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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.

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Physical Metallurgy

THIRD ENLARGED AND REVISED EDITION

PETER HAASEN

TRANSLATED BY JANET MORDIKE



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

xv *Meaning of frequently used symbols*

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