

Landolt-Börnstein

Numerical Data and Functional Relationships in Science and Technology  
New Series / Editor in Chief: W. Martienssen

Group III: Condensed Matter  
Volume 32

# Magnetic Properties of Metals

Supplement to Volume 19

Subvolume C

Alloys and Compounds of d-Elements  
with Main Group Elements. Part 2

Editor:

H.P.J. Wijn

Contributors:

K.-U. Neumann, T. Ohoyama, N. Yamada, K.R.A. Ziebeck



Springer

ISSN 1615-1925 (Condensed Matter)

ISBN 3-540-63278-6 Springer-Verlag Berlin Heidelberg New York

Library of Congress Cataloging in Publication Data

Zahlenwerte und Funktionen aus Naturwissenschaften und Technik, Neue Serie

Editor in Chief: W. Martienssen

Vol. III/32C; Editor: H.P.J. Wijn

At head of title: Landolt-Börnstein. Added t.p.: Numerical data and functional relationships in science and technology.

Tables chiefly in English.

Intended to supersede the Physikalisch-chemische Tabellen by H. Landolt and R. Börnstein of which the 6th ed. began publication in 1950 under title: Zahlenwerte und Funktionen aus Physik, Chemie, Astronomie, Geophysik und Technik.

Vols. published after v. 1 of group I have imprint: Berlin, New York, Springer-Verlag

Includes bibliographies.

1. Physics--Tables. 2. Chemistry--Tables. 3. Engineering--Tables.

I. Börnstein, R. (Richard), 1852-1913. II. Landolt, H. (Hans), 1831-1910.

III. Physikalisch-chemische Tabellen. IV. Title: Numerical data and functional relationships in science and technology.

QC61.23 502'.12

62-53136

This work is subject to copyright. All rights are reserved, whether the whole or part of the material is concerned, specifically the rights of translation, reprinting, reuse of illustrations, recitation, broadcasting, reproduction on microfilm or in other ways, and storage in data banks. Duplication of this publication or parts thereof is permitted only under the provisions of the German Copyright Law of September 9, 1965, in its current version, and permission for use must always be obtained from Springer-Verlag. Violations are liable for prosecution act under German Copyright Law.

Springer-Verlag Berlin Heidelberg New York

a member of BertelsmannSpringer Science+Business Media GmbH

© Springer-Verlag Berlin Heidelberg 2001

Printed in Germany

The use of general descriptive names, registered names, trademarks, etc. in this publication does not imply, even in the absence of a specific statement, that such names are exempt from the relevant protective laws and regulations and therefore free for general use.

*Product Liability:* The data and other information in this handbook have been carefully extracted and evaluated by experts from the original literature. Furthermore, they have been checked for correctness by authors and the editorial staff before printing. Nevertheless, the publisher can give no guarantee for the correctness of the data and information provided. In any individual case of application, the respective user must check the correctness by consulting other relevant sources of information.

Cover layout: Erich Kirchner, Heidelberg

Typesetting: Redaktion Landolt-Börnstein, Darmstadt

Printing: Computer to plate, Mercedes-Druck, Berlin

Binding: Lüderitz & Bauer, Berlin

SPIN: 1053 5463

63/3020 - 5 4 3 2 1 0 - Printed on acid-free paper

## Editor

**H.P.J. Wijn**

Institut für Werkstoffe der Elektrotechnik der Rheinisch-Westfälischen Technischen Hochschule  
Aachen, Templergraben 55, D-52062 Aachen, Germany  
e-mail: wijn@jole.nl

## Contributors to Subvolume III/32C

**K.-U. Neumann**

Department of Physics,  
Loughborough University,  
Loughborough, Leicestershire LE11 3TU,  
United Kingdom  
e-mail: k.u.neumann@lboro.ac.uk  
*Heusler alloys*

**T. Ohoyama**

Department of Applied Physics and Chemistry  
University of Electro-Communications  
1-5-1 Chofugaoka, Chofu, Tokyo 182-8585,  
Japan  
e-mail: ohoyama@psyche.pc.uec.ac.jp  
*3d elements and C, Si, Ge, Sn or Pb*

**N. Yamada**

Department of Applied Physics and Chemistry  
University of Electro-Communications  
1-5-1 Chofugaoka, Chofu, Tokyo 182-8585,  
Japan  
e-mail: yamadan@psyche.pc.uec.ac.jp  
*3d elements and C, Si, Ge, Sn or Pb*

**K.R.A. Ziebeck**

Department of Physics,  
Loughborough University,  
Loughborough, Leicestershire LE11 3TU,  
United Kingdom  
e-mail: k.r.ziebeck@lboro.ac.uk  
*Heusler alloys*

