

Metallurgy

for the
Non-Metallurgist™

Second Edition

Edited by

Arthur C. Reardon



**The Materials
Information Society**

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Contents

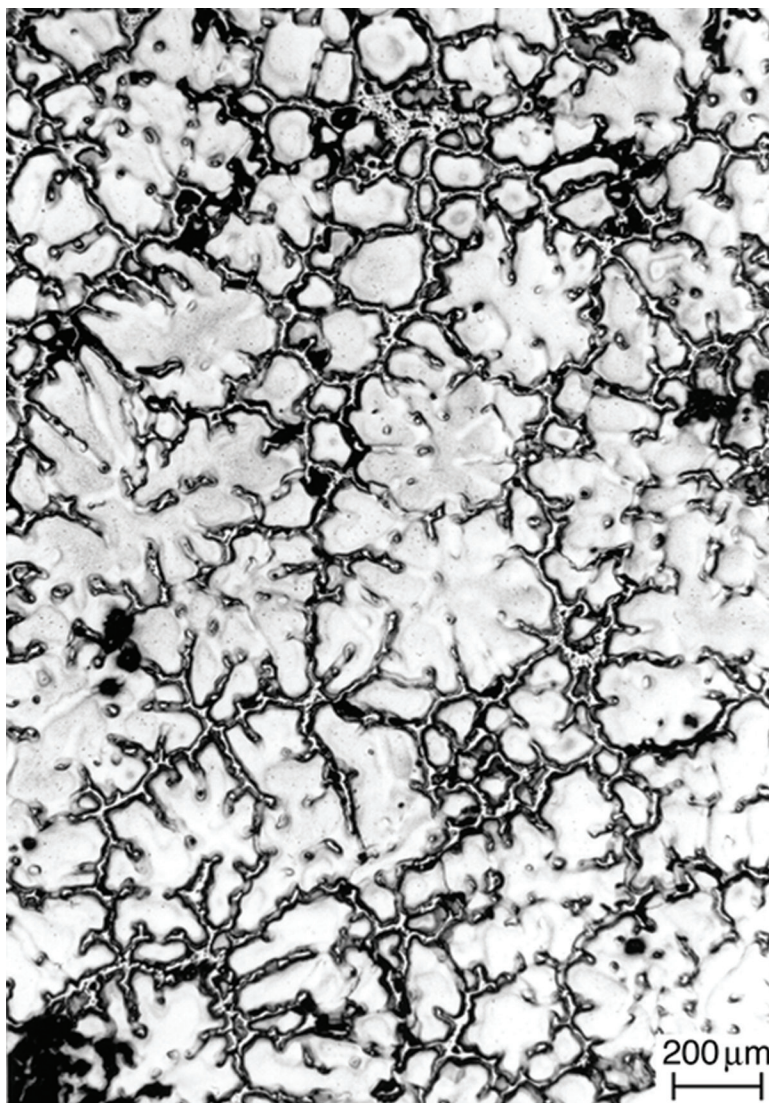
| | |
|--|-------------|
| About the Cover | vii |
| Preface..... | viii |
| About the Editor | x |
| Abbreviations and Symbols..... | xi |
| | |
| Chapter 1 The Accidental Birth of a No-Name Alloy | 1 |
| 1.1 Turning Points in Technology..... | 2 |
| 1.2 The Foundations of Innovation..... | 6 |
| 1.3 Continuing Material Innovations..... | 8 |
| | |
| Chapter 2 Structure of Metals and Alloys..... | 13 |
| 2.1 Profile of the Atom..... | 13 |
| 2.2 Bonding Between Atoms..... | 15 |
| 2.3 Crystal Structures and Defects | 19 |
| 2.4 Crystal Structure of Metals | 26 |
| 2.5 Diffusion..... | 33 |
| 2.6 Solid Solutions..... | 34 |
| 2.7 Allotropy of Iron | 37 |
| 2.8 Melting..... | 39 |
| 2.9 Solidification Structures | 42 |
| 2.10 Using Equilibrium Phase Diagrams..... | 44 |
| 2.11 Chemical Thermodynamics..... | 45 |
| 2.12 Phase Changes | 46 |
| | |
| Chapter 3 Mechanical Properties and Strengthening Mechanisms..... | 49 |
| 3.1 Mechanical Properties | 49 |
| 3.2 Strengthening Mechanisms | 59 |
| | |
| Chapter 4 Discovering Metals—A Historical Overview | 73 |
| 4.1 Native Metals..... | 73 |
| 4.2 The Bronze Age | 75 |
| 4.3 Making Metals—Extractive Practices..... | 76 |

