Physical Metallurgy elucidates the microstructure, transformations and properties of metallic materials by means of solid state physics and chemical thermodynamics. Experimental methods of physical metallurgy are also treated.

This third edition includes new sections on the permeation of hydrogen in metals, the Landau theory of martensitic transformation, as well as a section on order hardening and plasticity of intermetallics. Numerous other sections have been brought up-to-date in the light of new developments (e.g. scanning tunnelling microscopy, CALPHAD-method, diffusion in glasses, DIGM, recrystallization). New artwork and references have been added to complement the additions.

Professor Haasen's clear and concise coverage of a remarkably wide range of topics will appeal both to physics students at the threshold of their metallurgical careers, and to metallurgists who are interested in the physical foundation of their field.

PHYSICAL METALLURGY

Physical Metallurgy

THIRD ENLARGED AND REVISED EDITION

PETER HAASEN

TRANSLATED BY JANET MORDIKE

CAMBRIDGE
UNIVERSITY PRESS

Published by the Press Syndicate of the University of Cambridge
The Pitt Building, Trumpington Street, Cambridge CB2 1RP
40 West 20th Street, New York, NY 10011-4211, USA
10 Stamford Road, Oakleigh, Melbourne 3166, Australia

Originally published in German as *Physikalische Metallkunde*
by Springer-Verlag, 1984, and © Springer-Verlag, Berlin Heidelberg 1974

First published in English by Cambridge University Press 1978 as
Physical Metallurgy
Second edition 1986; Third enlarged and revised edition 1996

A catalogue record for this book is available from the British Library

Library of Congress cataloguing-in publication data

Haasen, P. (Peter)
[Physikalische Metallkunde. English]
Physical metallurgy / Peter Haasen; translated by Janet Mordike.
–3rd enl. and rev. ed.
p. cm.
Includes bibliographical references and index.
ISBN 0-521-55092-0 (hc). – ISBN 0-521-55925-1 (pbk.)
1. Physical metallurgy. I. Title.
TN690.H123 1996
669′.9–dc20 95-15904 CIP

ISBN 0 521 55092 0 hard covers
ISBN 0 521 55925 1 paperback

Transferred to digital printing 2003

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PREFACE TO THE ENGLISH EDITIONS

Preface to the First English Edition

A number of English and American colleagues have expressed a desire for an English translation of this book, which they feel would be useful in final year B.Sc. Honours Metallurgy or master's degree courses. I am very pleased that two of my friends and former co-workers, Janet and Barry Mordike, have undertaken this work since they are familiar with the Göttingen as well as the British lecture courses. I would like to thank them for their careful and sensitive translation.

The English edition has provided the opportunity to correct a number of errors in the German version which have been pointed out to me by students and colleagues, especially Professor A. W. Sleeswyk, Drs H. H. Homann and V. Schlett. SI units are now used wherever it seemed advisable. Drs L. Schultz and R. Wagner have helped in proof-reading.

Peter Haasen
Caen, July 1976

Preface to the Third English Edition

The third edition of this book follows that of the German original as it was revised and enlarged in 1993. I am pleased that many English and American colleagues use the text in their courses and give me the benefit of their comments.

Peter Haasen
Göttingen, Summer 1993

PREFACE

For more than 20 years P. Haasen's book *Physical Metallurgy* has been not only an introductory textbook for students of both physics and materials science, but has also been used by scientists as a concise review of the whole field of metal physics.

Based on classical methods of solid state physics and physical chemistry, it covers many methods and nearly all problems of physical metallurgy except magnetism and superconductivity. The latter were intentionally left out for a second volume, which P. Haasen was not able to finish.

Each chapter of the book is designed to guide the reader from the simpler to the more complex metallurgical phenomena, to give them some physical meaning and to lead the reader to the current state of knowledge.

The third edition was completely revised. Major additions deal with 'Hydrogen in Metals', with 'Shape-Memory Alloys' and with 'Plasticity of Intermetallics'. *These are rapidly developing areas of research in metal physics. At the time of my retirement I hope that this book will continue to be useful and to set standards.* (P. Haasen)

P. Haasen finished the manuscript of the third English edition only weeks before his death on 18th October, 1993.

Final revisions and corrections were accomplished with the help of Brian M. Watts, Haverhill, UK. Drs G. Brion, D. Isheim, and A. Pundt have helped in proof-reading.

