Fundamentals of Machining and Machine Tools

Second Edition

Geoffrey Boothroyd
Winston A. Knight

Fundamentals of Machining and Machine Tools

Second Edition

Geoffrey Boothroyd
Winston A. Knight

University of Rhode Island
Kingston, Rhode Island

MARCEL DEKKER, INC. New York and Basel

ISBN: 0-8247-7852-9
First edition copyright 1975 by Scripta Book Company (McGraw-Hill, Inc.)

MARCEL DEKKER, INC.
270 Madison Avenue, New York, New York 10016

Current printing (last digit):
10 9 8 7 6 5 4 3 2 1

PRINTED IN THE UNITED STATES OF AMERICA

MANUFACTURING ENGINEERING AND MATERIALS PROCESSING

A Series of Reference Books and Textbooks

SERIES EDITORS

Geoffrey Boothroyd

Chairman, Department of Industrial and Manufacturing Engineering
University of Rhode Island
Kingston, Rhode Island

George E. Dieter

Dean, College of Engineering
University of Maryland
College Park, Maryland

1. Computers in Manufacturing, *U. Rembold, M. Seth and J. S. Weinstein*
2. Cold Rolling of Steel, *William L. Roberts*
3. Strengthening of Ceramics: Treatments, Tests and Design Applications, *Henry P. Kirchner*
4. Metal Forming: The Application of Limit Analysis, *Betzalel Avitzur*
5. Improving Productivity by Classification, Coding, and Data Base Standardization: The Key to Maximizing CAD/CAM and Group Technology, *William F. Hyde*
6. Automatic Assembly, *Geoffrey Boothroyd, Corrado Poli, and Laurence E. Murch*
7. Manufacturing Engineering Processes, *Leo Alting*
8. Modern Ceramic Engineering: Properties, Processing, and Use in Design, *David W. Richerson*
9. Interface Technology for Computer-Controlled Manufacturing Processes, *Ulrich Rembold, Karl Armbruster, and Wolfgang Ülzmann*
10. Hot Rolling of Steel, *William L. Roberts*
11. Adhesives in Manufacturing, *edited by Gerald L. Schneberger*
12. Understanding the Manufacturing Process: Key to Successful CAD/CAM Implementation, *Joseph Harrington, Jr.*
13. Industrial Materials Science and Engineering, *edited by Lawrence E. Murr*
14. Lubricants and Lubrication in Metalworking Operations, *Elliot S. Nachtman and Serope Kalpakjian*
15. Manufacturing Engineering: An Introduction to the Basic Functions, *John P. Tanner*
16. Computer-Integrated Manufacturing Technology and Systems, *Ulrich Rembold, Christian Blume, and Ruediger Dillmann*
17. Connections in Electronic Assemblies, *Anthony J. Bilotta*

18. Automation for Press Feed Operations: Applications and Economics, *Edward Walker*
19. Nontraditional Manufacturing Processes, *Gary F. Benedict*
20. Programmable Controllers for Factory Automation, *David G. Johnson*
21. Printed Circuit Assembly Manufacturing, *Fred W. Kear*
22. Manufacturing High Technology Handbook, *edited by Donatas Tijunelis and Keith E. McKee*
23. Factory Information Systems: Design and Implementation for CIM Management and Control, *John Gaylord*
24. Flat Processing of Steel, *William L. Roberts*
25. Soldering for Electronic Assemblies, *Leo P. Lambert*
26. Flexible Manufacturing Systems in Practice: Applications, Design, and Simulation, *Joseph Talavage and Roger G. Hannam*
27. Flexible Manufacturing Systems: Benefits for the Low Inventory Factory, *John E. Lenz*
28. Fundamentals of Machining and Machine Tools, Second Edition, *Geoffrey Boothroyd and Winston A. Knight*

OTHER VOLUMES IN PREPARATION

Preface

This book is intended primarily for those studying and teaching the principles of machine tools and metal machining in universities and colleges. It should also prove useful to those concerned with manufacturing in industry.

The mathematical content of the book is deliberately limited. Those who have taken basic courses in statics and dynamics and who have had an introduction to calculus should have no difficulty in comprehending the material.

Many of the present texts dealing with the same material are purely descriptive. In this book, the approach is to illustrate, through fundamentals and analysis, the causes of various phenomena and their effects in practice. Emphasis is given to the economics of machining operations and the design of components for economic machining.

A significant portion of the book is based on a previous text written by one of the authors (Geoffrey Boothroyd) and published by McGraw-Hill. While much of this material has been retained, recent developments have been included where appropriate. Several new chapters have been introduced and others largely rewritten. The section on tool materials has been expanded to include the modern materials that are contributing significantly to increases in productivity in industry. A new chapter on machine tool vibrations has been included, which covers the fundamental aspects of machine tool chatter, the dynamic testing of machine tools, and the practical means of improving machine tool stability. The chapter on grinding has been expanded to include thermal aspects of the process and a description of new grinding processes, including creep feed grinding.