| | | |
|------------------|---|------------|
| 4.4 | Iron | 77 |
| 4.5 | Discovery of Modern Metals..... | 81 |
| 4.6 | Refining of Metals..... | 82 |
| Chapter 5 | Modern Alloy Production | 85 |
| 5.1 | Effects of Alloying on Solidification..... | 86 |
| 5.2 | Solidification Structures | 89 |
| 5.3 | Melting Furnaces | 93 |
| 5.4 | Molten Metal Processing..... | 100 |
| 5.5 | Primary Production Casting | 101 |
| 5.6 | Foundry Casting..... | 103 |
| 5.7 | Nonferrous Casting Alloys..... | 107 |
| 5.8 | Powder Metallurgy..... | 111 |
| Chapter 6 | Fabrication and Finishing of Metal Products..... | 117 |
| 6.1 | Deformation Processes | 118 |
| 6.2 | Primary Production Mills | 121 |
| 6.3 | Forging | 124 |
| 6.4 | Drawing and Extrusion | 129 |
| 6.5 | Forming | 130 |
| 6.6 | Powder Metallurgy..... | 134 |
| 6.7 | Material Removal Processes..... | 136 |
| 6.8 | Joining Processes | 139 |
| Chapter 7 | Testing and Inspection of Metals—The Quest for Quality | 149 |
| 7.1 | Metallography..... | 150 |
| 7.2 | Hardness Testing | 152 |
| 7.3 | Tensile Testing | 156 |
| 7.4 | Fracture Toughness..... | 159 |
| 7.5 | Impact Testing..... | 165 |
| 7.6 | Fatigue Testing | 165 |
| 7.7 | Nondestructive Testing..... | 169 |
| Chapter 8 | Steel Products and Properties | 175 |
| 8.1 | Classifications of Steels | 175 |
| 8.2 | Carbon Steels..... | 180 |
| 8.3 | Alloy Steels | 182 |
| 8.4 | Alloying Elements in Steel..... | 185 |
| 8.5 | Strength and Toughness..... | 188 |
| Chapter 9 | Heat Treatment of Steel | 197 |
| 9.1 | The Iron-Carbon System..... | 197 |
| 9.2 | Common Phases in Steels | 200 |
| 9.3 | Critical Temperatures and Transformation Diagrams..... | 210 |
| 9.4 | Annealing and Normalizing | 216 |
| 9.5 | Types of Annealing Treatments | 218 |
| 9.6 | Furnace Heating and Induction Heating | 220 |
| 9.7 | Hardening and Tempering..... | 226 |

