

STEEL METALLURGY FOR THE NON-METALLURGIST

JOHN D. VERHOEVEN



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

Copyright© 2007
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, November 2007

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 (2006–2007), James C. Foley, Chair.

ASM International staff who worked on this project include Scott Henry, Senior Manager of Product and Service Development; Steve Lampman, Technical Editor; Eileen De Guire, Associate Editor; Ann Briton, Editorial Assistant; Bonnie Sanders, Manager of Production; Madrid Tramble, Senior Production Coordinator; Diane Grubbs, Production Coordinator; and Kathryn Muldoon, Production Assistant

Library of Congress Control Number: 2007932445
ISBN-13: 978-0-87170-858-8
ISBN-10: 0-87170-858-2
SAN: 204-7586

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

Printed in the United States of America

Contents

Preface	vii
About the Author	xi
Chapter 1 Pure Iron	1
Summary of the Major Ideas in Chapter 1	4
Chapter 2 Solutions and Phase Diagrams	5
Solutions	5
Phase Diagrams	6
Summary of the Major Ideas in Chapter 2	7
Chapter 3 Steel and the Iron-Carbon Phase Diagram	9
Low-Carbon Steels (Hypoeutectoid Steels)	10
High-Carbon Steels (Hypereutectoid Steels)	13
Eutectoid Steel (Pearlite).....	15
The A_1 , A_{c1} , A_{c1} , and A_{r1} Nomenclature	16
Summary of the Major Ideas in Chapter 3	17
Chapter 4 The Various Microstructures of Room-Temperature Steel	21
Optical Microscope Images of Steel Grains	21
Room-Temperature Microstructures of Hypo- and Hypereutectoid Steels.....	23
Microstructure of Quenched Steel	26
Spheroidized Microstructures	35
Summary of the Major Ideas in Chapter 4	37
Chapter 5 Mechanical Properties	39
The Tensile Test	39
The Hardness Test	42
The Notched Impact Test	45
Fatigue Failure and Residual Stresses.....	48
Summary of the Major Ideas in Chapter 5	52
Chapter 6 The Low-Alloy AISI Steels	55
Manganese in Steel	56
Effect of Alloying Elements on the Iron-Carbon Phase Diagram	58
Summary of the Major Ideas in Chapter 6	60

Chapter 7 Diffusion—A Mechanism for Atom Migration within a Metal	63
Carburizing and Decarburizing	67
Summary of the Major Ideas in Chapter 7	69
Chapter 8 Control of Grain Size by Heat Treatment and Forging	71
Grain Size	71
Grain Growth	72
New Grains Formed by Phase Transformation	74
New Grains Formed by Recrystallization	75
Effect of Alloying Elements	77
Summary of the Major Ideas in Chapter 8	81
Chapter 9 Hardenability of Steel	83
Isothermal Transformation Diagrams	84
Continuous Transformation (CT) Diagrams	90
The Jominy End Quench	93
Summary of the Major Ideas in Chapter 9	97
Chapter 10 Tempering	99
Effects of Alloying Elements	102
Summary of the Major Ideas in Chapter 10	104
Chapter 11 Austenitization.....	107
Single-Phase Austenitization	107
Two-Phase Austenitization	111
Summary of the Major Ideas in Chapter 11	113
Chapter 12 Quenching.....	117
Special Quenching Techniques	117
Characterization of Quench Bath Cooling Performance	125
Oil Quenchants	127
Polymer Quenchants	127
Salt Bath Quenchants	129
Summary of the Major Ideas in Chapter 12	129
Chapter 13 Stainless Steels.....	133
Ferritic Stainless Steels	134
Martensitic Stainless Steels	137
Optimizing Martensitic Stainless Steel for Cutlery Applications	140
Austenitic Stainless Steels	147
Precipitation-Hardening Stainless Steels	151
Summary of the Major Ideas in Chapter 13	153
Chapter 14 Tool Steels	157
Tool Steel Classification	157
The Carbides in Tool Steels	159
Special Heat Treatment Effects with Tool Steels	161
Summary of the Major Ideas in Chapter 14	162
Chapter 15 Solidification	165
Microsegregation	166
Grain Size and Shape	170

Porosity 172
Summary of the Major Ideas in Chapter 15 173

Chapter 16 Cast Irons.....175
Gray and White Cast Irons 176
Ductile and Malleable Cast Iron 185
Summary of the Major Ideas in Chapter 16 187

Chapter 17 Surface Hardening Treatment of Steels189
Surface Heat Treatments 189
Surface Diffusion Layers. 191
Summary of the Major Ideas in Chapter 17 198

Appendix A Temperature Measurement201
Thermocouples 201
Radiation Pyrometers 203

Appendix B Stainless Steels for Knifemakers.....209

Index213

Preface

This book is an attempt to explain the metallurgical aspects of steel and its heat treatment to non-metallurgists, starting, from simple concepts taught in high-school-level chemistry classes and then building to more complex concepts involved in heat treatment of nearly all types of steel as well as cast iron. It was inspired by the author having worked with practicing bladesmiths for the past 15 to 20 years.

