Copyright © 2014 ASM International®
All rights reserved
asminternational.org

ASM Handbook®

Volume 4D
Heat Treating of Irons and Steels

Prepared under the direction of the
ASM International Handbook Committee

Volume Editors
Jon L. Dossett, FASM, Consultant
George E. Totten, FASM, Portland State University

Division Editors
Rafael A. Mesquita, Villares Metals SA
Reinhold E. Schneider, University of Applied Sciences, Upper Austria–Wels
Charles V. White, Kettering University (retired)

ASM International Staff
Steve Lampman, Content Developer
Vicki Burt, Content Developer
Amy Nolan, Content Developer
Susan Sellers, Editorial Assistant
Madrid Tramble, Manager, Production
Kate Fornadel, Senior Production Coordinator
Patty Conti, Production Coordinator
Diane Whitelaw, Production Coordinator
Karen Marken, Senior Managing Editor
Scott D. Henry, Senior Manager, Content Development

Editorial Assistance
Ed Kubel
Elizabeth Marquard
Jo Hannah Leyda
Scot Ryan
Buz Riley





Copyright © 2014
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 2014

This Volume is a collective effort involving hundreds of technical specialists. It brings together a wealth of information from worldwide sources to help scientists, engineers, and technicians solve current and long-range problems.

Great care is taken in the compilation and production of this Volume, 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 Volume 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 Volume 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.

Library of Congress Cataloging-in-Publication Data

ASM International

ASM Handbook
Includes bibliographical references and indexes
Contents: v.1. Properties and selection—irons, steels, and high-performance alloys—v.2. Properties and selection—nonferrous alloys and special-purpose materials—[etc.]—v.23. Materials for medical devices

1. Metals—Handbooks, manuals, etc. 2. Metal-work—Handbooks, manuals, etc. I. ASM International. Handbook Committee. II. Metals Handbook.
TA459.M43 1990 620.1'6 90-115
SAN: 204-7586

ISBN-13: 978-1-62708-066-8
ISBN-10: 1-62708-066-X

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

Printed in the United States of America

Copyright © 2014 ASM International®
All rights reserved
asminternational.org

Foreword

ASM Handbook Volume 4D is the fourth of five volumes to be published on heat treatment. Volume 4A covers the basic fundamentals and processes of steel heat treatment, while Volumes 4B and 4C cover the technological aspects of steel heat treating in terms of basic furnace system and controls (Volume 4B) and induction heating and heat treatment (Volume 4C).

Volume 4D concludes the coverage on ferrous heat treatment with over 40 articles on the heat treatment and properties of the many different types of steels and cast irons. The process of steel selection for direct hardening and surface hardening also is covered in more detail. This gives designers and heat treaters more data and reference information for both component and process design.

We thank the volunteer editors, authors, and reviewers for participating in this enormous effort. The result is a substantive reference work that reflects the continuing commitment of the Heat Treating Society and ASM International in serving technical communities with the tools to solve problems. We are especially indebted to the Volume Editors, Jon Dossett and George E. Totten.

Roger A. Jones
President, Heat Treating Society

C. Ravi Ravindran
President, ASM International

Thomas S. Passek
Managing Director, ASM International

Copyright © 2014 ASM International®
All rights reserved
asminternational.org

Preface

During the review of the *ASM Handbook*, Volume 4, *Heat Treating* published in 1991, it was apparent that just one volume could not accommodate updates and improvements in coverage. Better coverage on ferrous heat treatment necessitated an increase in scope, and coverage of nonferrous heat treatment could not be shortchanged. Furthermore, just the subject of steel treatment fundamentals and processes contained enough useful reference information for one volume, given the large collection of original references published by ASM International (and formerly the American Society for Metals) on steel heat treatment. Equipment, furnace technologies, process control and problems, and induction were other major topics that warranted separate volumes, even before addressing the particular processing and properties of the many types of heat treated iron and steels.

