84
6.3.1	Spatial Solution	86
6.4	Grain Growth Model in the Comprehensive Description of the Heating-Melting-Solidification Process (Multi-scale Approach)	99
	References	101
7	Computer-Aided Physical Simulations Within the Context of New Technology Development	103
7.1	Material and Test Methodology	105
7.1.1	Samples and Tools	106
7.1.2	The Determination of Characteristic Temperatures	107
7.1.3	Thermal Process Map (TPM)	110
7.2	Preliminary Experimental and Computer Simulation Research of Steel Deformation in the Semi-solid State	111
7.2.1	The Dependence of Steel Microstructure Parameters on the Cooling Rate During Solidification	116
7.2.2	High-Temperature Stress-Strain Relationships	119
7.2.3	Steel Ductility in the Continuous Casting Process	125
7.2.4	Deformation Above Nil Ductility Temperature	128
7.2.5	Macrostructure and Microstructure	131
7.3	Summary	143
	References	145
8	An Integrated Modelling Concept Based upon Axially Symmetrical Models	147
8.1	Direct Simulation Using the Gleeble Thermo-Mechanical Simulator	147
8.1.1	Testing the Temperature Distribution	148
8.1.2	Macrostructure and Microstructure	151
8.2	Application of Tomography to the Spatial Analysis of the Melting Zone	159
8.3	Numerical Modelling with the DEFFEM Simulation System	166
8.3.1	Modelling of the Resistance Heating Process	166
8.3.2	Modelling of the Deformation Process	177
8.4	Summary	198
	References	199

9 An Integrated Modelling Concept Based upon Three-Dimensional Models 201

9.1 Modified Experimental Research Methodology. 201

9.2 Resistance Heating Model 204

9.3 Modelling of the Resistance Heating Process 206

9.4 Modelling of the Deformation Process 216

9.5 Conceptual Microstructure Estimation Methodology. 220

9.6 Modelling Grain Growth in a Complex Approach of the Heating-Melting-Cooling Process 231

9.6.1 Research Methodology and Plan 235

9.6.2 Macrostructural Tests 236

9.6.3 Numerical Modelling of Grain Growth 242

9.7 Summary 255

References. 257

10 Summary and Future Work. 259

Appendix A: Thermo-physical Properties of the S355 Grade Steel. 263

Appendix B: Thermo-physical Properties of the C45 Grade Steel 267

Appendix C: Complete Source Code: Steady Heat Flow 273

Appendix D: Subroutine: Gauss Method. 287

Appendix E: Subroutine: Transformation and Integration (3D). 291

Appendix F: Function Calculating Geometry for Stereo Presentation 301

Nomenclature

σ_{ij}	Stress tensor components
σ_{kk}	Mean stress
δ_{ij}	Kronecker delta
σ_p	Yield stress
$\dot{\epsilon}_i$	Effective strain rate
$\dot{\epsilon}_{ij}$	Strain rate tensor components
(v_r, v_θ, v_z)	Components of vector of velocity in the cylindrical coordinate system
r, θ, z	Position vector components in a cylindrical coordinate system
W_σ	Work of plastic deformation
W_λ	Work related to the condition of mass conservation
W_f	Friction work
W	Work functional
σ_i	Effective stress
ϵ_{ij}	Strain tensor components
ϵ_i	Effective strain
$\dot{\epsilon}$	Strain rate
ϵ	Strain
m	Friction factor
λ	Thermal conductivity coefficient
T	Absolute temperature
Q	Heat generation rate for volume unit
c_p	Specific heat
ρ	Density
τ	Time
r	Radius
i, j	Particle index
W	Smoothing kernel
h	Smoothing length
m_j	Mass of particle j
ρ_j	Density of particle j

