

IRON AND STEEL

WILLIAM F. HOSFORD

CAMBRIDGE

IRON AND STEEL

William F. Hosford

University of Michigan



CAMBRIDGE
UNIVERSITY PRESS

CAMBRIDGE UNIVERSITY PRESS

Cambridge, New York, Melbourne, Madrid, Cape Town,
Singapore, São Paulo, Delhi, Mexico City

Cambridge University Press

32 Avenue of the Americas, New York, NY 10013-2473, USA

www.cambridge.org

Information on this title: www.cambridge.org/9781107017986

© William F. Hosford 2012

This publication is in copyright. Subject to statutory exception
and to the provisions of relevant collective licensing agreements,
no reproduction of any part may take place without the written
permission of Cambridge University Press.

First published 2012

Printed in the United States of America

A catalog record for this publication is available from the British Library.

Library of Congress Cataloging in Publication data

Hosford, William F.

Iron and steel / William F. Hosford.

p. cm.

Includes bibliographical references and index.

ISBN 978-1-107-01798-6 (hardback)

1. Iron – History. 2. Steel – History. 3. Iron – Metallurgy.

4. Steel – Metallurgy. I. Title.

TN703.H67 2012

669'.1–dc23 2011037262

ISBN 978-1-107-01798-6 Hardback

Cambridge University Press has no responsibility for the persistence or accuracy of URLs
for external or third-party Internet Web sites referred to in this publication and does not
guarantee that any content on such Web sites is, or will remain, accurate or appropriate.

Iron and Steel

Modern civilization as we know it would not be possible without iron and steel. Steel is essential in the machinery necessary for the manufacture of all our needs. Even the words themselves have come to suggest strength. Phrases such as *iron willed*, *iron fisted*, *iron clad*, *iron curtain*, and *pumping iron* imply strength. A *steely glance* is a stern look. A *heart of steel* refers to a very hard demeanor. The Russian dictator Stalin (which means “steel” in Russian) chose the name to invoke fear in his subordinates. This book is intended both as a resource for engineers and as an introduction to the layman about our most important metal system. After an introduction that deals with the history and refining of iron and steel, the rest of the book examines their physical properties and metallurgy.

William F. Hosford is Professor Emeritus of Materials Science at the University of Michigan. He is the author of numerous research publications and the following books: *The Mechanics of Crystals and Textured Polycrystals* (1993); *Physical Metallurgy* (2005); *Materials Science: An Intermediate Text* (2007); *Materials for Engineers* (2008); *Reporting Results: A Practical Guide for Scientists and Engineers* with David C. Van Aken (2008); *Mechanical Behavior of Materials*, 2nd edition (2009); *Wilderness Canoe Tripping* (2009); *Solid Mechanics* (2010); *Physical Metallurgy*, 2nd edition (2010); and *Metal Forming: Mechanics and Metallurgy*, 4th edition, with Robert M. Caddell (2011).

PREFACE

Modern civilization would not be possible without iron and steel. Steel is an essential component of all machinery used for manufacture of all our goods. The words *iron* and *steel* have come to suggest strength as evident in the following terms: *iron willed*, *iron fisted*, *iron clad*, *iron curtain*, and *pumping iron*. A *steely glance* is a stern look. A *heart of steel* implies a very hard demeanor. The Russian dictator Joseph Stalin (which means “steel” in Russian) chose that name to invoke fear in his subordinates.

This book is intended both as a resource for engineers and as an introduction to the layman to our most important metal system. The first few chapters cover the history and refining of iron and steel; the rest of the book covers physical properties and physical metallurgy.

I have drawn heavily on material from *Physical Metallurgy of Steels* by W. C. Leslie and *Steel Metallurgy for the Nonmetallurgist* by J. D. Verhoeven. However, this book includes material not covered in either of those.

Professors Robert Pehlke, Ronald Gibala, John Keough, and Paul Trojan were very helpful. Kathy Hayrynen supplied a number of micrographs.