From this enormous effort, *ASM Handbook*, Volume 4D, *Heat Treating of Irons and Steels* concludes the *ASM Handbook* print volumes on ferrous heat treatment—but which will still be followed by Volume 4E, *Heat Treating of Nonferrous Alloys*, in development for publication in 2016. This volume details the heat treatment and properties of the many different types of steels and cast irons and describes the processing and properties that influence the selection of steels for heat treatment. Updates are part of this new Volume, but content also is significantly expanded in several ways. For example, new articles are devoted to the industrially significant topics of gear and bearing steel heat treatment. New articles address the heat treatment of boron steels, copper steels, and forged steels, and coverage is expanded on the workhorse carbon and low-alloy steels. In addition, the heat treatment of tool steels and stainless steels is covered much more extensively. This represents a major update, although we still recognize some compromises in scope and effort as inevitable.

In acknowledging this effort, we thank all the editors, authors, reviewers, and the supporting staff of ASM International. We are especially indebted to the following editors who were instrumental in this overall effort:

- **Valery Rudnev**, Inductoheat Inc.
- **Ronald R. Akers**, Ajax Tocco Magnethermic Inc.
- **Egbert Baake**, Leibniz Universität of Hannover
- **Vicki Burt**, ASM International
- **Madhu Chatterjee**, Bodycote
- **Rafael Colás**, Universidad Autónoma de Nuevo León
- **Edward (Derry) Doyle**, RMIT University
- **B. Lynn Ferguson**, FASM, Deformation Control Technology, Inc.
- **Gregory A. Fett**, Dana Corporation
- **Kiyoshi Funatani**, IMST Institute (Consultant)
- **Robert J. Gaster**, Deere & Company
- **Peter Hodgson**, Institute for Frontier Materials, Deakin University
- **Franz Hoffmann**, IWT Bremen
- **Jürgen Hoffmeister**, Karlsruhe Institute of Technology
- **Ron Hoppe**, Nexteer Automotive Corp.
- **Steve Lampman**, ASM International
- **Thomas Lübben**, Stiftung Institut für Werkstofftechnik (Foundation Institute of Materials Science)
- **D. Scott MacKenzie**, Houghton International
- **David Matlock**, Colorado School of Mines
- **Rafael A. Mesquita**, Villares Metals SA
- **Bernard Nacke**, Leibniz Universität of Hannover
- **Philip Nash**, Illinois Institute of Technology
- **Amy Nolan**, ASM International
- **George Pfaffmann**, Ajax Tocco Incorporated
- **Michael J. Schneider**, The Timken Company
- **Reinhold E. Schneider**, University of Applied Sciences, Upper Austria–Wels
- **Volker Schulze**, Karlsruhe Institute of Technology
- **Richard Sisson**, FASM, Worcester Polytechnic Institute
- **Chester J. Van Tyne**, Colorado School of Mines
- **Charles V. White**, Kettering University (retired)
- **Stan Zinn**, Ferrotherm Incorporated



Jon Dossett, *FASM*
Consultant



Dr. George Totten, *FASM*
Editor
President, G.E. Totten & Associates, LLC
Seattle, Washington, USA

Copyright © 2014 ASM International®
All rights reserved
asminternational.org

Policy on Units of Measure

By a resolution of its Board of Trustees, ASM International has adopted the practice of publishing data in both metric and customary U.S. units of measure. In preparing this Handbook, the editors have attempted to present data in metric units based primarily on Système International d'Unités (SI), with secondary mention of the corresponding values in customary U.S. units. The decision to use SI as the primary system of units was based on the aforementioned resolution of the Board of Trustees and the widespread use of metric units throughout the world.

For the most part, numerical engineering data in the text and in tables are presented in SI-based units with the customary U.S. equivalents in parentheses (text) or adjoining columns (tables). For example, pressure, stress, and strength are shown both in SI units, which are pascals (Pa) with a suitable prefix, and in customary U.S. units, which are pounds per square inch (psi). To save space, large values of psi have been converted to kips per square inch (ksi), where 1 ksi = 1000 psi. The metric tonne (kg $\times$ 10^3) has sometimes been shown in megagrams (Mg). Some strictly scientific data are presented in SI units only.

To clarify some illustrations, only one set of units is presented on artwork. References in the accompanying text to data in the illustrations are presented in both SI-based and customary U.S. units. On graphs and charts, grids corresponding to SI-based units usually appear along the left and bottom edges. Where appropriate, corresponding customary U.S. units appear along the top and right edges.

Data pertaining to a specification published by a specification-writing group may be given in only the units used in that specification or in dual units, depending on the nature of the data. For example, the typical yield strength of steel sheet made to a specification written in customary U.S. units would be presented in dual units, but the sheet thickness specified in that specification might be presented only in inches.

