



# PROCESSES AND MATERIALS OF MANUFACTURE

**Fourth Edition**

**ROY A. LINDBERG**

Emeritus Professor of Production Engineering  
University of Wisconsin

**ALLYN AND BACON**

**Boston**

**London**

**Sydney**

**Toronto**

This book is part of the

ALLYN AND BACON SERIES IN ENGINEERING

CONSULTING EDITOR: FRANK KREITH  
UNIVERSITY OF COLORADO



Copyright © 1990, 1983, 1977, 1964 by Allyn and Bacon  
A division of Simon & Schuster, Inc.  
160 Gould Street  
Needham Heights, Massachusetts 02194

All rights reserved. No part of the material  
protected by this copyright notice may be reproduced  
or utilized in any form or by any means, electronic  
or mechanical, including photocopying, recording,  
or by any information storage and retrieval system,  
without written permission from the copyright owner.

Library of Congress Cataloging-in-Publication Data

Lindberg, Roy A.

Processes and materials of manufacture/Roy A. Lindberg.—4th  
ed.

p. cm.—(Allyn and Bacon series in engineering)

Includes bibliographies and index.

ISBN 0-205-11817-8

1. Manufacturing processes. 2. Materials. I. Title.

II. Series.

TS183.L56 1990

670—dc20

89-32561

CIP

Printed in the United States of America

10 9 8 7 6 5 4 3 2 1 93 92 91 90 89

# Preface

Manufacturing is the essential basic strength of any industrialized nation. Although increasingly larger segments of the population may be employed in service industries, it is manufacturing that produces the wealth of the nation.

The objective of this book is to provide engineering and management personnel with a background knowledge of the processes and materials of manufacture as used in modern industry.

The fact that computers now permeate the entire gamut of manufacturing has made it mandatory that this topic be integrated into an early discussion of all manufacturing processes. As examples, the lathe and milling machine are introduced in the traditional manner, but then the text emphasizes the lathe as a turning center and the milling machine as a machining center. To understand how these and other machines are using computer control, terminology such as NC, CNC, and DNC (numerical control, computer numerical control, and direct numerical control) is introduced. This terminology is then used throughout the book.

Modern machine systems are being developed with the ultimate goal of an automatic factory. Some of the essential elements that are included in the development of an automatic factory are probes, both contact and noncontact, automatic tool changing, robot loading and unloading, automatic guided vehicles (AGV), and pallet-shuttle arrangements for workpiece handling. Although the automatic factory has not been achieved as yet, a big step in that direction is flexible manufacturing systems (FMS), now a byword in the machine tool industry.

Even though heavy emphasis has been placed on the integration of the computer into the manufacturing area, basic subjects such as tool geometry, tool life, cutting forces, and metal forming theory have not been neglected.

In addition to questions and problems at the end of each chapter, most chapters have one or more case studies. The case studies are designed to give the student insight into the type of problems actually encountered in an everyday industrial setting. The discussion of a case study in the solutions manual should be viewed as an illustration of one of a number of logical solutions.

The author is indebted to Mr. Raj Kawlra, an engineer with the Advanced Engineering Staff of the General Motors Technical Center, for his many helpful contributions and for checking all the problems.

The author also wishes to acknowledge the work of his colleagues in reviewing the manuscript: Professor Norman Braton, for the chapters on welding, Professor Marvin DeVries, for the remainder of the manuscript, and Professor Harold Steudel, who contributed Chapter 19 on process planning, which is new in this fourth edition.

Acknowledgments are also due to the editor, Mr. Ray Short, for his help in supplying reviews of the manuscript and in obtaining comments from those who have used previous editions of this book.

Preface  
R. A. L.

Manufacturing is the essential basic strength of any industrialized nation. Although increasingly larger segments of the population may be employed in service industries, it is manufacturing that produces the wealth of the nation.

The objective of this book is to provide engineering and management personnel with a background knowledge of the processes and materials of manufacture as used in modern industry.