The reader is assumed to have had a course in materials science and to be familiar with phase diagrams, Fick’s laws of diffusion, and the concept of free energy.

CONTENTS

Preface	<i>page xi</i>
1 General Introduction	1
Nomenclature	1
Phases	2
Production	3
2 Early History of Iron and Steel	4
Native Iron	4
Wrought Iron	6
Steel	8
References	10
3 Modern Steel Making	11
Blast Furnace	11
Coke	13
Bessemer Steel-Making Process	13
Open-Hearth Steel-Making Process	15
Basic Oxygen Furnace	16
Electric Arc Process	18
Furnace Linings and Slags	19
Casting	20
Hot Rolling	21
Cold Rolling	22
Recycling	22
References	24

4 Constitution of Carbon Steels	25
Microstructures of Carbon Steels	25
Pearlite Formation	30
References	34
5 Plastic Strength	35
Dislocation Density	35
Strain Hardening	35
Grain Size	37
Solute Effects	39
Temperature Dependence	39
Hardness	40
Strain-Rate Dependence of Flow Stress	40
Combined Effects of Temperature and Strain Rate	46
Superplasticity	49
Strength Differential Effect	49
References	50
6 Annealing	51
General	51
Recovery	51
Relief of Residual Stresses	54
Recrystallization	54
Grain Growth	58
References	65
7 Deformation Mechanisms and Crystallographic Textures	66
Slip and Twinning Systems	66
Wire Textures in bcc Metals	66
Rolling Texture	71
Compression Texture	72
Recrystallization Textures	77
References	79
8 Substitutional Solid Solutions	80
Phase Diagrams	80
Ternary Phase Diagrams	80
Effects of Solutes on the Eutectoid Transformation	80
Effect of Solutes on Physical Properties	81
Solid Solution Hardening	81
Carbide-Forming Tendencies	88

Solute Segregation to Grain Boundaries	89
References	89
9 Interstitial Solid Solutions	90
Atomic Diameters	90
Lattice Sites for Interstitials	90
Lattice Expansion with C, N	92
Solubility of Carbon and Nitrogen	93
Snoek Effect in bcc Metals	95
References	97
10 Diffusion	98
General	98
Mechanisms of Diffusion	99
Diffusion of Interstitials	102
References	103
11 Strain Aging	104
Yielding and Lüders Bands	104
Strain Aging	105
Dynamic Strain Aging	109
References	112
12 Austenite Transformation	113
Kinetics of Austenization	113
Pearlite Formation	113
Isothermal Transformation	120
Bainite	123
Continuous Cooling Diagrams	123
Martensite	125
Retained Austenite	126
Transformation to Martensite	128
Martensite Types	132
Special Heat Treatments	133
Miscellany	135
References	136
13 Hardenability	137
Jominy End-Quench Test	137
Hardenability Bands	140
Ideal Diameter Calculations	142

Boron	146
Miscellany	149
References	149
14 Tempering and Surface Hardening	150
Tempering	150
Secondary Hardening	156
Temper Embrittlement	157
Carburizing	158
Carburizing Kinetics	159
Kinetics of Decarburization	162
Carboaus tempering	163
Nitriding	163
Carbonitriding	164
Case Hardening Without Composition Change	165
Furnace Atmospheres	165
References	165
15 Low-Carbon Sheet Steel	167
Sheet Steels	167
Strength	168
Grades of Low-Carbon Steel	168
Weathering Steel	174
Heating During Deformation	174
Taylor-Welded Blanks	175
Special Sheets	176
Surface Treatment	177
Special Concerns	178
References	178
16 Sheet Steel Formability	179
Anisotropic Yielding	182
Effect of Strain Hardening on the Yield Locus	186
Deep Drawing	187
Stamping	189
Forming Limits	191
References	193
17 Alloy Steels	195
Designation System	195
Effect of Alloying Elements	195

