Metallurgy for the Non-Metallurgist™

Second Edition

Edited by

Arthur C. Reardon

The Materials
Information Society

ASM International®
Materials Park, Ohio 44073-0002
www.asminternational.org

Copyright © 2011
by
ASM International®
All rights reserved

No part of this book may be reproduced, stored in a retrieval system, or transmitted, in any form or by any means, electronic, mechanical, photocopying, recording, or otherwise, without the written permission of the copyright owner.

First printing, October 2011

Great care is taken in the compilation and production of this book, but it should be made clear that NO WARRANTIES, EXPRESS OR IMPLIED, INCLUDING, WITHOUT LIMITATION, WARRANTIES OF MERCHANTABILITY OR FITNESS FOR A PARTICULAR PURPOSE, ARE GIVEN IN CONNECTION WITH THIS PUBLICATION. Although this information is believed to be accurate by ASM, ASM cannot guarantee that favorable results will be obtained from the use of this publication alone. This publication is intended for use by persons having technical skill, at their sole discretion and risk. Since the conditions of product or material use are outside of ASM's control, ASM assumes no liability or obligation in connection with any use of this information. No claim of any kind, whether as to products or information in this publication, and whether or not based on negligence, shall be greater in amount than the purchase price of this product or publication in respect of which damages are claimed. THE REMEDY HEREBY PROVIDED SHALL BE THE EXCLUSIVE AND SOLE REMEDY OF BUYER, AND IN NO EVENT SHALL EITHER PARTY BE LIABLE FOR SPECIAL, INDIRECT OR CONSEQUENTIAL DAMAGES WHETHER OR NOT CAUSED BY OR RESULTING FROM THE NEGLIGENCE OF SUCH PARTY. As with any material, evaluation of the material under end-use conditions prior to specification is essential. Therefore, specific testing under actual conditions is recommended.

Nothing contained in this book shall be construed as a grant of any right of manufacture, sale, use, or reproduction, in connection with any method, process, apparatus, product, composition, or system, whether or not covered by letters patent, copyright, or trademark, and nothing contained in this book shall be construed as a defense against any alleged infringement of letters patent, copyright, or trademark, or as a defense against liability for such infringement.

Comments, criticisms, and suggestions are invited, and should be forwarded to ASM International.

Prepared under the direction of the ASM International Technical Book Committee (2010–2011), Michael J. Pfeifer, Chair.

ASM International staff who worked on this project include Scott Henry, Senior Manager of Product and Service Development; Eileen De Guire, Senior Content Developer; Steve Lampman, Content Developer; Ann Briton, Editorial Assistant; Bonnie Sanders, Manager of Production; Madrid Tramble, Senior Production Coordinator; and Diane Whitelaw, Production Coordinator.

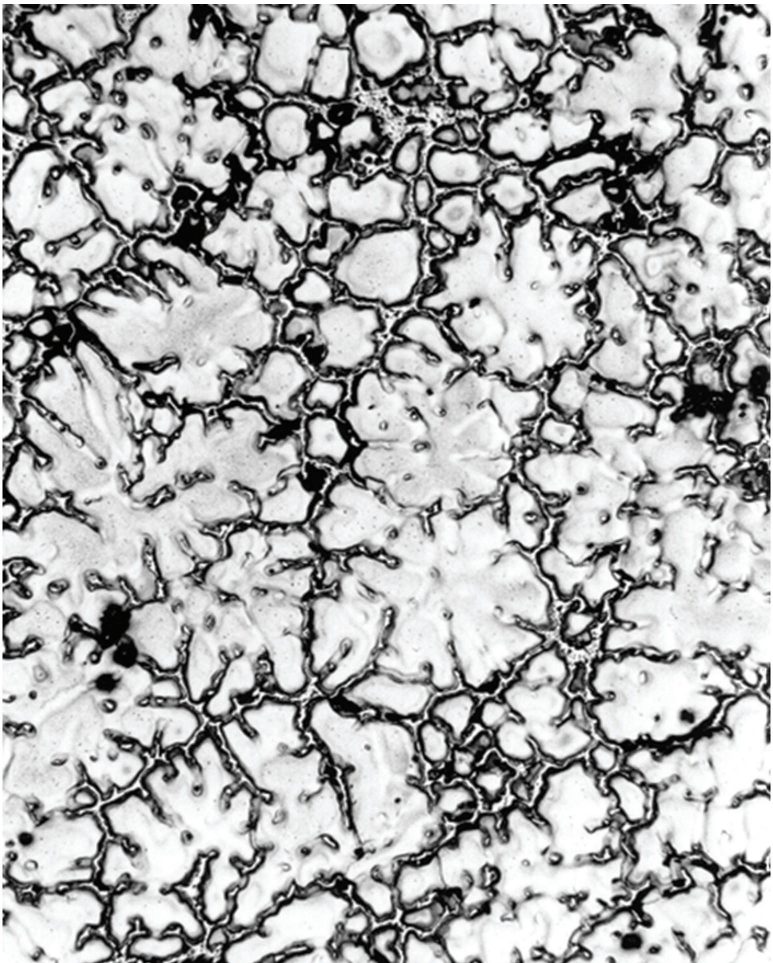
Library of Congress Control Number: 2011930444
ISBN-13: 978-1-61503-821-3
ISBN-10: 1-61503-821-3
SAN: 204-7586