The fact that computers now permeate the entire gamut of manufacturing has made it mandatory that this topic be integrated into an early discussion of all manufacturing processes. As examples, the lathe and milling machine are introduced in the traditional manner, but then the text emphasizes the lathe as a turning center and the milling machine as a machining center. To understand how these and other machines are using computer control, terminology such as NC, CNC, and DNC (numerical control, computer numerical control, and direct numerical control) is introduced. This terminology is then used throughout the book.

Modern machine systems are being developed with the ultimate goal of an automatic factory. Some of the essential elements that are included in the development of an automatic factory are probes, both contact and noncontact, automatic tool changing, robot loading and unloading, automatic guided vehicles (AGV), and pallet/shuttle arrangements for workpiece handling. Although the automatic factory has not been achieved as yet, a big step in that direction is flexible manufacturing systems (FMS), now a keyword in the machine tool industry.

Even though heavy emphasis has been placed on the integration of the computer into the manufacturing area, basic subjects such as tool geometry, tool life, cutting forces, and metal forming theory have not been neglected.

In addition to questions and problems at the end of each chapter, most chapters have one or more case studies. The case studies are designed to give the student insight into the type of problems actually encountered in an everyday industrial setting. The discussion of a case study in the solution manual should be viewed as an illustration of one of a number of logical solutions.

The author is indebted to Mr. Raj Kauria, an engineer with the Advanced Engineering Staff of the General Motors Technical Center, for his many helpful contributions and for checking all the problems.

# Contents

## **PREFACE**    **xiii**

## **1 THE MANUFACTURING ENGINEER**    **1**

- Manufacturing: Related Functions, 5
- Manufacturing Data Base, 7
- Group Technology (GT), 8
- Manufacturing and Economics, 14
- Questions*, 15
- Case Study 1*, 15
- Case Study 2*, 16
- Case Study 3*, 16
- Case Study 4*, 17

## **2 CLASSIFICATION AND FABRICATING CHARACTERISTICS OF METALS AND COMPOSITES**    **18**

- Fabricating Characteristics of Metals, 18
- Classification of Carbon and Alloy Steels, 21
- Fabrication of Carbon and Alloy Steels, 23
- Classification of High-Strength Low-Alloy Steels, 27
- Fabrication of HSLA and Ultra-High Strength Steels, 27
- Tool Steels, 29
- Steel Castings, 29
- Cast Iron, 31
- Stainless Steels, 42
- Light Metals and Alloys, 46
- Fabricating Characteristics of Aluminum, 48
- Copper and Copper-Based Alloys, 51
- Composites, 54
- Questions*, 58
- Problems*, 59
- Case Study*, 60
- Bibliography*, 60

### **3 NUMERICAL CONTROL AND COMPUTER STEPS TO THE AUTOMATED FACTORY 62**

- Numerical Control, 62
- NC Operation, 63
- The Coordinate System, 66
- Data Input Devices, 69
- Data Storage, 72
- Program Editing, 73
- Machining Centers, 76
- Advantages of Numerical Control, 79
- Computers and Numerical Control Manufacturing, 81
- Computer Systems, 82
- CAD/CAM, 87
- Computer Graphics, 89
- Computer-Aided Manufacture, 93
- Advantages of Computer Control, 94
- Robots, 95
- Flexibility in Manufacture, 103
- Automatic Sensing for the Flexible Manufacturing System, 107
- Areas Affected by Flexible Manufacturing Systems, 109
- Steps Toward the Automatic Factory, 113
- Questions, 115
- Problems, 117
- Case Study 1, 118
- Case Study 2, 118
- Case Study 3, 118
- Bibliography, 119

### **4 PRECISION MEASUREMENT AND STATISTICAL QUALITY CONTROL 121**

- Coordinate Measuring Machines, 133
- Geometric Form Measurement, 147
- Surface-Texture Measurement, 150
- Surface-Texture Measurement Instruments, 155
- Optical Tooling, 159
- Abbé Offset Errors, 162
- Comparators, 165
- Automating Gaging, 168
- Statistical Quality Control, 171
- Control Charts, 174
- Acceptance Sampling and Variance, 176
- Computer-Aided SQC Systems, 176
- Statistical Process Control, 178