Most of the chapters in the book contain a summary at the end. These summaries provide a short review of the contents of each chapter. It may be useful to read these summaries before and perhaps after reading the chapter contents.

The Materials Information Society, ASM International, has published a book, *Heat Treater's Guide: Practices and Procedures for Irons and Steels*, 2nd ed., 1995, that contains a wealth of information on available steels and is extremely useful to those who work and heat treat steel. A major goal of this book is to provide the necessary background that will permit a metal worker, not trained in metallurgy, to understand how to use the information in the ASM book, as well as other Handbooks published by ASM International.

I would like to acknowledge the help of two bladesmiths who have contributed to this book in several ways: Alfred Pendray and Howard Clark. Both men have helped me understand the level of work being done by U.S. bladesmiths, and they have also contributed to some of the experiments used in this book. They are also responsible for the production of this book, because of their encouragement to write it. In addition, I would like to acknowledge many useful discussions with fellow metallurgist William Dauksch, retired vice president of Nucor Steel, and my colleague, Prof. Brian Gleeson, who made many useful suggestions on the stainless steel chapter.

I am particularly indebted to Iowa State University and their Materials Science and Engineering Department for providing me with the opportunity to teach metallurgical engineering students about steel for over two decades, as well as to the Ames Laboratory, DoE, that provided access to optical and electron microscopes and supported most of my research activity. Many of the pictures and all of the methods of presentation in this book result from my experience teaching both laboratory and lecture courses to students and doing research at Iowa State University and its Ames Laboratory.

Ames, Iowa, February 2007

About the Author

Dr. John Verhoeven is a Distinguished Emeritus Professor in the Engineering College at Iowa State University. He earned a B.S. in chemical engineering in 1957 and his M.S. and Ph.D. in metallurgical engineering in 1959 and 1963, all from the University of Michigan. His professional career was spent at Iowa State University teaching metallurgy in the Department of Materials Science and Engineering and doing research at the Ames Laboratory of the U.S. Department of Energy.

Dr Verhoeven's research was in the primary area of physical metallurgy. He has over 200 research publications in refereed journals and owns eighteen patents. He received three Advanced Sustained Research Awards from the DoE, in 1981, 1987 and 1988. He is a fellow of the ASM.

Dr Verhoeven's teaching led to the publication of a textbook, *The Fundamentals of Physical Metallurgy*, John Wiley, 1975, which was used widely in the late 1970s and 1980s. At Iowa State, he was awarded the Outstanding Teaching Award in the Engineering College in 1976 and in the Metallurgical Engineering Program in 1980, and the Iowa Legislature outstanding teaching award in the Engineering College at ISU for sustained outstanding teaching, November 1991. He was appointed an Anson Marston Distinguished Professor of Engineering in 1985.



ASM International is the society for materials engineers and scientists, a worldwide network dedicated to advancing industry, technology, and applications of metals and materials.

ASM International, Materials Park, Ohio, USA
www.asminternational.org

This publication is copyright © ASM International®. All rights reserved.

Publication title	Product code
Steel Metallurgy for the Non-Metallurgist	05214G

To order products from ASM International:

Online Visit www.asminternational.org/bookstore

Telephone 1-800-336-5152 (US) or 1-440-338-5151 (Outside US)

Fax 1-440-338-4634

Mail Customer Service, ASM International
9639 Kinsman Rd, Materials Park, Ohio 44073-0002, USA

Email CustomerService@asminternational.org

In Europe American Technical Publishers Ltd.
27-29 Knowl Piece, Wilbury Way, Hitchin Hertfordshire SG4 0SX,
United Kingdom
Telephone: 01462 437933 (account holders), 01462 431525 (credit card)
www.ameritech.co.uk

In Japan Neutrino Inc.
Takahashi Bldg., 44-3 Fuda 1-chome, Chofu-Shi, Tokyo 182 Japan
Telephone: 81 (0) 424 84 5550

Terms of Use. This publication is being made available in PDF format as a benefit to members and customers of ASM International. You may download and print a copy of this publication for your personal use only. Other use and distribution is prohibited without the express written permission of ASM International.

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. 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 publication 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 publication 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.