Data obtained according to standardized test methods for which the standard recommends a particular system of units are presented in the units of that system. Wherever feasible, equivalent units are also presented. Some statistical data may also be presented in only the original units used in the analysis.

Conversions and rounding have been done in accordance with IEEE/ASTM SI-10, with attention given to the number of significant digits in the original data. For example, an annealing temperature of 1570 °F contains three significant digits. In this case, the equivalent temperature would be given as 855 °C; the exact conversion to 854.44 °C would not be appropriate. For an invariant physical phenomenon that occurs at a precise temperature (such as the melting of pure silver), it would be appropriate to report the temperature as 961.93 °C or 1763.5 °F. In some instances (especially in tables and data compilations), temperature values in °C and °F are alternatives rather than conversions.

The policy of units of measure in this Handbook contains several exceptions to strict conformance to IEEE/ASTM SI-10; in each instance, the exception has been made in an effort to improve the clarity of the Handbook. The most notable exception is the use of g/cm^3 rather than kg/m^3 as the unit of measure for density (mass per unit volume).

SI practice requires that only one virgule (diagonal) appear in units formed by combination of several basic units. Therefore, all of the units preceding the virgule are in the numerator and all units following the virgule are in the denominator of the expression; no parentheses are required to prevent ambiguity.

Copyright © 2014 ASM International®
All rights reserved
asminternational.org

List of Contributors and Reviewers

Herwig Altena
Aichelin GmbH

John M. Beswick
SKF Group Technology Development

Charles Carson
Consultant

Luis Carlos Casteletti
University of São Paulo

Alan J. Chidester
The Timken Company

Thomas L. Christiansen
Technical University of Denmark

Rafael Colás
Universidad Autónoma de Nuevo León

Sunniva R. Collins
Swagelok Company

Craig V. Darragh
The Timken Company

Anjana Deva
Steel Authority of India

Jon L. Dossett
Consultant

Frank Ernst
Case Western Reserve University

James D. Fritz
TMR Stainless

Liming Fu
Shanghai Jiao Tong University

Kiyoshi Funatani
IMST Institute

Nelson F. Garza-Montes-de-Oca
CIIDIT-UANL

Christian Sales Gonçalves
Villares Metals SA

Antonio Augusto Gorni
Usiminas

Larry Hanke
Materials Evaluation and Engineering, Inc.

Kathy Hayrynen
Applied Process, Inc.

Arthur Heuer
Case Western Reserve University

Peter Hodgson
Institute for Frontier Materials, Deakin University

Robert C. Hoff
The Timken Company

John R. Imundo
The Timken Company

B.K. Jha
Steel Authority of India

Hal Kahn
Case Western Reserve University

Prakash Kolli
University of Maryland

Zoltan Kolozsvary
Plasmaterm SA Romania

George Krauss
Colorado School of Mines

Li Ling
Shanghai University

C.T. Liu
City University of Hong Kong

James L. Maloney III
The Timken Company

Steven V. Marx
Swagelok Company

Rafael A. Mesquita
Villares Metals SA

Thomas Müller
Rübig GmbH & Co KG

Amadeu Lombardi Neto
Federal Technological University of Parana–Londrina

Joseph W. Newkirk
Missouri University of Science and Technology

Dan Nitescu
The Timken Company

Cory Padfield
American Axle & Manufacturing

Toby Padfield
American Axle & Manufacturing

Arthur Reardon
The Gleason Works

Satyam S. Sahay
John Deere Asia Technology Innovation Center, India

Reinhold E. Schneider
University of Applied Sciences, Upper Austria–Wels

Wolfgang Schützenhöfer
Böhler Edelstahl GmbH & Co KG

Peter Seemann
Ebner Industrieofenbau GmbH

David N. Seidman
Northwestern University

Aidang Shan
Shanghai Jiao Tong University

Marcel A.J. Somers
Technical University of Denmark

Hiroaki Tahira
NSCSM Corporation

George E. Totten
Portland State University

George F. Vander Voort
Consultant–Struers Inc.