Quality Circles, 178  
 Reliability, 180  
 Product Liability, 181  
*Questions*, 183  
*Problems*, 184  
*Case Study 1*, 187  
*Case Study 2*, 188  
*Bibliography*, 188

## 5 METAL-CUTTING THEORY AND PRACTICE 189

Tool Materials, 189  
 Tool Geometry, 200  
 Mechanics of Metal Cutting, 204  
 Tool Failures, 207  
 Tool Wear in Metal Cutting, 210  
 Tool Wear Retardation, 215  
 Tool Life, 216  
 Cutting Forces and Power, 217  
 Machinability, 222  
 Metal-Cutting Economics, 223  
 Cutting Fluids, 227  
*Questions*, 229  
*Problems*, 230  
*Case Study 1*, 232  
*Case Study 2*, 232  
*Bibliography*, 232

## 6 TURNING AND RELATED OPERATIONS 234

Engine Lathe, 234  
 Engine Lathe Operations, 238  
 Turret Lathes, 238  
 Turning Center, 240  
 Automatic Screw Machines, 254  
 Multispindle Automatic Lathes, 254  
 Vertical Turning Centers, 254  
 Machine Structures, 257  
 Drives, 259  
*Questions*, 259  
*Problems*, 260  
*Case Study*, 262  
*Bibliography*, 263



## 7 HOLE MAKING AND RELATED OPERATIONS 264

- Drill Geometry and Cutting Actions, 264
- Special Drills, 271
- Drilling Machines, 288
- Boring, 296
- Hole Punching, 300
- Laser Drilling, 301
- Questions, 302
- Problems, 302
- Case Study 1, 303
- Case Study 2, 303
- Bibliography, 304

## 8 MILLING, BROACHING, AND SAWING 305

- Milling Machine Types, 305
- Machining Center, 311
- Milling Fundamentals, 322
- The Milling Process, 326
- Broaching, 330
- Broaching Machines, 333
- Sawing, 336
- Questions, 344
- Problems, 345
- Case Study, 346
- Bibliography, 346

## 9 GRINDING AND RELATED ABRASIVE-FINISHING PROCESSES 347

- Abrasives, 347
- Grinding Operations, 362
- Abrasive-Belt Machining, 370
- Lapping, Honing, and Superfinishing, 377
- Questions, 389
- Problems, 389
- Case Study 1, 390
- Case Study 2, 391
- Bibliography, 391

## 10 METAL-CASTING PROCESSES 393

- Sand Casting, 393
- Expendable Pattern Techniques, 408

- Permanent-Mold Casting, 413
- Casting Processes Comparison, 425
- Casting Processes Considerations, 425
- Casting Design Principles, 430
- Economic Considerations, 433
- Quality Control, 436
- When to Use the Casting Process, 436
- Computers and the Casting Process, 437
- Questions*, 440
- Problems*, 441
- Bibliography*, 443

## 11 PLASTICS AND ADHESIVES 444

- Plastic Processing, 454
- Thermoforming, 475
- Solid Phase Forming, 488
- Bonding of Thermoplastics, 490
- Machining Plastics, 495
- Plating Plastics, 496
- Plastic Design Principles, 497
- Adhesive Bonding, 501
- Classification of Structural Adhesives, 502
- Surface Preparation, 507
- Adhesive-Joint Design, 508
- Adhesives and Temperature, 510
- Questions*, 513
- Problems*, 514
- Case Study 1*, 516
- Case Study 2*, 516
- Bibliography*, 517

## 12 POWDER METALLURGY 518

- Metal Powder Production, 518
- The Powder Metallurgy Process, 521
- Questions*, 537
- Problems*, 538
- Case Study 1*, 539
- Case Study 2*, 540
- Bibliography*, 541