Applications	197
References	197
18 Other Steels	198
Hadfield Austenitic Manganese Steel	198
Maraging Steels	198
Tool Steels	199
Heat Treatment of Tool Steels	201
Note of Interest	202
References	204
19 Stainless Steels	205
General Corrosion Resistance	205
Ferritic Stainless Steels	205
Martensitic Stainless Steels	208
Austenitic Stainless Steels	209
Other Stainless Steels	212
Sensitization	214
Oxidation Resistance	216
References	217
20 Fracture	218
Ductile Fracture	218
Brittle Fracture	222
Transition Temperature	226
Liquid Metal Embrittlement	227
Hydrogen Embrittlement	227
Fatigue	229
References	233
21 Cast Irons	234
Production	234
General	234
White Irons	237
Gray Irons	237
Compact Graphite Iron	242
Ductile Cast Iron	244
Malleable Cast Iron	244
Matrices	246
Austempering of Cast Irons	250

Damping Capacity	254
References	255
22 Magnetic Behavior of Iron	256
General	256
Ferromagnetism	257
Magnetostatic Energy	261
Magnetocrystalline Energy	262
Magnetostriiction	262
Physical Units	263
The B-H Curve	264
Bloch Walls	266
Soft Versus Hard Magnetic Materials	266
Soft Magnetic Materials	266
Silicon Steel	270
Hard Magnetic Materials	272
Summary	274
References	275
23 Corrosion	276
Corrosion Cells	276
Polarization and Passivity	279
Pourbaix Diagram	283
Types of Corrosion	284
Corrosion Control	285
Rust	287
Direct Oxidation	287
References	289
Appendix I: Physical Properties of Pure Iron	291
Appendix II: Approximate Hardness Conversions	
and Tensile Strengths of Steels	293
Index	295

GENERAL INTRODUCTION

NOMENCLATURE

The terms *iron* and *steel* are often confusing to the general public. *Iron* is an element (26 on the periodic table). The word *iron* comes from the Scandinavian word *iarn*. The chemical symbol *Fe* comes from the Latin word for iron, *ferrum*. The French word for iron is *fer*, the German word, *Eisen*. The Dutch word is *ijzeret*, and the Spanish is *hierro*.

The word *steel* is used to describe almost all alloys of iron. It is often said that steel is an alloy of iron and carbon. However, many steels contain almost no carbon. Carbon contents of some steels are as low as 0.002% by weight. The most widely used steels are low-carbon steels that have less than 0.06% carbon. Low-carbon steels are used for automobile bodies, appliances, cans, and cabinets. Higher carbon contents are used in steel with higher strengths. Tools are made from steels containing up to about 1.2% carbon.

The Sanskrit word for steel is *stakati*. The German word is *Stahl*; the Russian, *stalin*; the French, *acier*; the Spanish, *acero*; and the Dutch, *staal*. *Chalybs* is the Latin word for steel.

Wrought iron was an iron-based product with entrapped slag stringers that contained very little carbon. It is no longer produced, having been replaced by much cheaper low-carbon steel. The term *wrought iron* is still applied to garden furniture and similar products that are made today from low-carbon steel.

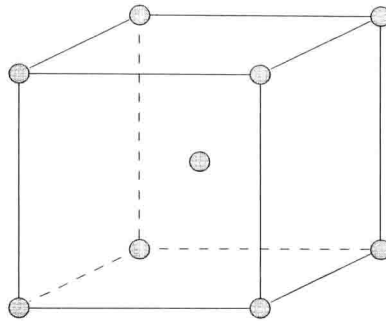


Figure 1.1. Unit cell of a body-centered cubic crystal.

Cast irons are iron-based alloys that contain 2.5 to 4% carbon and 2 to 3% silicon. In white cast iron, the carbon is present as iron carbide, whereas in gray and ductile cast irons, most of the carbon is present as graphite.

PHASES

Pure iron undergoes several phase changes. Above 1538°C , it is liquid. On cooling below 1538°C , it transforms to a body-centered cubic (bcc) structure, delta (δ)-ferrite, as shown in Figure 1.1.