G	Derivative of the kernel function W
\mathbf{v}	Velocity
p	Pressure
\mathbf{F}	External force
θ	Second-order tensor containing τ_{ij} stresses
\bar{c}_{ij}	Mean speed of sound of particle i and j
$\bar{\rho}_{ij}$	Mean density of particle i and j
T_l	Liquidus temperature
T_s	Solidus temperature
NST	Nil strength temperature
NDT	Nil ductility temperature
DRT	Ductility recovery temperature
T_d	Deformation temperature (physical and computer simulation)
V_{ch}	Cooling rate
R_f	Fracture resistance indicator
G	Temperature gradient before the crystallisation front
D	Diffusion coefficient of admixture atoms
ΔT_0	Difference between the solidus and liquidus temperatures
V_c	Critical crystallisation front speed
V_n	Tool stroke rate in the Gleeble 3800 simulator system
F_{max}	Maximum measured force
$\tau_{melting}$	Remelting time
f_s, f_l	Solid- and liquid-phase fraction
\aleph_1, \aleph_2	Distances between the primary and secondary dendrite branches
A_{dend}	Dendritic structure area
\mathbf{n}	Vector of the shape function
\mathbf{n}^T	Transposed vector of the shape function in the heat transfer model
\mathbf{H}	Main matrix of the discrete form for the steady heat flow
\mathbf{p}	Vector of free terms for the steady heat flow
$\bar{\mathbf{H}}$	Main matrix of the discrete form for the transient heat flow
$\bar{\mathbf{p}}$	Vector of free terms for the transient heat flow
\mathbf{M}	Matrix of thermal capacity
q	Density of heat flux on the heat transfer zone surface
\mathbf{T}	Vector of the temperature nodal values
T_0	Initial temperature
T_{env}	Temperature of medium in contact with the area concerned
α	Heat transfer coefficient
S	Boundary surface
V	Volume of medium analysed
λ	Vector of thermal conductivity distribution function
n_r, n_z	The direction cosines of normal to the outer surface
\mathbf{T}_1	Vector of temperature nodal values at the beginning of the time step
\mathbf{T}_2	Vector of temperature nodal values at the end of the time step
\mathbf{f}	Vector of free terms

\widehat{H}	Enthalpy
ρ_s	Density of solid phase
ρ_l	Density of liquid phase
\underline{v}	Displacement vector
\underline{A}	Nodal displacement vector
ξ, η, ζ	Coordinates of the consecutive Gauss points in the local coordinate system
\underline{C}^T	Transposed unit vector
\underline{B}	Shape function derivative matrix
$\underline{\underline{\varepsilon}}$	Strain rate vector
$\underline{\varepsilon}$	Strain vector
\underline{D}	Unit matrix
v_0	Grip velocity

Abstract

The monograph constitutes a summary of seven years of work of the author in the areas of physical and computer-based simulations, concerning the description of a unique methodology of integrated high-temperature process modelling (temperatures exceeding hot rolling range or semi-solid state) within the context of design aid for new metal processing technologies. The issues of physical and computer-based modelling of phenomena accompanying high-temperature processes, due to their specifics and complexity, is one of the most difficult issues in the area of metal processing. With respect to industrial applications and the development of integrated continuous casting and sheet rolling technologies (including “soft-reduction” or Direct Strip Casting processes), issues related to broadly understood modelling are gaining importance. Due to high execution costs of industrial trials that are necessary in case of traditional technology design methods, the idea came to life of describing the concepts of integrated modelling characterised by selected physical phenomena accompanying high-temperature processes.

Comprehensive tests were applied to solve problems related to the high-temperature deformation of steel. The tests covered both physical tests using specialist laboratory instruments (thermo-mechanical simulator Gleeble 3800, computer tomograph NANOTOM 180N, testing machine Zwick Z250, 3D systems of blue light scanning ATOS Triple Scan and Barco Gemini stereoscopic projection package), and advanced mathematical modelling (hybrid and multi-scale approach): finite element method (FE), smoothed particle hydrodynamics method (SPH) and Monte Carlo method (MC).

The approach, integrating the fields of physical and computer-based simulations in case of full or partial exchange of information between these fields, forms the basis for the described concept of integrated high-temperature process modelling, presented in detail in this monograph.