## Landolt-Börnstein

### Editorial Office

Gagernstr. 8, D-64283 Darmstadt, Germany  
fax: +49 (6151) 171760  
e-mail: lb@springer.de

### Internet

<http://www.landolt-boernstein.com/>

## Preface

The intrinsic magnetic properties of metals, alloys and metallic compounds have been systematically compiled in the various subvolumes 19A–F of the Landolt-Börnstein New Series Group III. Each subvolume is devoted to a separate and, from a point of view of the Periodic Table of the Elements, coherent group of substances. The amount of experimental data that became available since the publishing of each of these subvolumes in the years 1986 to 1994 gave us every reason to ask the various authors to consider the appropriateness of preparing supplements to their original work. As a result the first subvolume LB III/32A has been published in 1996, dealing with the magnetic properties of substances consisting of 3d, 4d and 5d elements, and of alloys between these elements, as well as alloys and compounds between 4d or 5d elements and main group elements.

The present subvolume LB III/32C is the second of two volumes dedicated to alloys and compounds of 3d elements and main group elements. The first volume, LB III/32B, has been published in 1999. LB III/32C is the supplement to volume LB III/19C covering the literature up to 1996. The alloys considered comprise Heusler alloys as well as alloys consisting of 3d elements and C, Si, Ge, Sn or Pb.

Many thanks are due to the authors for the continued agreeable cooperation and their patience with the delay in the publication of this volume, Frau G. Burfeindt and Dr. W. Finger of Landolt-Börnstein's editorial office for the great help in the editorial work, especially in preparing the electronic files that were used in printing, and, last but not least, Springer-Verlag for the carefulness with respect to the publication of this volume.

Aachen, January 2001

**The Editor**

# Contents of Subvolume III/32 C

List of symbols . . . . .	IX
List of abbreviations . . . . .	XII
<b>1</b>	<b>Magnetic properties of 3d, 4d, and 5d elements, alloys and compounds . . . . . 1</b>
<b>1.1</b>	<b>3d elements (H.P.J. WIJN) . . . . . see subvolume III/32A</b>
<b>1.2</b>	<b>Alloys between 3d elements (H.P.J. WIJN) . . . . . see subvolume III/32A</b>
<b>1.3</b>	<b>4d and 5d elements, alloys and compounds between themselves or with main group elements (S. MISAWA, K. KANEMATSU) . . . . . see subvolume III/32A</b>
<b>1.4</b>	<b>Alloys and compounds of 3d elements with 4d or 5d elements (M. SHIGA, H. WADA) . . . . . see subvolume III/32A</b>
<b>1.5</b>	<b>Alloys and compounds of 3d elements with main group elements</b>
<b>1.5.1</b>	<b>3d elements with Cu, Ag or Au (Y. NAKAI, Y. TSUNODA) . . . see subvolume III/32B</b>
<b>1.5.2</b>	<b>3d elements and Be, Mg, Zn or Hg (H.P.J. WIJN) . . . . . see subvolume III/19B</b>
<b>1.5.3</b>	<b>3d elements with B, Al, Ga, In or Tl (J.G. BOOTH) . . . . . see subvolume III/32B</b>
<b>1.5.4</b>	<b>3d elements and C, Si, Ge, Sn or Pb (T. OHYAMA, N. YAMADA) . . . . . 1</b>
<b>1.5.4.1</b>	<b>Introduction . . . . . 1</b>
<b>1.5.4.2</b>	<b>Ti and V alloys and compounds . . . . . 4</b>
<b>1.5.4.3</b>	<b>Cr alloys and compounds . . . . . 6</b>
<b>1.5.4.4</b>	<b>Mn alloys and compounds . . . . . 13</b>
<b>1.5.4.5</b>	<b>Fe alloys and compounds . . . . . 38</b>
1.5.4.5.1	Alloys and compounds with C and Si . . . . . 38
1.5.4.5.2	Alloys and compounds with Ge . . . . . 47
1.5.4.5.3	Alloys and compounds with Sn . . . . . 52
<b>1.5.4.6</b>	<b>Co and Ni alloys and compounds . . . . . 54</b>
<b>1.5.4.7</b>	<b>MM'X ternary compounds . . . . . 55</b>
<b>1.5.4.8</b>	<b>References for 1.5.4 . . . . . 59</b>

