Advanced Structured Materials

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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

Nomenclature

σ_{ij}	Stress tensor components
σ_{kk}	Mean stress
δ_{ij}	Kronecker delta
σ_p	Yield stress
$\dot{\varepsilon}_i$	Effective strain rate
$\dot{\varepsilon}_{ij}$	Strain rate tensor components
$(\mathrm{v_r}, \mathrm{v}_\theta, \mathrm{v_z})$	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_t	Friction work
W	Work functional
σ_i	Effective stress
ε_{ij}	Strain tensor components
ε_i	Effective strain
$\dot{\varepsilon}$	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
$\boldsymbol{v}$	Velocity
p	Pressure
$\boldsymbol{F}$	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
$\boldsymbol{n}$	Vector of the shape function
$\boldsymbol{n}^T$	Transposed vector of the shape function in the heat transfer model
$\boldsymbol{H}$	Main matrix of the discrete form for the steady heat flow
$\boldsymbol{p}$	Vector of free terms for the steady heat flow
$\overline{\boldsymbol{H}}$	Main matrix of the discrete form for the transient heat flow
$\overline{\boldsymbol{p}}$	Vector of free terms for the transient heat flow
$\boldsymbol{M}$	Matrix of thermal capacity
q	Density of heat flux on the heat transfer zone surface
$\boldsymbol{T}$	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
$\boldsymbol{\lambda}$	Vector of thermal conductivity distribution function
n_r, n_z	The direction cosines of normal to the outer surface
$\boldsymbol{T}_1$	Vector of temperature nodal values at the beginning of the time step
$\boldsymbol{T}_2$	Vector of temperature nodal values at the end of the time step
$\boldsymbol{f}$	Vector of free terms

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