ASM International®
Materials Park, OH 44073-0002
www.asminternational.org

Printed in the United States of America

Contents

About the Cover



The background image on the cover was obtained from the microstructure of thixocast magnesium alloy AZ91 shown above. Courtesy of E. Schaberger, Gießerei-Institut, RWTH Aachen. See also Fig. 5.11

Metallurgy for the Non-Metallurgist, Second Edition
A.C. Reardon, editor

Preface

In North America and in many other parts of the world, the number of formally trained metallurgical experts employed in industry has steadily declined over the course of the last several decades. This trend is the result of several different contributing factors. Seasoned professionals that have served in this capacity for many years may not be replaced on a permanent basis as they retire either due to cost containment efforts by their companies, or because it has become increasingly difficult for these companies to identify qualified replacement candidates. At the same time, the metallurgical departments of many academic institutions that were responsible for training the next generation of metallurgists have gradually been disbanded, or have been absorbed into other academic departments and programs. As fewer individuals choose to enter the field, and as an ever increasing number of metallurgical experts retire from the work force, their former responsibilities often fall upon the shoulders of the remaining members of the engineering, scientific, and design staff.

For those not formally trained in the discipline of metallurgy, or who possess only a peripheral knowledge of the subject, this can lead to a number of potential problems. These include a lack of understanding in the relationships between parameters involved in the processing of metallic materials such as melting, forging, rolling, cold working, machining, heat treatment, welding, etc. and their effects upon the resulting material properties; the relationship between alloying elements and their effects on the properties of the materials in which they are used; the forensic analysis of components that failed in service or that do not meet the requirements of the relevant material standards and specifications; quality assurance issues associated with the testing and manufacture of parts, components, and assemblies; uncertainty in the relevant parameters associated with the proper selection of materials for a given application; and the general process for assessing and understanding the relevant aspects of extractive, physical, and mechanical metallurgy. If you find yourself in any of these categories, or are a student or practicing professional who requires a working knowledge of metallurgy, this book was written for you.

From a commercial perspective, there are over 100,000 materials available today to select among for engineering applications, a far greater number than at any other time in history. And due to the continuing development of new alloys and new classes of engineering materials, the list continues to grow. The judicious selection of one material among this vast array of choices for a specific application requires an in-depth understanding of the properties and characteristics of the various classes of materials. And, the metallurgical characteristics and properties of metallic materials are often critical in assessing their capability to satisfy the requirements for a given application. This book may serve as an introductory text for those who have not been formally trained in the discipline of metallurgy. It may also serve as a reference for those who have received formal training in the discipline, but who need to reacquaint themselves with the subject. The reader will be introduced to the various working concepts in extractive, physical, and mechanical metallurgy, and to their practical application. The historical aspects in the development of these metallurgical concepts, practices, and tools are also provided in selected areas to educate the reader on the history behind many of the discoveries that led to the development of metallurgy as a scientific discipline.