## 13 METAL STAMPING AND FORMING 542

- Sheet Metal Forming Operations, 547
- Formability of Metals, 556

- High-Strength, Low-Alloy Steels Developed for Formability, 567
- Stretch Forming, 570
- Metal Spinning, 572
- Continuous-Roll Forming, 574
- Embossing and Coining, 575
- Press Classification, 575
- Sheet Metal Systems, 584
- Questions*, 584
- Problems*, 585
- Bibliography*, 586

## 14 BULK DEFORMATION OF METALS 587

- Forging Materials, 587
- Forging Processes, 589
- Forging Techniques, 596
- Forging Presses, 600
- Automation of Forging, 602
- CAD/CAM in Forging, 603
- FMS and Forging, 603
- Forging Pressure Distribution and Forging Force, 605
- Swaging, 606
- Drawing, 607
- Extrusion, 608
- High-Energy-Rate Forming, 613
- Questions*, 620
- Problems*, 621
- Bibliography*, 622

## 15 WELDING PRINCIPLES AND ARC WELDING 263

- Weldability, 623
- Welding Metallurgy, 624
- Controlling Weld Cracks, 626
- Arc Welding Energy Sources, 629
- Arc Welding Principles, 634
- Arc-Welding Processes, 640
- Shielded Metal-Arc Welding (SMAW), 641
- Gas Tungsten-Arc Welding (GTAW), 642
- Gas Metal-Arc Welding (GMAW), 643
- Flux-Cored Arc Welding (FCAW), 652
- Plasma-Arc Welding (PAW), 655
- Submerged-Arc Welding (SAW), 658

Electroslag Welding (ESW), 660  
 Stud-Arc Welding (SW), 661  
 Arc-Welding Process Summary, 663  
 Welded Joint Design, 663  
 Welded Connections, 674  
 Welding Distortion, 677  
 Weld Positioners and Fixtures, 681  
 Robots for Automatic Arc Welding, 683  
 Economics of Arc Welding, 689  
 Welding Symbols, 690  
*Questions*, 692  
*Problems*, 693  
*Case Study 1*, 696  
*Case Study 2*, 697  
*Case Study 3*, 697  
*Case Study 4*, 697  
*Case Study 5*, 698  
*Bibliography*, 698

## **16 GAS WELDING, BRAZING, CUTTING SYSTEMS, AND WELD TESTING 700**

Oxyacetylene Welding, 700  
 Brazing, 705  
 Soldering, 712  
 Flame Cutting Quality, 716  
 Plasma-Arc Cutting, 721  
 Metal Overlays, 724  
 Weld Inspection, 733  
 Destructive Testing, 739  
*Questions*, 745  
*Problems*, 745  
*Case Study 1*, 746  
*Case Study 2*, 747  
*Bibliography*, 747

## **17 RESISTANCE, SPECIALIZED, AND SOLID-STATE WELDING 748**

Resistance Welding Power, 748  
 Types of Resistance Welds, 750  
 Seam Welding, 757  
 Projection Welding, 757

## x CONTENTS

- High-Frequency Resistance Welding, 758
- Resistance Butt Welds, 759
- Homopolar-Pulse Resistance Welding (HPRW), 762
- Specialized Welding Processes, 762
- Laser Welding, 768
- Solid-State Welding Processes, 770
- Questions*, 782
- Problems*, 783
- Bibliography*, 783

## 18 NONTRADITIONAL MACHINING 785

- Chemical Milling (CM), 785
- Photochemical Milling (PCM), 787
- Electric-Discharge Machining (EDM), 790
- Traveling-Wire EDM (TW/EDM), 796
- Electrochemical Machining (ECM), 802
- Abrasive-Jet Machining, 806
- Laser Beam Machining (LBM), 807
- Electron Beam Machining (EBM), 815
- Water-Jet Cutting, 817
- Questions*, 819
- Problems*, 820
- Case Study*, 821
- Bibliography*, 822

## 19 PROCESS PLANNING 823

- Process Planning Activities, 824
- Objectives for Process Planning Systems, 832
- Approaches to Process Planning, 834
- Developing Manufacturing Logic and Knowledge, 838
- Selecting a Process Planning System, 842
- Questions*, 844
- References*, 845