Guijin Wang
Central Iron & Steel Research Institute (Beijing) (retired)

Charles V. White
Kettering University (retired)

Peter C. Williams
Swagelok Company

Copyright © 2014 ASM International®
All rights reserved
asminternational.org

Officers and Trustees of ASM International (2013–2014)

C. Ravi Ravindran
President
Ryerson University
Sunniva R. Collins
Vice President Case Western Reserve University
Gernant E. Maurer
Immediate Past President
Carpenter Technology Corporation
Thomas Passek
Managing Director
ASM International
Robert Fulton
Treasurer
Hoeganaes Corporation (Retired)
Iver Anderson
Ames Laboratory
Jacqueline M. Earle
Caterpillar, Inc.
John R. Keough
Applied Process, Inc.
Mitchell Dorfman
Sulzer Metco (US), Inc.
James C. Foley
Los Alamos National
Laboratory
Jeffrey A. Hawk
National Energy Technology
Laboratory
William J. Lenling
Thermal Spray Technologies Inc.
Linda S. Schadler
Rensselaer Polytechnic Institute
Zi-Kui Liu
The Pennsylvania State University
Student Board Members
Jessica A. Booth
Case Western Reserve University
Karly N. Chester
Rensselaer Polytechnic Institute
Raymond T. Hickey
Lehigh University

Members of the ASM Handbook Committee (2013–2014)

Joseph Newkirk, Chair
Missouri University of Science & Technology
George Vander Voort, Vice Chair
Vander Voort Consulting L.L.C.
Craig Clauser, Immediate Past Chair
Craig Clauser Engineering Consulting
David Alman
National Energy Technology Laboratory
Scott Beckwith
SAMPE
Rodney Boyer
RBTi Consulting
Narendra Dahotre
University of North Texas
Jon Dossett
Consultant
Alan Druschitz
Virginia Tech
Jeffrey Hawk
U.S. Department of Energy
Steven Heifner
Sypris Technologies Incorporated
Paul Jablonski
U.S. Department of Energy
Kent Johnson
Applied Materials
John Keough
Applied Process Incorporated
Li Ling
Shanghai University
Brett Miller
IMR Metallurgical Services
Erik Mueller
National Transportation Safety Board
Thomas Prucha
American Foundry Society
Prasan Samal
Consultant
Roch Shipley
Professional Analysis
Consulting Inc
Manas Shirgaokar
Ellwood National Crankshaft
Jeffery Smith
Material Processing Technology LLC
Jaimie Tiley
US Air Force Research Lab
George Totten
G.E. Totten & Associates LLC
Michael West
South Dakota School of Mines
and Technology
Charles White
Kettering University

Chairs of the ASM Handbook Committee

J.F. Harper
(1923–1926) (Member 1923–1926)
W.J. Merten
(1927–1930) (Member 1923–1933)
L.B. Case
(1931–1933) (Member 1927–1933)
C.H. Herty, Jr.
(1934–1936) (Member 1930–1936)
J.P. Gill
(1937) (Member 1934–1937)
R.L. Dowdell
(1938–1939) (Member 1935–1939)
G.V. Luerssen
(1943–1947) (Member 1942–1947)
J.B. Johnson
(1948–1951) (Member 1944–1951)
E.O. Dixon
(1952–1954) (Member 1947–1955)
N.E. Promisel
(1955–1961) (Member 1954–1963)
R.W.E. Leiter
(1962–1963) (Member 1955–1958, 1960–1964)
D.J. Wright
(1964–1965) (Member 1959–1967)
J.D. Graham
(1966–1968) (Member 1961–1970)
W.A. Stadtler
(1969–1972) (Member 1962–1972)
G.J. Shubat
(1973–1975) (Member 1966–1975)
R. Ward
(1976–1978) (Member 1972–1978)
G.N. Maniar
(1979–1980) (Member 1974–1980)
M.G.H. Wells
(1981) (Member 1976–1981)
J.L. McCall
(1982) (Member 1977–1982)
L.J. Korb
(1983) (Member 1978–1983)
T.D. Cooper
(1984–1986) (Member 1981–1986)
D.D. Huffman
(1986–1990) (Member 1982–2005)
D.L. Olson
(1990–1992) (Member 1982–1988, 1989–1992)
R.J. Austin
(1992–1994) (Member 1984–1985)
W.L. Mankins
(1994–1997) (Member 1989–)
M.M. Gauthier
(1997–1998) (Member 1990–2000)
C.V. Darragh
(1999–2002) (Member 1989–)
Henry E. Fairman
(2002–2004) (Member 1993–2005)
Jeffrey A. Hawk
(2004–2006) (Member 1997–)
Larry D. Hanke
(2006–2008) (Member 1994–)
Kent L. Johnson
(2008–2010) (Member 1999–)
Craig D. Clauser
(2010–2012)(Member 2005–)
Joseph W. Newkirk
(2012–) (Member 2005–)