| | | |
|-------------------|---|------------|
| 9.8 | Cold Treating of Steel..... | 231 |
| 9.9 | Case Hardening..... | 233 |
| 9.10 | Heat Treating Equipment | 240 |
| Chapter 10 | Cast Irons | 247 |
| 10.1 | Basic Metallurgy of Cast Irons..... | 248 |
| 10.2 | Classification of Cast Irons..... | 255 |
| 10.3 | Gray Cast Iron | 255 |
| 10.4 | Ductile Iron | 260 |
| 10.5 | Malleable Iron | 267 |
| 10.6 | Compacted Graphite Iron | 269 |
| 10.7 | Special Cast Irons | 270 |
| Chapter 11 | Tool Steels and High-Speed Steels | 273 |
| 11.1 | A Brief History | 273 |
| 11.2 | Modern Alloys | 274 |
| 11.3 | Wrought Tool Steels | 281 |
| 11.4 | Effects of Alloying and Carbides on Wear Resistance..... | 282 |
| 11.5 | Heat Treating High-Speed and Tool Steels..... | 283 |
| 11.6 | Powder Metallurgy Tool Steels | 286 |
| 11.7 | Cutting Tool Coatings..... | 288 |
| Chapter 12 | Stainless Steels..... | 291 |
| 12.1 | The History of Stainless Steels..... | 291 |
| 12.2 | Modern Alloys | 293 |
| 12.3 | Austenitic Stainless Steels..... | 295 |
| 12.4 | Ferritic Stainless Steels | 299 |
| 12.5 | Duplex Stainless Steels | 302 |
| 12.6 | Martensitic Stainless Steels..... | 304 |
| 12.7 | Precipitation-Hardening Stainless Steels..... | 309 |
| 12.8 | Cast Stainless Steels | 310 |
| 12.9 | Powder Metallurgy Stainless Steels | 313 |
| Chapter 13 | Nonferrous Metals— A Variety of Possibilities..... | 315 |
| 13.1 | Light Metals (Al, Be, Mg, Ti)..... | 316 |
| 13.2 | Corrosion-Resistant Alloys (Co, Cu, Ni, Ti, Al)..... | 317 |
| 13.3 | Superalloys | 321 |
| 13.4 | Refractory Metals (Mo, Nb, Re, Ta, W)..... | 323 |
| 13.5 | Low-Melting-Point Metals (Bi, In, Pb, Sn, Zn) | 324 |
| 13.6 | Reactive Metals (Be, Hf, Nb, Ta, Ti, and Zr) | 327 |
| 13.7 | Precious Metals | 327 |
| 13.8 | Rare Earth Metals..... | 328 |
| 13.9 | Metalloids (Semimetals)..... | 329 |
| 13.10 | Special-Purpose Metals and Alloys | 330 |
| Chapter 14 | Heat Treatment of Nonferrous Alloys | 333 |
| 14.1 | Recovery and Recrystallization Annealing | 334 |
| 14.2 | Heat-Treatable Aluminum Alloys | 336 |

| | | |
|-------------------|--|------------|
| 14.3 | Cobalt Alloys | 341 |
| 14.4 | Copper Alloys | 342 |
| 14.5 | Magnesium Alloys | 351 |
| 14.6 | Nickel Alloys | 352 |
| 14.7 | Titanium Alloys | 355 |
| 14.8 | Other Nonferrous Alloys | 365 |
| Chapter 15 | Coping with Corrosion | 369 |
| 15.1 | The Mechanism of Corrosion | 369 |
| 15.2 | Forms of Corrosion | 374 |
| 15.3 | Corrosion Prevention or Mitigation | 380 |
| Chapter 16 | The Durability of Metals and Alloys..... | 385 |
| 16.1 | The Many Faces of Wear | 385 |
| 16.2 | Temperature-Induced Failures | 393 |
| 16.3 | Brittle versus Ductile Failure | 396 |
| 16.4 | Fatigue | 401 |
| Chapter 17 | The Materials Selection Process..... | 407 |
| 17.1 | Materials Selection in Design | 408 |
| 17.2 | Performance and Properties | 413 |
| 17.3 | Physical Property Considerations | 414 |
| 17.4 | Mechanical Properties and Durability..... | 415 |
| 17.5 | Other Selection Considerations..... | 419 |
| 17.6 | Standards and Specifications..... | 422 |
| Appendix 1 | Glossary..... | 429 |
| Appendix 2 | Universal Constants and Conversion Factors..... | 463 |
| Appendix 3 | Steel Hardness Conversions..... | 465 |
| Appendix 4 | Physical Properties of Metals and the Periodic Table..... | 469 |
| Index..... | | 473 |

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

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.