## APPENDIX 847

- Table A: Properties of Metals, 848
- Table B: Application of Carbides, 850
- Table C: Materials Machinable by Ceramic, 850
- Table D: Recommended Starting Parameters for Machining with Polycrystalline Tools, 851

|          |   |
|----------|---|
| Table E: | Speeds for HSS Twist Drills, 852                                |
| Table F: | Feeds for HSS Twist Drills in Mild Steel, 852                   |
| Table G: | Work Materials Constants for Calculating Torque and Thrust, 852 |
| Table H: | Solder Shear Strength (PSI), 853                                |
| Table I: | Basic Welding Symbols and Their Location Significance, 854      |

**INDEX 856**

# 1

## The Manufacturing Engineer

Traditionally, the task of the manufacturing engineer has been to use an engineering design to produce a new part or product. A product starts with an idea for a better part or for a whole new concept, such as an airplane that can take off or land in a vertical direction. Eventually, a particular design approach is selected. After the design has been "frozen" it is turned over to manufacturing. In the past it was said that the design was "thrown over the wall," denoting that there was little if any communication between design engineers and manufacturing engineers. This is no longer the case since each design must be carefully examined for maximum producibility and profit or, in other words, designed for economical manufacture. A big step in the integration of design and manufacture has been brought about by the computer in computer-aided design (CAD), and computer-aided manufacture (CAM) leading to computer-integrated manufacturing (CIM).

After the design is completed and, in many cases, several prototypes have been built and tested, the manufacturing engineer begins the intricate, intellectually demanding job of creating a system that will produce the product. The design must be judged for feasibility of manufacture by several different methods, such as casting, forging, welding, powder metallurgy, machining, or cold forming.

The manufacturing engineer is not only familiar with all the various processes that are available to produce a given product but also with the materials required and their fabricating qualities, such as machinability, formability, castability, and weldability. He or she must be able to give detailed information to the purchasing department concerning the selection of materials, machines, and equipment required and whether some of the components should be purchased or made in house. New equipment, upon arrival, must be properly installed at the desired location and must perform according to specifications.

Many products require special tooling such as jigs, fixtures, dies, templates, and gages. The manufacturing engineer must be able not only to design such special tooling, but also to prepare estimates as to its cost and the cost of each step of production.

As can be seen, manufacturing engineering covers a wide spectrum of specializations that no single person, however talented, could possibly master. This



## 2 THE MANUFACTURING ENGINEER

chapter is intended to give a brief overview of some of the important aspects of manufacturing engineering, some of which will be discussed in more detail in the chapters that follow.

Manufacturing engineering can be divided into the following areas of specialization: process planning, tool engineering, work standards engineering, materials handling, facilities planning, and quality control.

### Process Planning

The process planning engineer lays out a logical sequence of manufacturing operations for each component, subassembly, and the final assembly of all subassemblies into a finished product.

Processing, as it is normally called, requires a detailed knowledge of machining processes, forming processes, and assembly processes. It also requires an exhaustive knowledge of the plant capabilities. In other words, the development of the process plan must be based largely on the physical capabilities of existing equipment.

Most important to the success of the plan is the logical integrity of the sequence steps. Most of us have purchased equipment that requires assembly. If we faithfully follow the steps outlined for the assembly, the process proceeds well; but if a step is skipped, we have to retrace our steps to find where we deviated from the proper sequence.

Similarly, every mass-produced part has its own process sheet. This sheet is developed by process planning engineering and establishes the rules for the production of the part. Once these sheets are finalized, any deviation creates significant problems.

The master process sheet (Fig. 1-1) shows the sequence of operations for a given part, the machines used, the tooling required, and the setup and cycle time. More detailed process sheets are used to give exact information on the fixtures, tools, and gages required. Today the information on process sheets is often stored in computer memory and used in management information systems so that an entire process, or even a factory, can be simulated by means of mathematical models. Simulation techniques are useful in determining the relationships between system parameters such as production rate, number of modules, and module types. A *module* is a device that performs a process on a part at a *station* or a group of stations. *Station* refers to the physical location where a part normally stops either to have an operation performed on it or to wait for clearance to proceed to the next station.