On further cooling, it transforms to a denser face-centered cubic (fcc) structure, gamma (γ)-austenite, at 1400°C (Figure 1.2).

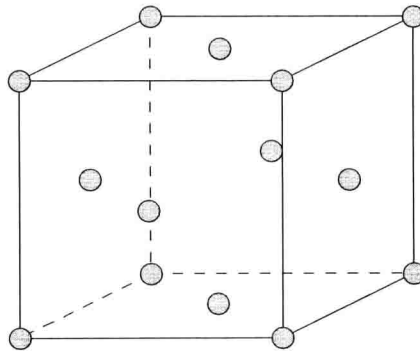


Figure 1.2. Unit cell of a face-centered cubic crystal.

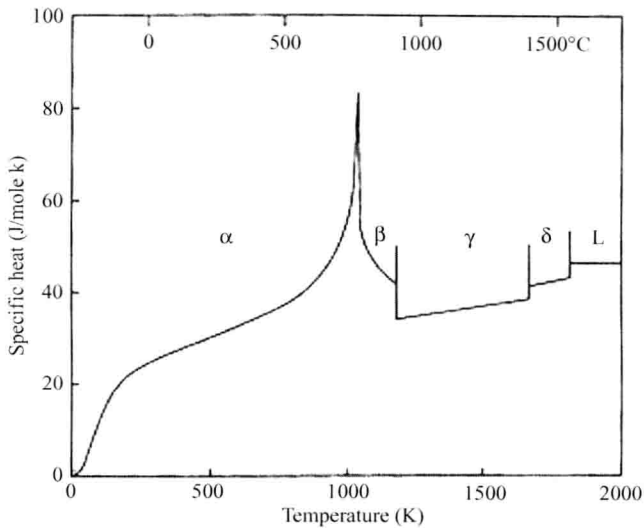


Figure 1.3. Temperature dependence of the specific heat of iron.

Below 911°C, it transforms back to bcc α -ferrite (which is the same as δ -ferrite). There is a paramagnetic-to-ferromagnetic transformation at the Curie temperature (770°C). Early researchers mistook a peak in the specific heat as a latent heat of transformation (Figure 1.3) and designated the structure between 770°C and 911°C as β -iron.

Physical properties of iron are listed in Appendix I.

PRODUCTION

The production of iron is very much greater than other metals. In the U.S. the annual tonnage of iron and steel is almost 40 times as great as that of aluminum and almost 65 times greater than the production of copper. Recycling accounts for over 80% of the steel.

EARLY HISTORY OF IRON AND STEEL

NATIVE IRON

The only sources of iron available to early humans were meteoric iron and native (telluric) iron. Both were scarce. Most meteorites are non-metallic; only about 6% are iron, and these contain about 7 to 15% nickel. In 1808, William Thomson sectioned and etched a meteorite, noting the remarkable patterns. Although he published his findings in 1808, they attracted little interest. Also in 1808, an Austrian, Alois von Widmannstätten, also etched a meteorite and observed the structure that is now known by his name. In 1820, he and Carl von Schreibers published a book on meteorites, which contained a print from a heavily etched meteorite (Figure 2.1). Native iron is even scarcer, being limited to small particles in western Greenland. Archeological finds of iron with considerable amounts of nickel suggest that they were made from meteorites.

The first production of iron dates back to at least 2000 bc in India and Sri Lanka. By 1200 bc, production of iron was widespread in China and the Near East. The most common iron ores are hematite (Fe_2O_3) and magnetite (Fe_3O_4). Smelting of iron involved heating iron ore (oxides of iron) with charcoal. The reaction of iron oxide with carbon produced carbon monoxide and carbon dioxide. The air was supplied by either a natural draft or some means of blowing. Early furnaces were of various types. An open-pit furnace is shown