Ferdinand Haider, Fritz D. Wöhler
Göttingen, Summer 1995

MEANING OF FREQUENTLY USED SYMBOLS

A	amplitude of wave, of dislocation stress at unit distance
a	lattice parameter, shear strain
$\dot{a}$	strain rate
a_i	activity of component i
B	dislocation friction coefficient
$\mathbf{b}$	Burgers vector
c	height of tetragonal cell (c/a axial ratio), velocity of light
c_i	volume concentration of component i
c_j	number of jogs per unit length
c_V	fraction of vacant lattice sites
c_I	fraction of interstitial atoms
c_D	fraction of double vacancies
c_t	transverse sound velocity
c_v	specific heat at constant volume
D	diffusion coefficient
$\tilde{D}$	concentration dependent inter-diffusion coefficient
D_L	lattice diffusion coefficient
D_G	grain boundary diffusion coefficient
D_S	surface diffusion coefficient
d	(atomic) distance, grain size
d$\mathbf{s}$	line element
E	internal energy
E_F	Fermi energy
$\hat{E}$	energy per unit area
E_L	line energy of dislocation
$\check{E}$	Young's modulus
$\mathscr{E}$	electric field strength
EN	electronegativity
e	strain energy density
e/a	number of electrons per atom
F	free energy
f	scattering amplitude of an atom, free energy per unit volume, number of degrees of freedom
$\mathscr{f}$	correlation factor
G	Gibbs free energy, shear modulus
$\mathbf{g}$	reciprocal lattice vector
H	enthalpy, magnetic field strength
h	distance, Miller index
$\hbar$	Planck's constant divided by 2π
I	intensity, current
Im	imaginary part of a complex quantity
J	flux
j	flux density
K	force, reaction rate constant
$\mathbf{k}$	wave vector
k	Boltzmann constant, Miller index
k_0	distribution coefficient
k_y	Petch parameter
k_z	oxidation rate parameter
L	latent heat, domain size, dislocation mean free path
l	length, Miller index
M	mass, Taylor factor, period of superlattice
M_{ij}	Onsager mobility parameter
m	atomic mass, slope of liquidus
m'	strain rate sensitivity
m^*	effective mass of electron
m_s	Schmid factor
N	number of atoms, dislocation density, group number in the periodic system, number of cycles
$\mathbf{n}$	normal to a plane
n	number of nearest neighbours, number of components
n_i	number of atoms of component i
P^{AB}	probability for AB pair
$\mathbf{p}$	phonon wave vector
p	pressure
Q	activation energy of grain boundary motion
Q^*	heat of transport
q	cross-section
R	rate
Re	real part of a complex quantity

r	position, distance, number of phases
r_0	atomic radius
S	entropy, lamellar spacing
s	distance (from **g**) in reciprocal space, degree of long-range order
T	absolute temperature
T_m	melting temperature
t	time, thickness
U	voltage, activation energy of dislocation motion
u	displacement, vibrational energy
V	volume, (electrostatic) potential
v	velocity
W	work
w	width of dissociation of a dislocation
X	volume fraction
x	coordinate
y	coordinate
Z	partition function, ionic charge
z	coordinate
α	angle
α_m	degree of short range order in mth shell
β	angle, spinodal wave number
Γ	jump frequency
γ	stacking fault energy
γ_i	activity coefficient of component i
Δ	angle
δ	size misfit, grain boundary thickness
ε	strain, pair interchange energy
η	(shear) modulus defect, grain boundary (diffusion) factor
ζ	width of dislocation core
Θ	angle, Debye temperature, work hardening coefficient
$\boldsymbol{\kappa}$	wave vector difference
κ	coefficient of gradient energy
Λ	slip-line length parameter
λ	wavelength, angle
μ	linear absorption coefficient
μ_i	chemical potential of component i
ν	frequency, Poisson's ratio
ν_i	molar fraction of component i
ν_0	attack frequency
ν_V	vacancy jump frequency
ξ	extinction distance
ρ	density of dislocation line elements
ρ_{el}	electrical resistivity
ρ_M	mass density
σ	stress, electrical conductivity
τ	relaxation time, shear stress
Φ	complex scattering amplitude
φ	angle, statistical scattering amplitude
χ	angle
ψ	wave function
Ω	atomic volume
ω	angular frequency, number of states of energy E

CONVERSION OF UNITS

1 joule = 1 newton metre = 1 watt second = 0.24 calories = 10^7 ergs

1 eV/atom = 23 kilocalories/mole = 96 kilojoules/mole = R (11 600 kelvin)
$R \approx 2$ calories/(mole kelvin)

1 kgf/mm² $\approx$ 10 meganewtons/metre² = 10^8 dynes/centimetre² $\approx 7 \times 10^2$ psi = 10^7 pascal