<b>1.5.5</b>	<b>Heusler alloys (K.R.A. ZIEBECK, K.-U. NEUMANN)</b>	64
<b>1.5.5.1</b>	<b>Introduction</b>	64
<b>1.5.5.2</b>	<b>Structural properties</b>	64
1.5.5.2.1	Crystallography	64
1.5.5.2.2	Ternary phase diagrams	67
	Ni-Mn-Sn	67
	Ni-Fe-Al	69
	Ni-Hf-Al	72
	Mg-(R)-Ag	76
	Pd-Y-Sn	82
1.5.5.2.3	Kinematics of phase transition	84
1.5.5.2.4	Deformation	88
1.5.5.2.5	Hydrogen absorption	89
1.5.5.2.6	Films/ribbons	91
<b>1.5.5.3</b>	<b>Bulk magnetic properties</b>	95
1.5.5.3.1	Introduction	95
1.5.5.3.2	Arrott plots	95
1.5.5.3.2.1	Introduction	95
1.5.5.3.2.2	Mean field description of magnetic phase transition and Landau form of the free energy	96
1.5.5.3.2.3	Magnetisation and Arrott plots	103
1.5.5.3.2.4	Arrott plots for two magnetic subsystems	105
1.5.5.3.2.5	Ferromagnetic and / or antiferromagnetic order	108
1.5.5.3.2.6	Discussion	113
1.5.5.3.3	Experimental results	113
1.5.5.3.3.1	Ferromagnets	113
1.5.5.3.3.2	Antiferromagnetism	130
1.5.5.3.3.3	Paramagnetic	132
1.5.5.3.3.4	C1b compounds	140
1.5.5.3.3.5	Quaternary	154
<b>1.5.5.4</b>	<b>Neutron scattering</b>	166
1.5.5.4.1	Neutron diffraction	166
1.5.5.4.2	Crystalline electric fields	184
<b>1.5.5.5</b>	<b>Phase transitions</b>	193
<b>1.5.5.6</b>	<b>Electrical properties</b>	206
1.5.5.6.1	Electrical resistivity	206
1.5.5.6.2	Galvanomagnetic properties	217
1.5.5.6.3	Superconductivity	224
<b>1.5.5.7</b>	<b>Thermal properties</b>	235
<b>1.5.5.8</b>	<b>Hyperfine fields</b>	244
<b>1.5.5.9</b>	<b>Band structure</b>	315
1.5.5.9.1	Introduction	315
1.5.5.9.2	Cohesion and phase transitions	344
<b>1.5.5.10</b>	<b>Electronic structures</b>	358
<b>1.5.5.11</b>	<b>Magneto-optics</b>	373
<b>1.5.5.12</b>	<b>References for 1.5.5</b>	409

## List of symbols

Symbol	Unit	Quantity
$a, b, c$	nm, Å	lattice parameters
$a_{\text{us}}$	db cm <sup>-1</sup>	ultrasonic attenuation
$B$	Pa	bulk modulus
$B$	T, G	magnetic induction
$B_{\text{cr}}$	T, G	metamagnetic transition field
$B_{\text{r}}$	T, G	residual induction
$(BH)_{\text{max}}$	J m <sup>-3</sup> , G Oe	maximum energy product
$C_p$	J kg <sup>-1</sup> K <sup>-1</sup>	heat capacity at constant pressure
$C_V$	J kg <sup>-1</sup> K <sup>-1</sup>	heat capacity at constant volume
$c$	m s <sup>-1</sup>	sound velocity
$c_{ij}$	Pa	elastic constants
$D$	eV Å <sup>2</sup> , THz Å <sup>2</sup>	$q^2$ -expansion coefficient of the spinwave energy
$E$	J, erg, eV, Ry	energy
$E$	Pa	Young's modulus
$E_{\text{a}}$	J m <sup>-3</sup> , Pa	anisotropy energy
$\Delta E_{\text{a}}$	J m <sup>-3</sup> , Pa	magnetoelastic anomaly
$E_{\text{b}}$	eV	binding energy
$E_{\text{F}}$	eV	Fermi energy
$e/a$		electrons per atom
$e^2 q Q$	mm s <sup>-1</sup>	nuclear quadrupole coupling constant
$e Q V_{zz}$	mm s <sup>-1</sup>	nuclear quadrupole coupling constant
$f$		magnetic form factor
$f$	T	de Haas – van Alphen frequency
$G$	Hz	Gilbert damping parameter
$G$	Pa	shear modulus
$g$		$g$ -factor
$H$	J	enthalpy
$H$	A m <sup>-1</sup> , Oe	magnetic field
$H_{\text{A}}$	A m <sup>-1</sup> , Oe	magnetic anisotropy field
$H_{\text{c}}$	A m <sup>-1</sup> , Oe	coercive field
$H_{\text{ext}}$	A m <sup>-1</sup> , Oe	external magnetic field
$H_{\text{hf}}, H_{\text{hyp}}$	A m <sup>-1</sup> , Oe	magnetic hyperfine field
$h$	J s	Planck's constant
$\hbar$	J s	Planck's constant divided by $2\pi$
$h, k, l$		Miller indices
$I$		intensity
$I$	A	electrical current
$J$		total angular momentum
$J$	eV	exchange constant
$K$		Knight shift
$K$	Å <sup>-1</sup>	wavevector