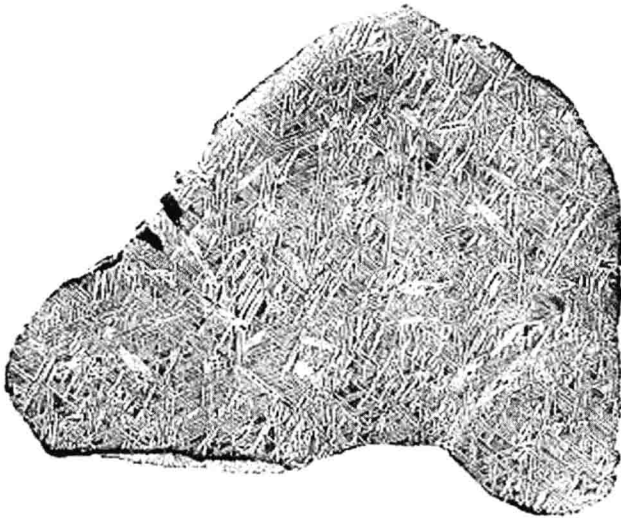


Figure 2.1. The imprint from an iron meteorite heavily etched by Widmannstätten.

in Figure 2.2. The carbon content of iron produced in pit furnaces was usually low because of the low temperatures achieved and resulted in semisolid sponge.

With shaft furnaces (Figure 2.3), the higher temperatures resulted in higher carbon contents. In the furnaces, charcoal reacted with the air to form carbon monoxide, which reduced some of the ore. The resulting carbon dioxide reacted with charcoal to form more carbon monoxide.

The product of the lower-temperature furnaces was low in carbon and much like wrought iron. It was soft and formable. If heated in

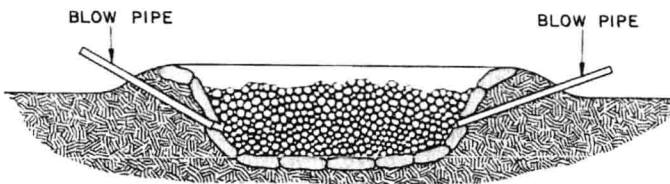


Figure 2.2. An early open-pit iron furnace. From *The Making, Shaping and Treating of Steel*, 9th ed. U.S. Steel Co. (1971).

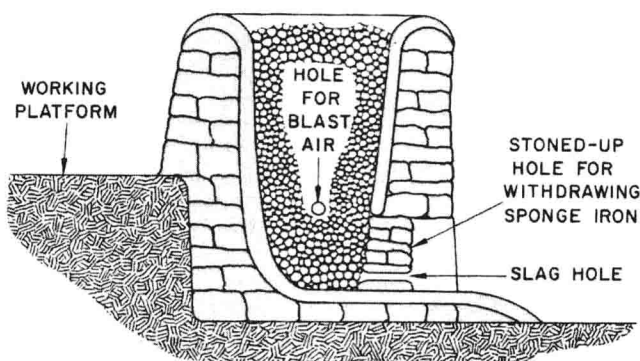


Figure 2.3. An early shaft-type iron furnace. From *The Making, Shaping and Treating of Steel*, *ibid.*

charcoal, it would absorb more carbon and could be made into useful steel tools. The higher-temperature furnaces produced molten iron that contained up to 4% carbon. After it solidified, it formed a brittle material that was at first discarded. Later it was learned that the carbon content could be reduced by remelting in contact with air. By 200 BC, the Chinese had started casting the high-carbon material into useful objects.

WROUGHT IRON

There is a wrought-iron pillar in Delhi, India, that dates back to at least the late fourth century. It is more than 7 m in height and has resisted corrosion over the many centuries. Wrought iron is the principal material in the Eiffel Tower, constructed in 1887.

After about AD 1300, wrought iron was produced in a Catalan furnace (Figure 2.4). The resulting semisolid product was pried out and hammered into bars. The American bloomery was a modification of this process, differing in that the charge of ore and charcoal were mixed together, and waterpower was used to create the blast.

The microstructure of wrought iron is shown in Figure 2.5, together with a typical fracture. Before the introduction of cheap