For individuals who are unable to find the answers they seek in this book, or who require more in-depth knowledge on a particular subject, there are several references that are recommended throughout the text for further reading. Where this is insufficient, the reader may consult me directly through my website at www.EngineeringMetallurgy.com. Where appropriate, answers will be provided to the submitted questions, and additional resources suggested for further reading. I enjoy hearing from readers, and welcome their comments on the content, organization, and relevance of this book to their daily work.

I would like to acknowledge the assistance provided by the ASM International staff in the development of this book. In particular, I would like to thank Charles Moosbrugger who initially approached me about writing the second edition. And, I am especially grateful for Steven Lampman's critiquing of the manuscript, and for his tireless assistance in editing the various chapters of this work. I would also like to acknowledge Ann Britton for providing access to reference materials that were used in writing the second edition. And, I would also like to acknowledge the countless others who contributed in some small way. Thank you all.

Art Reardon
May 2011

About the Editor

Dr. Reardon earned his bachelor's degree in physics and mathematics in 1986 at the State University of New York College at Oswego. He later earned his M.S. in mechanical and aerospace sciences, and his Ph.D. in materials science at the University of Rochester in upstate New York. He is an experienced professional in materials science, engineering, and metallurgy with extensive work experience in research and development, alloy design, process metallurgy, mechanical engineering, material selection, and customer technical support. Dr. Reardon has worked in the industry for over 18 years; more than ten years were spent working as a senior process metallurgist at Crucible Specialty Metals where he led projects in the melting, forging, rolling, finishing, and inspection operations, and provided metallurgical support for the annealing and heat treating operations; this included processing of a large number of 300 and 400 series stainless steels, valve steels, tool steels, high speed steels, and a variety of other specialty steel grades. He worked closely with the members of the research division on the design and development of state-of-the-art alloys using both traditional air-melt and powder metallurgy processing techniques.

Dr. Reardon worked as an Adjunct Assistant Professor in the L.C. Smith College of Engineering at Syracuse University where he taught a junior level engineering course entitled Materials, Properties, and Processing for nine consecutive years. He earned his professional engineering license in the discipline of metallurgy, and is licensed in the states of New York, Pennsylvania, and Colorado. He has numerous technical publications in refereed scientific journals spanning subjects from low temperature physics and fracture mechanics to the simulation of atomic solidification processes and laser theory. He has been a member of ASM International since 1988, and currently serves as a member of the ASM International Technical Books Committee.

Metallurgy for the Non-Metallurgist, Second Edition
A.C. Reardon, editor

Abbreviations and Symbols

Å	angstrom
a	crack length or cross section
ac	alternating current
Ac$_1$	The critical temperature when some austenite begins to form during heating, with the “c” being derived from the French *chauffant*
Ac$_3$	The temperature at which transformation of ferrite to austenite is completed during heating
Ac$_{cm}$	In hypereutectoid steel, the temperature during heating when all cementite decomposes and all the carbon is dissolved in the austenitic lattice
ADI	austempered ductile iron
Ae$_1$	The critical temperature when some austenite begins to form under conditions of thermal equilibrium (i.e., constant temperature)
Ae$_3$	The upper critical temperatures when all the ferrite phase has completely transformed into austenite under equilibrium conditions
Ae$_{cm}$	In hypereutectoid steel, the critical temperature under equilibrium conditions between the phase region of an austenite-carbon solid solution and the two-phase region of austenite with some cementite (Fe_3C)
AHSS	advanced high-strength steels
AOD	argon oxygen decarburization
Ar$_1$	The temperature when all austenite has decomposed into ferrite or a ferrite-cementite mix during cooling, with the “r” being derived from the French *refroidissant*
Ar$_3$	The upper critical temperature when a fully austenitic microstructure begins to transform to ferrite during cooling
Ar$_{cm}$	In hypereutectoid steel, the temperature when cementite begins to form (precipitate) during cooling of an austenite-carbon solid solution
Ar$_4$	The temperature at which delta ferrite transforms to austenite during cooling
at.%	atomic percent
bcc	body-centered cubic
bct	body-centered tetragonal
BH	bake-hardening
BOF	basic oxygen furnace
CCT	continuous cooling transformation
CE	carbon equivalent
CN	coordination number
CP	complex phase or commercial purity
CS	Commercial Standard
CSE	copper sulfate reference electrode
CVD	chemical vapor deposition
DBTT	ductile-brittle transition temperature
dc	direct current
D.C.	direct chill
DIN	Deutsche Industrie-Normen (standards)
DP	dual phase
e_f	engineering strain at fracture (elongation)
EAF	electric arc furnace
EB	electron beam
ECT	equicohesive temperature
ECM	electrochemical machining
EDM	electrical discharge machining
ELI	extra-low interstitial
emf	electromotive force
EN	European Norm (specification and standards)
ESR	electroslag remelting
EP	extreme pressure
eV	electron volt
FCAW	flux cored arc welding
fcc	face-centered cubic
FEA	finite-element analysis
FLC	forming limit curve
FM	frequency modulation