Copyright © 2014 ASM International®
All rights reserved
asminternational.org

Contents

Introduction 1

Heat Treatment Problems Associated with Design and Steel Selection 3
- Introduction 3
- Steel Selection for Heat Treated Parts 3
- Residual Stresses 7
- Distortion 10
- Calculation of Size Changes 12
- Techniques for Controlling Distortion 15
- Decarburization 17
- Problems Associated with Heating 19
- Cracking due to Heat Treatment 19
- Problems Associated with Materials 21
- Problems Associated with Design 22
- Design Examples for Heat Treatment 23

Steel Selection for Hardening 29
- Alloying 29
- Alloy Selection 32
- Depth of Hardening 33
- Tensile Mechanical Properties 35
- Hardness and Hardenability for Wear Resistance 35

Simulation of Steels Prone to Quench Cracking
K. Arimoto 44
- Early History of the Problem 44
- Concepts of Quench Cracking Analysis and Simulation 49
- Examples of Quench Cracking Simulation 51
- Prevention of Quench Cracking Using Simulation 55

Selecting Steels for Case Hardening 58
- Carburizing Steels 59
- Carbonitriding Steels 63
- Nitriding Steels 65
- Steels for Induction or Flame Hardening 65

Selection of Carburizing Steels 68
- Hardenability of Carburized Steels 68
- Quench Medium 69
- Stress Considerations 69
- Case Depth and Type 70
- Heat Treatment Methods 71
- Steels for Carburized Gears 72

Microstructures and Properties of Carburized Steels
George Krauss 76
- Carbon and Hardness Profiles 76
- Martensite and Austenite 77
- Alloying Effects 79
- Intergranular Fracture at Austenite Grain Boundaries 79
- Microcracking in Carburized Steels 81
- Excessive Retained Austenite and Massive Carbides 81
- Residual Stresses 82
- Surface and Internal Oxidation 84
- Fatigue Mechanisms 84

Nitriding Structure and Properties of Nitrided Layers
Z. Kolozsváry 88
- The Nitrided Layer 88
- Types of Steels for Nitriding 88
- Nitriding Processes and Their Effects on Structure and Properties 90
- The Future 95

Heat Treating of Carbon and Low-Alloy Steels 97

Heat Treating of Carbon Steels
G. Wang and J.L. Dossett 99
- Unified Numbering System 100
- Heat Treat Processes 100
- Classification for Heat Treatment 103
- Transformation Diagrams 104
- Hardenability of Carbon Steels 109
- Tempering 112
- Heat Treating Guidelines 113
- Free-Machining Carbon Steels 118
- Cast Carbon Steels 119

Heat Treating of Low-Alloy Steels 122
- Classification of Low-Alloy Steels 122
- Effects of Alloying 126
- Manganese Low-Alloy Steels 136
- Molybdenum Low-Alloy Steels 138
- Chromium-Molybdenum Low-Alloy Steels 142
- Nickel-Chromium-Molybdenum Low-Alloy Steels 148
- Nickel-Molybdenum Low-Alloy Steels 156
- Chromium Low-Alloy Steels 158
- Chromium-Vanadium Low-Alloy Steels 161
- Silicon-Manganese Low-Alloy Steels 164

Heat Treating of Air-Hardening High-Strength Structural Steels
Aidang Shan, Liming Fu 169
- Principles of Heat Treatment of Air-Hardening Steel 169
- Recommended Heat Treating Practices for Air-Hardening High-Strength Structural Steels 170
- Recommended Heat Treating Practices for Air-Hardening Martensitic Stainless Steels 174

Heat Treating of Boron Steels
Anjana Deva and Bimal Kumar Jha 179
- Hardenability of Boron Steel 179
- Heat Treatment of Boron Steel 181
- Heat Treatment Simulation 184
- Applications 186