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 <i>chauffant</i> | Ar_4 | The temperature at which delta ferrite transforms to austenite during cooling |
| Ac_3 | The temperature at which transformation of ferrite to austenite is completed during heating | at.% | atomic percent |
| Ac_{cm} | In hypereutectoid steel, the temperature during heating when all cementite decomposes and all the carbon is dissolved in the austenitic lattice | bcc | body-centered cubic |
| ADI | austempered ductile iron | bct | body-centered tetragonal |
| Ae_1 | The critical temperature when some austenite begins to form under conditions of thermal equilibrium (i.e., constant temperature) | BH | bake-hardening |
| Ae_3 | The upper critical temperatures when all the ferrite phase has completely transformed into austenite under equilibrium conditions | BOF | basic oxygen furnace |
| 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) | CCT | continuous cooling transformation |
| AHSS | advanced high-strength steels | CE | carbon equivalent |
| AOD | argon oxygen decarburization | CN | coordination number |
| 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 <i>refroidissant</i> | CP | complex phase or commercial purity |
| Ar_3 | The upper critical temperature when a fully austenitic microstructure begins to transform to ferrite during cooling | CS | Commercial Standard |
| Ar_{cm} | In hypereutectoid steel, the temperature when cementite begins to form (precipitate) during cooling of an austenite-carbon solid solution | 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 | Mg | megagram (metric tonne, or $\text{kg} \times 10^3$) |
| gf | gram-force | MHz | megahertz |
| GMAW | gas metal arc welding | MIG | metal inert gas (welding) |
| GP | Guinier-Preston (zone) | MIM | metal injection molding |
| GPa | gigapascal | mm | millimeter |
| GTAW | gas tungsten arc welding | mN | milliNewtons |
| h | hour | mol | mole |
| HAZ | heat-affected zone | MP | melting point |
| HB | Brinell hardness | MPa | megapascal |
| hcp | hexagonal close-packed | mph | miles per hour |
| HIP | hot isostatic pressing | MRI | magnetic resonance imaging |
| HK | Knoop hardness | n | strain-hardening exponent |
| hp | horsepower | NDT | nondestructive testing |
| HPDC | high-pressure die casting | nm | nanometer |
| HRB | Rockwell "B" hardness | ODS | oxide dispersion strengthened |
| HRC | Rockwell "C" hardness | OFHC | oxygen-free high conductivity (copper) |
| HSLA | high-strength, low-alloy (steel) | PH | precipitation- hardenable/hardening |
| HSS | high-speed steel | PM | powder metallurgy |
| HV | Vickers hardness (diamond pyramid hardness) | ppm | parts per million |
| IF | interstitial free | psi | pounds per square inch |
| IF-HA | interstitial free, high-strength | PTA | plasma tungsten arc |
| IG | intergranular corrosion | PVD | physical vapor deposition |
| IQ | integral quench | QT | quenched and tempered |
| IS | isotropic steels | R | universal gas constant, ratio of the minimum stress to the maximum stress |
| IT | isothermal transformation | RA | reduction in area |
| ITh | isothermal transformation diagram | rpm | revolutions per minute |
| K | Kelvin | RW | resistance welding |
| K | stress-intensity factor in linear elastic fracture mechanics | SAW | submerged arc welding |
| K_{Ic} | plane-strain fracture toughness | SCC | stress-corrosion cracking |
| K_{Id} | Dynamic fracture toughness | SEM | scanning electron microscopy |
| K_t | theoretical stress-concentration factor | SFE | stacking fault energy |
| kg | kilogram | SMAW | shield metal arc welding |
| kgf | kilogram force | $S-N$ | stress-number of cycles (fatigue) |
| kJ | kilo (10^3) Joules | T_β | β transus temperature (titanium) |
| km | kilometer | TIG | tungsten inert gas (welding) |
| ksi | 1000 lbf per square inch (kips) | T_m, T_M | melt/melting temperature |
| kW | kilowatt | TMAZ | thermomechanical-affected zone |
| L | liter | TRIP | transformation-induced plasticity (steels) |
| L | length | tsi | tons per square inch |
| lb | pound | TTT | time-temperature-transformation |
| LBM | laser beam machining | UNS | Unified Numbering System (ASTM-SAE) |
| LD | Linz-Donawitz | UTM | universal testing machine |
| LEFM | linear elastic fracture mechanics | UTS | ultimate tensile strength |
| m | meter | V | volt |
| MART | martensitic (sheet steels) | VAR | vacuum arc remelting |
| MC | metal carbides | VIM | vacuum induction melting |
| M_f | temperature at which martensite formation finishes during cooling | | |
| M_s | temperature at which martensite starts to form from austenite on cooling | | |