gal	gallon
gf	gram-force
GMAW	gas metal arc welding
GP	Guinier-Preston (zone)
GPa	gigapascal
GTAW	gas tungsten arc welding
h	hour
HAZ	heat-affected zone
HB	Brinell hardness
hcp	hexagonal close-packed
HIP	hot isostatic pressing
HK	Knoop hardness
hp	horsepower
HPDC	high-pressure die casting
HRB	Rockwell "B" hardness
HRC	Rockwell "C" hardness
HSLA	high-strength, low-alloy (steel)
HSS	high-speed steel
HV	Vickers hardness (diamond pyramid hardness)
IF	interstitial free
IF-HA	interstitial free, high-strength
IG	intergranular corrosion
IQ	integral quench
IS	isotropic steels
IT	isothermal transformation
ITh	isothermal transformation diagram
K	Kelvin
K	stress-intensity factor in linear elastic fracture mechanics
K_{Ic}	plane-strain fracture toughness
K_{Id}	Dynamic fracture toughness
K_t	theoretical stress-concentration factor
kg	kilogram
kgf	kilogram force
kJ	kilo (10^3) Joules
km	kilometer
ksi	1000 lbf per square inch (kips)
kW	kilowatt
L	liter
L	length
lb	pound
LBM	laser beam machining
LD	Linz-Donawitz
LEFM	linear elastic fracture mechanics
m	meter
MART	martensitic (sheet steels)
MC	metal carbides
M_f	temperature at which martensite formation finishes during cooling
M_s	temperature at which martensite starts to form from austenite on cooling
Mg	megagram (metric tonne, or kg × 10^3)
MHz	megahertz
MIG	metal inert gas (welding)
MIM	metal injection molding
mm	millimeter
mN	milliNewtons
mol	mole
MP	melting point
MPa	megapascal
mph	miles per hour
MRI	magnetic resonance imaging
n	strain-hardening exponent
NDT	nondestructive testing
nm	nanometer
ODS	oxide dispersion strengthened
OFHC	oxygen-free high conductivity (copper)
PH	precipitation- hardenable/hardening
PM	powder metallurgy
ppm	parts per million
psi	pounds per square inch
PTA	plasma tungsten arc
PVD	physical vapor deposition
QT	quenched and tempered
R	universal gas constant, ratio of the minimum stress to the maximum stress
RA	reduction in area
rpm	revolutions per minute
RW	resistance welding
SAW	submerged arc welding
SCC	stress-corrosion cracking
SEM	scanning electron microscopy
SFE	stacking fault energy
SMAW	shield metal arc welding
S-N	stress-number of cycles (fatigue)
T_β	β transus temperature (titanium)
TIG	tungsten inert gas (welding)
T_m,T_M	melt/melting temperature
TMAZ	thermomechanical-affected zone
TRIP	transformation-induced plasticity (steels)
tsi	tons per square inch
TTT	time-temperature-transformation
UNS	Unified Numbering System (ASTM-SAE)
UTM	universal testing machine
UTS	ultimate tensile strength
V	volt
VAR	vacuum arc remelting
VIM	vacuum induction melting