Heat Treatment of Copper Precipitation-Strengthened Steels
R. Prakash Kolli and David N. Seidman 188
- Overview 188
- Applications 188
- ASTM International Standards 189
- Types of Phases in Copper Steels 190
- Chemical Composition and the Effects of Alloying Elements 191
- Thermomechanical Treatment 192
- Heat Treatment 192
- Heat Treatment, Microstructure, and Mechanical Property Relationships 198

Heat Treatment of Steel Gears
Satyam S. Sahay 204
- Overview of Gear Heat Treating 205

Copyright © 2014 ASM International®
All rights reserved
asminternational.org

Heat Treating of Large Gears . . . 213
Process Modeling and Design Optimization . . . 214
Integrated Computational Materials Engineering and Design Optimization . . . 216
Heat Treatment of Bearings
Alan J. Chidester, Craig V. Darragh, Robert C. Hoff, John R. Imundo, James L. Maloney, III and Dan Nitescu . . . 219
Types of Bearings . . . 219
Bearing Design Parameters, Performance Characteristics, and Material Needs . . . 220
Metallurgical Requirements and Heat Treat Process Selection . . . 220
Through Hardening . . . 220
Martensitic Heat Treating . . . 221
Heat Treating Distortion Control . . . 221
Dimensional Stability in Through-Hardening Bearing Steels . . . 221
Grain Size in Through-Hardening Bearing Steels . . . 222
Quench Problems That Can Affect Through-Hardening Bearing Steels . . . 222
High-Hardenability Steels in the 52100 Family . . . 223
Bainitic Heat Treating (Austempering) . . . 224
Special Purpose Through-Hardening Bearing Steels . . . 224
Duplex Hardening . . . 229
Carburizing . . . 230
Special Purpose Carburizing Grades . . . 232
Carburizing and Nitriding Practices for Specialty Steels . . . 234
Carbonitriding . . . 236
Surface Induction Hardening . . . 237
Forge and Direct Heat Treatment Processes and Technologies
H. Tahira and K. Funatani . . . 241
Definition and Purposes of Direct-Forge Quenching and Heat Treatment . . . 241
Microalloyed Steels for Direct Heat Treatment Technology . . . 243
Control Rolling Technology to Produce Fine Microstructure Bars and Wires . . . 245
Influence of Carbon Contents on Toughness of Microalloyed Direct Heat Treated Steels . . . 246
Typical Applications of Microalloyed Steels for Automotive Components . . . 248
Connecting Rods . . . 248
Equipment for Forging and Direct Heat Treatment . . . 249
Heat Treatment of Powder Metallurgy Steels
Joseph W. Newkirk . . . 253
Overview of Powder Metallurgy Processing . . . 253
Designation System for Powder Metallurgy Steels . . . 256
Overview of Heat Treatment . . . 257
Effect of Porosity on the Heat Treatment of Powder Metallurgy Steels . . . 258
Effect of Alloy Content on Powder Metallurgy Hardenability . . . 260
Effect of Starting Material on Homogenization . . . 261
Quenching and Tempering . . . 263
Sinter Hardening . . . 264
Warm Compaction . . . 264
Powder Forging . . . 265
Case Hardening . . . 266
Nitriding . . . 268
Steam Treating . . . 268
Black Oxidizing . . . 269
Induction Hardening . . . 270