Symbol	Unit	Quantity
$K$	$\text{J m}^{-3}, \text{erg cm}^{-3}, \text{Pa}$	anisotropy constant
$K_n$	$\text{J m}^{-3}, \text{erg cm}^{-3}, \text{Pa}$	$n^{\text{th}}$ -order magnetocrystalline anisotropy constants
$k_B$	$\text{J K}^{-1}$	Boltzmann constant
$L$		orbital angular momentum
$\Delta l/l$		linear magnetostriction
$M$	$\text{A m}^{-1}, \text{T}, \text{G}$	magnetization
$M_r$	$\text{A m}^{-1}, \text{T}, \text{G}$	remanence
$M_s$	$\text{A m}^{-1}, \text{T}, \text{G}$	saturation magnetization
$m_z$	$\text{A m}^{-1}, \text{T}, \text{G}$	magnetization component
$N(E_F), N_F$	states $\text{eV}^{-1} \text{at}^{-1}$	density of states at the Fermi energy
$n$	states $\text{eV}^{-1} \text{at}^{-1}$	density of states
$P$		neutron polarization
$P(H)$		probability distribution
$p$	$\text{Pa}, \text{bar}$	pressure
$\bar{p}$	$\mu_B$	atomic magnetic moment
$\bar{p}$	$\mu_B$	average atomic magnetic moment
$p_{\text{at}}$	$\mu_B$	magnetic moment per atom
$p_{\text{eff}}$	$\mu_B$	effective paramagnetic moment
$Q$	$\text{J g}^{-1}$	heat of transformation
$Q$	$\text{mm s}^{-1}$	quadrupole shift
$Q$	$\text{V K}^{-1}$	thermoelectric power
$Q, q$	$\text{\AA}^{-1}$	wavevector
$q/q_s$		Rhodes – Wohlfarth ratio
$R$	$\text{J mol}^{-1} \text{K}^{-1}$	gas constant
$R$	$\Omega$	electrical resistance
$R$	$\text{m}^3 \text{C}^{-1}$	Hall coefficient
$R_0$	$\text{m}^3 \text{C}^{-1}$	ordinary Hall coefficient
$R_s$	$\text{m}^3 \text{C}^{-1}$	extraordinary Hall coefficient
$S$		spin angular momentum
$S$	$\text{J K}^{-1}$	entropy
$S$	$\text{V K}^{-1}$	thermoelectric power
$S(K)$	$\text{barn sr}^{-1} \text{at}^{-1}$	elastic differential scattering function
$T$	$\text{K}, ^\circ\text{C}$	temperature
$T_a$	$\text{K}$	annealing temperature
$T_C$	$\text{K}$	Curie temperature
$T_{\text{cr}}$	$\text{K}$	critical temperature
$T_f$	$\text{K}$	spin-freezing temperature
$T_g$	$\text{K}$	spin-glass transition temperature
$T_N$	$\text{K}$	Néel temperature
$T_R$	$\text{K}$	spin reorientation temperature
$T_t$	$\text{K}$	transition temperature
$T_1$	$\text{s}$	longitudinal nuclear spin relaxation time
$t$	$\text{s}$	time
$V$	$\text{V}$	voltage
$V_{zz}$	$\text{V cm}^{-2}$	zz-component of electric field gradient
$V$	$\text{m}^3$	volume
$v$	$\text{m s}^{-1}$	velocity
$x, y$		composition
$\alpha$	$\text{V K}^{-1}$	thermoelectric power
$\alpha$	$\text{K}^{-1}$	linear thermal expansion coefficient