Process engineering is not an academic subject, nor can it be taught effectively in a classroom situation. Much of the basics can be learned from process texts such as this, but to be effective the text must be accompanied by manufacturing experience.

### Tool Engineering

*Tools* in the world of manufacturing refer to a vast array of standard and specially designed devices used to perform specific work tasks. Tools are used in forming flat



| 12-4-73<br>Form No. X-1  |   | Master Process Sheet                 |                      | Page of pages       |  |
|--|---|--------------------------------------|----------------------|---------------------|--|
| Written by <i>J.B.</i>   |   | Order no. 19278-B                    |                      | Dwg. No. 15620      |  |
| Date 1/4/73  |   | Date 2/1/73 Pcs. req'd. 50           |                      | Part. No. 3567      |  |
| Enters assembly at stage 15  |   | D-56 Loader                          |                      | Part name Rope Drum |  |
| Material condition Gray Iron Casting<br>190 BHN - Bore cored 1" dia. |   | Rough weight 153#                    |                      | Finish weight       |  |
| Oper. no.  | Description   | Set-up hrs                           | Cycle hrs            | Mach. no.           |  |
| 10   | Turn O.D. of body and rims. Face inside rims, face hub and rim on one side - 2AW&S turret lathe.  | .50                                  | .70                  | M6-41               |  |
| 20   | Rough, semi-finish, and finish bore 1.500/1.501 hole, face hub and rim on other end - 2AW&S turret lathe.   | .80                                  | .27                  | M6-41               |  |
| 30   | Cut 3/8 keyway and finish push broach - Davis keyseater and hand arbor press  | .25                                  | .17                  | M4-53               |  |
| 40   | Drill and tap (1) 1/2" pipe tap hole 2-Spindle upright drill press.   | .30                                  | .17                  | M3-45               |  |
| 50   | Groove - 20" Engine lathe   | .50                                  | .30                  | M4-46               |  |
| 60   | Rotary file - Bench   |                                      | .21                  |                     |  |
| 50   | 1-special taper shank arbor with drive key<br>1-Forged H.S.S. grooving tool   | 35                                   |                      | T-205<br>T-206      |  |
| 40   | 1-1/2 pipe tap and driver<br>1-23/32 H.S.T.S. drill<br>1-Type K, drill press vise   |                                      |                      |                     |  |
| 30   | 1-Finish push broach<br>1-1-1/2 die x 3/8 slot locating bush<br>1-3/8 standard keyway cutter  |                                      |                      | T-204<br>T-203      |  |
| 20   | 1-1.500 setting ring<br>1-dial bore gage<br><br>1-set of (3) 9X blocks to fin. 1.500<br>1-special 1-1/4" Davis bar with pilot bush<br>1-1-3/8 dia. core drill straight shank<br>1-stub boring bar to start core drill<br>1-set soft jaws, external grip | rough 249<br>semi fin 249<br>fin 189 | .011<br>.011<br>.011 | T-202<br>T-202      |  |
| 10   | 2-90 L.H. Offset tools, type B<br>2-90 R.H. Offset tools, type B<br>1-special offset round nose tool<br>1-set of hard coarse jaws, internal grip  | body 134<br>rim 187<br>hub 101       | .011<br>.011<br>.011 |                     |  |
| Oper. no.  | Tool Description  | Speed RPM                            | Feed IPM             | Tool no.            |  |

**Figure 1-1** Master process sheet for a small manufacturing organization. (Courtesy of the Society of Manufacturing Engineers.)

sheets into automobile fenders or airplanes fuselages. Tools are used in holding two or more pieces of metal together in the proper relationship so that they can be welded. Tools are used in producing the finish on cylinder blocks as they advance through a giant transfer line (which itself is a tool). These are only a few examples of the tools that must be designed and used by the tool engineer.

Standard tools, such as drills, reamers, taps, counterbores, dial gages for size