Tool Steels . . . 275

Introduction to Heat Treating of Tool Steels
Rafael A. Mesquita and Reinhold E. Schneider . . . 277
Classification of Tool Steels . . . 277
Production of Tool Steels . . . 278
Heat Treatment Applied to Tool Steels . . . 279
Processes and Furnace Equipment for Heat Treating of Tool Steels
R. Schneider, R. Mesquita, H. Altena, T. Müller and P. Seemann . . . 288
Equipment for Austenitizing, Quenching, and Tempering of Tool Steels . . . 288
Equipment for Nitriding and Nitrocarburizing of Tool Steels . . . 296
Distortion in Tool Steels
Reinhold Schneider, Rafael Mesquita and Wolfgang Schützenhöfer . . . 300
Nature and Causes of Distortion . . . 300
Process Aspects of Distortion . . . 302
Material Aspects of Distortion . . . 304
Prediction of Distortion and Residual Stresses by Numerical Simulation . . . 307
Control of Distortion in Tool Steels . . . 312
Design . . . 312
Chemical Composition . . . 312
Initial Condition . . . 313
Machining Procedure . . . 313
Main Heat Treatment . . . 315
Stabilizing Treatments . . . 316
Commercial Practice . . . 319
Heat Treating of Cold-Work Tool Steels—Low- and Un-Alloyed Water and Oil Hardening Steels
Rafael Agnelli Mesquita, Reinhold Schneider, and Cristiane Sales Gonçalves . . . 320
Water-Hardening Tool Steels . . . 320
Shock-Resisting Tool Steels . . . 322
Oil Hardening Cold-Work Tool Steels . . . 324
Low-Alloy Special-Purpose Tool Steels . . . 326
Carbon-Tungsten Special-Purpose Tool Steels . . . 327
Heat Treating of Cold-Work Tool Steels—Medium-Alloy Air-Hardening, High-Carbon High-Chromium and High-Vanadium-Powder Metallurgy Steels
Rafael Agnelli Mesquita, Reinhold S.E. Schneider and Cristiane Sales Gonçalves . . . 329
Recommended Heat Treating Practices . . . 330
Heat Treating of Hot-Work Tool Steels
Rafael Agnelli Mesquita, Reinhold Schneider, and Cristiane Sales Gonçalves . . . 336
Heat Treatment of H Series and Low-Alloy Hot-Work Steels . . . 339
Examples of Heat-Treating Procedure for Hot-Work Tools . . . 344
NADCA Requirements for Steel Grades and Heat Treating . . . 345
Heat Treating of High-Speed Tool Steels
Rafael Agnelli Mesquita, Reinhold Schneider, and Cristiane Sales Gonçalves . . . 347
Recommended Heat-Treating Procedures . . . 350
Hardening of Specific Machine Tools . . . 354
Heat Treating of Mold Steels and Corrosion-Resistant Tool Steels
Rafael Agnelli Mesquita, Reinhold Schneider, and Cristiane Sales Gonçalves . . . 358
Mold Steels . . . 358
Recommended Heat Treating Practices . . . 358
Corrosion-Resistant Tool Steels . . . 359
Recommended Heat Treating Practices . . . 360

Heat Treated High-Alloy Steels . . . 363

Heat Treating of Ferritic Stainless Steels . . . 365
Metallurgy of Ferritic Stainless Steels . . . 365
Alloy Types . . . 366
Annealing . . . 368
Stabilization . . . 368
Castings . . . 368
Properties . . . 369

Copyright © 2014 ASM International®
All rights reserved
asminternational.org

Heat Treating of Austenitic and Duplex Stainless Steels
James D. Fritz . . . 370
Metallurgy . . . 370
Sensitization . . . 372
Intermediate Phases (Sigma, Chi, and Laves) . . . 372
Soaking . . . 373
Annealing . . . 373
Bright Annealing . . . 377
Stress Relieving . . . 377
Duplex Stainless Steels . . . 379
Heat Treating of Martensitic Stainless Steels . . . 382
Alloying . . . 382
Thermal Process Metallurgy . . . 384
Heat Treatment Preparations . . . 384
Annealing . . . 386
Hardening . . . 386
Stress Relieving . . . 388
Tempering . . . 388
Casting Alloys . . . 392
Heat Treating of Precipitation-Hardenable Stainless Steels and Iron-Base Superalloys
Lin Li . . . 397
Precipitation Hardening Process . . . 399
Equipment . . . 399
Protective Atmospheres . . . 399
Surface-Related Problems . . . 400
General Procedures . . . 400
Martensitic Precipitation-Hardenable Stainless Steels . . . 401
Semiaustenitic Precipitation-Hardenable Stainless Steels . . . 406
Austenitic Precipitation-Hardenable Stainless Steels (A-286) . . . 409
Cast Precipitation-Hardenable Stainless Steels . . . 410
Iron-Nickel Precipitation-Hardenable Superalloys . . . 410
Nitriding of Stainless Steels
Luiz Carlos Casteletti, Amadeu Lombardi Neto, and George E. Totten . . . 418
Stainless Steels . . . 418
The S-Phase . . . 420
Thermochemical Nitriding Treatments . . . 427
Future Directions . . . 437
Low-Temperature Surface Hardening of Stainless Steels
M.A.J. Somers and T.L. Christiansen . . . 439
Brief History of Low-Temperature Surface Hardening of Stainless Steel . . . 439
Physical Metallurgy of Expanded Austenite . . . 440
Gaseous Low-Temperature Surface Hardening of Austenitic Stainless Steel . . . 442
Low-Temperature Nitriding and Nitrocarburizing of Other Stainless Steels . . . 445
Industrial Applications . . . 446
Low-Temperature Carburization of Austenitic Stainless Steels
S.R. Collins, P.C. Williams, S.V. Marx, A. Heuer, F. Ernst, and H. Kahn . . . 451
Overview . . . 451
Background and Competing Technologies . . . 451
Process Considerations . . . 452
Microstructure of the Low-Temperature Carburized Layer . . . 454
Performance Properties of the Low-Temperature Carburized Layer . . . 455
Heat Treatment of High-Alloy Nickel-Cobalt Steels . . . 461
9Ni-4Co (HP 9-4) Steels . . . 461
AF 1410 . . . 462
AerMet Alloys . . . 464
Heat Treating of Maraging Steels
Charles Carson . . . 468
Introduction . . . 468
Alloy Developments . . . 469
Martensite Formation . . . 471
Martensite Aging . . . 472
Solution Annealing . . . 475
Grain Refinement Using Thermal Cycling . . . 476
Age Hardening . . . 477
Transformation-Induced Plasticity Maraging Method . . . 478
Other Treatments . . . 479