Symbol	Unit	Quantity
$\alpha_V$	$K^{-1}$	volume thermal expansion coefficient
$\Gamma$	$\text{erg g}^{-1}$	torque
$\Gamma$	$\text{meV}$	linewidth, damping constant
$\gamma$	$\text{Hz G}^{-1}$	gyromagnetic ratio
$\gamma$	$\text{J mol}^{-1} K^{-2}$	electronic specific heat coefficient
$\Delta$	$\text{mm s}^{-1}$	quadrupole splitting
$\delta$	$\text{mm s}^{-1}$	isomer shift
$\delta$		incommensurability factor, $\delta = 1 - Qa/2\pi$
$\varepsilon$		linear strain
$\zeta$		reduced wavevector
$\Theta$	$K$	paramagnetic Curie temperature
$\Theta_D$	$K$	Debye temperature
$\theta$	$\text{deg}$	angle
$\kappa$	$\text{\AA}^{-1}$	inverse correlation length
$\kappa$	$\text{W m}^{-1} K^{-1}$	thermal conductivity
$\lambda$		magnetostriction
$\lambda$	$\text{\AA}$	wavelength
$\lambda$	$\text{s}^{-1}$	relaxation rate
$\mu$		relative permeability
$\mu_i$		initial permeability
$\mu_0$	$\text{T m A}^{-1}$	permeability of the vacuum
$\nu$	$\text{s}^{-1}$ , $\text{Hz}$	frequency
$\nu_Q$	$\text{mm s}^{-1}$	quadrupole splitting
$\rho$	$\text{g cm}^{-3}$	density
$\rho$	$\text{cm}^{-2}$	dislocation density
$\rho$	$\Omega \text{ m}$	electrical resistivity
$\rho_H$	$\Omega \text{ m}$	Hall resistivity
$\Delta\rho/\rho$		magnetoresistance
$\sigma$	$\text{A m}^2 \text{ kg}^{-1}$ , $\text{V s m kg}^{-1}$ , $\text{G cm}^3 \text{ g}^{-1}$	bulk magnetic moment per unit of mass
$\sigma$	$\text{A m}^2 \text{ mol}^{-1}$ , $\text{V s m mol}^{-1}$ , $\text{G cm}^3 \text{ mol}^{-1}$	bulk magnetic moment per mole
$\sigma$	$\text{Pa}$	stress
$\sigma$	barn	cross section
$\tau$	$\text{s}$	relaxation time
$\tau$	$\text{s}^{-1}$	relaxation rate
$\phi$	$\text{deg}$	angle
$\chi_g$	$\text{m}^3 \text{ kg}^{-1}$ , $\text{cm}^3 \text{ g}^{-1}$	magnetic susceptibility per unit of mass
$\chi_V$		magnetic susceptibility per unit of volume
$\chi_m$	$\text{m}^3 \text{ mol}^{-1}$ , $\text{cm}^3 \text{ mol}^{-1}$	magnetic susceptibility per mole
$\chi_P$		Pauli susceptibility
$\chi'$		real part of the complex magnetic susceptibility
$\chi''$		imaginary part of the complex magnetic susceptibility
$\chi_1, \chi_2$		nonlinear magnetic susceptibility
$\Omega$	$\text{sr}$	solid angle
$\omega$		volume magnetostriction
$\omega$	$\text{rad s}^{-1}$	angular precession frequency
$\hbar\omega$	$\text{eV}$	excitation energy

## List of abbreviations

a.u.	atomic unit	IRM	isothermal remanent
ac	alternating current		magnetization
AF	antiferromagnetic	mag	magnetic
ASRO	atomic short range order	max	maximum
at	atom	mc	multicritical
av	average	ME	Mössbauer effect
bcc	body-centered cubic	min	minimum
bct	body-centered tetragonal	$\mu$ SR	muon spin resonance
BPP	Bloembergen – Purcell – Pound	NF	nonordered ferromagnetic
CG	cluster glass	nl	nonlinear
cl	cooling	NMR	nuclear magnetic resonance
cr	critical	orth	orthorhombic
ct	centroid	P	paramagnetic
cub	cubic	PAC	perturbed angular correlation
dc	direct current	ppm	parts per million
dHvA	de Haas – van Alphen	res	resonance
dis	disordered	rf	radio frequency
DOS	density of states	RT	room temperature
eff	effective	s	spontaneous; saturation
el	electronic	sc	single crystal
ESR	electron spin resonance	SCR	self-consistent renormalization
ext	external	SDW	spin-density wave
F	ferromagnetic	S-K	Sherrington – Kirpatrick
FC	field-cooled	tetr	tetragonal
fcc	face-centered cubic	trans	transmitted
fct	face-centered tetragonal	TRM	thermoremanent magnetization
FWHM	full width at half maximum	UPS	ultraviolet photoelectron spectroscopy
hcp	hexagonal close-packed		
HF	high field	us	ultrasonic
hf	hyperfine field	wt	weight
inf	inflection	XPS	X-ray photoelectron spectroscopy
int	internal	ZFC	zero-field cooled