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 2013

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 (2012–2013), Bradley J. Diak, Chair.

ASM International staff who worked on this project include Scott Henry, Senior Manager, Content Development and Publishing; Karen Marken, Senior Managing Editor; Steven Lampman, Content Developer; Sue Sellers, Editorial Assistant; Madrid Tramble, Manager of Production; and Diane Whitelaw, Production Coordinator.

SAN: 204-7586

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

Printed in the United States of America
Flake Campbell passed away shortly after completing his work on this volume. His 38-year career at The Boeing Co. was split equally between engineering and manufacturing. He worked in the engineering laboratories, manufacturing R&D, engineering on four production aircraft programs, and in production operations. He was a 2001 recipient of Boeing’s Senior Technical Fellow award for accomplishments in his field. At retirement, Campbell was a director and senior technical fellow in the field of manufacturing technology within Boeing’s Phantom Works service. Campbell received an M.B.A. from Maryville University in St. Louis, 1994, and an M.S. in metallurgical engineering, from the University of Missouri at Rolla, 1972.

## Contents

Preface ........................................... ix

CHAPTER 1  
Primary Mill Fabrication ........................ 1  
  Ironmaking ........................................ 1  
  Steelmaking ....................................... 4  
  Alloy Steel Refining ............................. 8  
  Stainless Steel Refining ......................... 16  
  Ingot Casting ..................................... 19  
  Continuous Casting ................................ 21  
  Rolling ............................................ 22  
  Aluminum Production ............................ 37  
  Titanium Production ............................. 42

CHAPTER 2  
Casting ........................................... 47  
  Casting Alloys ..................................... 49  
  Solidification ..................................... 49  
  Casting Defects ................................... 56  
  Gating and Risering ............................... 61  
  Melting Methods .................................. 63  
  Casting Methods .................................. 71

CHAPTER 3  
Bulk Deformation ................................. 103  
  Hot Working ...................................... 104  
  Cold Working ..................................... 107  
  Forging .......................................... 109  
  Hammers and Presses ............................. 110  
  Die Design and Materials ....................... 113
Die Steels ........................................ 116
Friction and Lubrication in Forging .......... 117
Forging Imperfections .......................... 119
Forging Processes ............................... 122
Open-Die Forging ............................... 122
Closed-Die Forging .............................. 124
Hot Upset Forging .............................. 130
Roll Forging .................................. 132
High-Energy-Rate Forging ..................... 134
Ring Rolling .................................. 137
Rotary Swaging of Bars and Tubes .......... 138
Radial Forging ................................ 140
Rotary Forging ................................ 141
Isothermal and Hot-Die Forging .......... 144
Precision Forging .............................. 146
Cold Forging .................................. 148
Cold Extrusion ................................. 151
Hot Extrusion .................................. 154
Drawing ....................................... 157

CHAPTER 4
Forming ...................................... 163
Preparation of Plate and Flat Sheet ........ 163
Forming ....................................... 169
Die Materials for Sheet Metal Forming ...... 170
Selection and Use of Lubricants in Forming Sheet Metal . 173
Blanking ...................................... 176
Piercing ..................................... 178
Fine-Edge Blanking and Piercing .......... 178
Bending and Springback ..................... 180
Defects in Sheet Metal Parts ................. 181
Press Bending ................................ 183
Press-Brake Forming .......................... 186
Deep Drawing ................................ 189
Fundamentals of Drawing .................... 190
Stretch Forming ................................ 194
Spinning ..................................... 196
Rubber-Pad Forming ........................... 199
Fluid-Cell Process ............................. 201
Fluid Forming ................................ 202
Drop Hammer Forming ....................... 203
Electromagnetic Forming (EMF) ............ 204
Superplastic Forming (SPF) .................. 206
CHAPTER 5
Machining ................................. 213
   Types of Machining Processes ..................... 213
   Types of Machining Equipment .................... 215
   Workpiece Machinability .......................... 215
   Dimensional and Surface Finish Tolerances .......... 217
   Surface Integrity ................................. 217
   The Mechanics of Chip Formation ................... 222
   Tool Wear in Metal Cutting ....................... 225
   Cutting Tool Materials ............................ 229
   Application/Grade Selection ........................ 235
   Cutting Fluids ................................. 237
   Basic Chip Producing Processes and Equipment ....... 241
   Machining Parameters ............................ 250
   Forces and Power ................................ 254
   Grinding .................................... 257
   Grinding Wheels ................................ 258
   Nontraditional Machining Processes ................ 261

CHAPTER 6
Heat Treatment .......................... 271
   The Iron-Carbon System .......................... 272
   Annealing .................................. 276
   Normalizing .................................. 277
   Spheroidizing .................................. 277
   Quench Hardening ................................ 278
   Continuous Cooling Transformation Diagrams ......... 279
   Austenitizing .................................. 281
   Quenching .................................... 283
   Hardenability .................................. 286
   Tempering .................................... 288
   Interrupted Quenching ............................ 291
   Temper Embrittlement ............................. 295
   Surface Hardening of Steel ....................... 297
   Flame Hardening ................................ 298
   Induction Hardening .............................. 299
   Case Hardening .................................. 300
   Carburizing ................................... 301
   Nitriding ..................................... 310
   Carbonitriding .................................. 313
   Precipitation Hardening ........................... 314
   Precipitation Hardening of Aluminum Alloys ......... 317
### CHAPTER 7