Heat Treatment of Cast Irons . . . 481

Introduction to Cast Iron Heat Treatment
J.L. Dossett and C.V. White . . . 483
Types of Cast Irons . . . 483
Critical Temperature Ranges . . . 485
General Considerations . . . 485
Heat Treatment Processes . . . 485
Temperature Control . . . 486
Atmosphere Control . . . 486
Stress Relieving . . . 487
Annealing . . . 489
Normalizing . . . 489
Through Hardening . . . 490
Surface Hardening . . . 490
Hardness Measurement . . . 492
Heat Treating of Gray Irons
J.L. Dossett and C.V. White . . . 493
Introduction . . . 493
Classes of Gray Iron . . . 493
Stress Relief . . . 494
Examples of Stress Relief . . . 495
Annealing . . . 496
Normalizing . . . 497
Transformation Hardening . . . 498
Quenched and Tempered Properties . . . 500
Austempering . . . 503
Martempering . . . 503
Flame Hardening . . . 505
Induction Hardening . . . 507
Other Surface-Hardening Methods . . . 507
Heat Treating and Properties of Ductile Iron
K. Hayrynen . . . 508
Standards for Heat Treatment of Ductile Iron . . . 508
General Characteristics . . . 509
Austenitizing Ductile Cast Iron . . . 510
Annealing Ductile Iron . . . 512
Hardenability of Ductile Cast Iron . . . 512
Normalizing Ductile Iron . . . 515
Quenching and Tempering Ductile Iron . . . 515
Marquenching (Martempering) Ductile Iron . . . 516
Austempering Ductile Iron . . . 516
Surface Hardening of Ductile Iron . . . 518
Stress Relieving of Ductile Iron . . . 520
Effect of Heat Treatment on Fatigue Strength . . . 520
Heat Treatment of Malleable and Compacted-Graphite Irons . . . 522
Compacted Graphite Iron . . . 523
Malleable Iron . . . 523
Heat Treating of High-Alloy White Cast Irons . . . 527
Alloy Types and Properties . . . 527
Nickel-Chromium White Irons . . . 528
High-Chromium White Irons . . . 529
Heat Treating of High-Alloy Graphitic Irons . . . 536
Austenitic Nickel-Alloyed Graphitic Irons . . . 536
Heat Treatment of Austenitic Ductile Irons . . . 538
High-Silicon Irons for High-Temperature Service . . . 538
High-Silicon Irons for Corrosion Resistance . . . 539

Copyright © 2014 ASM International®
All rights reserved
asminternational.org

Reference Information **541**

Iron-Carbon Phase Diagrams 543
Austenitizing and Typical Heat Treatment Temperatures for Steels 545
Temper Colors for Steels 550
Hardenability Bands of Alloy Steels 552
Steel Cross Reference—AISI/SAE to Other Designations 563
Steel Cross Reference to AISI/SAE Designations 572
Steel Hardness Conversions 577
Thermal Properties of Carbon and Low-Alloy Steels 583
Thermal Expansion 583
Alloy Index 589
Subject Index 629