**Finishing and Coating** .......................... 325  
- Environmental Regulations .......................... 325  
- Cleaning .............................................. 326  
- Abrasive Finishing Methods ......................... 330  
- Polishing and Buffing .................................. 331  
- Lapping .................................................. 334  
- Electropolishing ....................................... 335  
- Mass Finishing ......................................... 335  
- Rust-Preventive Compounds ............................ 338  
- Phosphate Conversion Coatings ....................... 338  
- Chromate Conversion Coatings ....................... 339  
- Electroplating Processes .................................. 339  
- Selective Plating Processes ........................... 343  
- Electroless Plating Processes ......................... 344  
- Hot Dip Coating of Steels ............................. 346  
- Babbitting ............................................. 348  
- Weld-Overlay Coatings ................................ 349  
- Thermal Spray Coatings ................................ 350  
- Porcelain Enameling ................................... 353  
- Ceramic Coatings ..................................... 353  
- Pack Cementation ...................................... 355  
- Chemical Vapor Deposition .............................. 357  
- Physical Vapor Deposition .............................. 360  
- Ion Implantation ....................................... 365  
- Painting .................................................. 365  

### CHAPTER 8

**Powder Metallurgy** ................................. 373  
- Powder Characteristics ................................ 374  
- Powder Production Processes .......................... 380  
- Powder Treatments .................................... 388  
- Powder Consolidation ................................... 393  
- Powder Metallurgy Part Defects ....................... 406  
- Secondary Operations .................................. 408  

**Index** .................................................. 413
Preface

This book deals with the fabrication processes used to produce metallic products. It is intended primarily for technical personnel who want to learn more about metallic fabrication processes. This book is useful to designers, structural engineers, materials and process engineers, manufacturing engineers, technicians, production personnel, management, faculty, and students.

The first chapter gives an introduction to the processes used at the mill to produce metals and their alloys. Procedures for the primary melting, casting, and hot rolling of steel, aluminum, and titanium are covered. The importance of ladle metallurgy and secondary melting operations, such as vacuum induction melting, vacuum arc remelting, electroslag remelting, and stainless steel refining by argon oxidation decarburization, are emphasized. Both ingot casting and continuous casting are included. Rolling methods covered include hot and cold rolling, along with annealing procedures (batch and continuous).

The second chapter on casting discusses the basics of solidification, casting imperfections, and the important casting methods—sand casting, plaster and shell casting, evaporative pattern casting, investment casting, permanent mold casting, cold and hot chamber die casting, squeeze casting, semisolid metal processing, and centrifugal casting.

The third chapter is on the bulk deformation processes—forging, extrusion, and drawing. The differences between hot and cold working are initially covered. This is followed by a discussion of forging including hammers and presses, die design and materials, lubrication, forging defects, and forging processes. Forging process descriptions are given for open-die forging, closed-die impression forging, hot upset forging, roll forging, high-energy-rate forging, ring rolling, radial forging, isothermal and hot-die forging, precision forging, and cold forging. The chapter concludes with cold and hot extrusion and the various drawing operations.

Sheet metal forming processes (fourth chapter) usually employ hot or cold rolled sheet or strip material that is formed into a desired shape. Topics covered include cutting of plate and flat sheet, die materials for forming,
forming lubricants, and the forming processes of blanking, piercing, fine-
edge blanking and piercing, press bending and press-brake forming, deep
drawing, stretch forming, spinning, rubber-pad forming, fluid-cell forming,
drop hammer forming, electromagnetic forming, and superplastic forming.

The fifth chapter covers traditional, abrasive, and nontraditional machin-
ing processes with an emphasis on conventional machining. Topics include
workpiece machinability, dimensional and surface finish requirements,
surface integrity, the mechanics of chip formation, tool wear and cutting
tool materials, cutting and grinding fluids, machining equipment, machin-
ing parameters, and machining forces and power requirements.

The sixth chapter discusses the various heat treatments used to thermally
alter the property of the metal. Included are steel heat treatments—
annealing, stress relieving, normalizing, spheroidizing, and hardening by
quenching and tempering. Direct and interrupted quenching processes are
explained. The second section of the chapter discusses the various surface-
hardening processes, such as flame hardening, induction hardening, case
hardening by carburization, nitriding, and carbonitriding. The third part
of the chapter covers precipitation hardening with an emphasis of alumi-
num alloys. However, precipitation hardening is also used extensively to
strengthen magnesium alloys, nickel-base superalloys, beryllium-copper
alloys, and precipitation-hardening (PH) stainless steels.

The seventh chapter covers the rather wide topic of surface finishing
and coatings. Areas included are cleaning methods, abrasive finishing,
polishing and buffing, electropolishing, mass finishing methods such as
barrel and vibratory finishing, phosphate and chromate conversion coat-
ings, electroplating (e.g., copper plating, chromium plating, and cadmium
plating), electroless plating, weld overlay coatings, thermal spray coatings,
high-temperature ceramic coatings, and chemical vapor deposition (CVD)
and physical vapor deposition (PVD).

Powder metallurgy (eighth chapter) is the process of blending fine pow-
dered materials, pressing them into a desired shape or form (compacting),
and then heating the compressed material in a controlled atmosphere to
bond the material together (sintering). The powder metallurgy process
generally consists of four basic steps: powder manufacture, powder blend-
ing, compacting, and sintering. Compacting is generally performed at
room temperature, and the elevated-temperature process of sintering is
usually conducted at atmospheric pressure. Full-density processes are also
included. Optional secondary processing is often used to obtain special
properties or enhanced precision.

I would like to acknowledge the help and guidance of Karen Marken,
ASM International, and the staff at ASM for their valuable contributions.

F.C. Campbell
St. Louis, Missouri
October 2012