New emphasis in the book has been placed on the utilization of machine tools through the inclusion of chapters on manufacturing systems and automation and on computer-aided manufacturing, together with an expanded chapter on design for machining, which serves as an introduction to an area of growing importance, that of design for manufacturability. Various types of automation in machine tools are outlined and an introduction to cellular plant layouts and flexible manufacturing systems is included. Aspects of the programming of numerical control machine tools are discussed in some detail. Finally, because of their growing importance, the main nonconventional machining processes are described and examples of their application given.

We are indebted to those with whom we have been associated in recent years and who have assisted both directly and indirectly in the preparation of this book, including colleagues and graduate students whose work has been helpful in the preparation of this book. Finally, we would like to thank Ms. Kathleen Yorkery for typing the manuscript.

Geoffrey Boothroyd
Winston A. Knight

Conventions Used in This Book

STANDARDIZATION

Every attempt is made in this book to follow the latest International Organization for Standardization (ISO) recommendations for units and definitions. The most important of these is, of course, the International System (SI) of basic and derived units. The basic system is described in ISO Standard 1000, and recommendations for its application are specified in ISO Recommendation R31. The latter document includes suggested symbols for the various derived units.

In addition, numerous standards are becoming available covering various aspects of machining and are followed as closely as possible. Unfortunately, some of these new standards include symbols and definitions that are at variance with the SI; this variance leads to a certain amount of duplication. For example, the recommended symbol for the feed applied in a machining operation is f, which is also the recommended symbol for frequency of vibration. Confusion among measurements and symbols is avoided, however, by the use of appropriate suffixes and subscripts, respectively.

This book is written entirely in SI units because the U.S. manufacturing industry is already in the process of conversion to the SI system.

Table S1.1 Units Derived from the Basic SI Units

Unit being measured	Symbol	Name of unit	Symbol for unit
Angle, plane	α, β, γ, etc.	Radian	rad
Angular velocity	ω	-	rad/s
Angular acceleration	α	-	rad/s^2
Frequency	f	Hertz	Hz
Rotational frequency	n	Reciprocal second	s^{-1}
Area	A	-	m^2
Volume	V	-	m^3
Velocity	v	-	m/s
Acceleration	a	-	m/s^2
Density	ρ	-	kg/m^3
Force	F	Newton	kg · m/s^2, or N
Energy, work, heat	W	Joule	N · m, or J
Pressure, stress	p	Pascal	N/m^2, or Pa
Power	P	Watt	J/s, or W
Temperature difference	θ	Degree Celsius	K − 273.15, or °C

Where SI units are specified in the text, the approximate English (U.S. Customary System [USCS]) equivalents are given in parentheses. Graphs and results from previously published work are reproduced with the original scales in English (USCS) units, and the corresponding SI scales are added at the right and along the top where appropriate. Graphs produced specifically for this book are given in SI units with the equivalent English units added at the right and along the top.

Table SI.2 Prefixes Used with SI Units

Multiple and submultiple[a]	Prefix	Symbol
10^9, or $E + 09$	giga	G
10^6, or $E + 06$	mega	M
10^3, or $E + 03$	kilo	k
10^{-3}, or $E - 03$	milli	m
10^{-6}, or $E - 06$	micro	μ
10^{-9}, or $E - 09$	nano	n
10^{-12}, or $E - 12$	pico	p

[a] $E \pm ab = 10^{\pm ab}$

Table SI.3 USCS-SI Conversion Table

Quantity	To convert from	To	Multiply by[a]	
Length	inch (in.)	meter (m)	2.54*	$E-02$
	foot (ft)	meter (m)	3.048*	$E-01$
Mass	pound (lb)	kilogram (kg)	4.535 924	$E-01$
Time	minute (min)	second (s)	6.0*	$E+01$
	hour (hr)	second (s)	3.6*	$E+03$
Force	pound force (lbf)	newton (N)	4.448 222	$E+00$
Speed	foot per minute (ft/min)	meter per second (m/s)	5.08*	$E-03$
	inch per second (in./sec)	meter per second (m/s)	2.54*	$E-02$
	inch per minute (in./min)	meter per second (m/s)	4.233*	$E-04$
	revolution per minute (rpm)	radian per second (rad/s)	1.047 192	$E-01$
Acceleration	foot per second per second (ft/sec^2)	meter per second per second (m/s^2)	3.048*	$E-01$
	inch per second per second (in./sec^2)	meter per second per second (m/s^2)	2.54*	$E-02$
Area	square inch (in.^{2})	square meter (m^2)	6.451 6*	$E-04$
Volume	cubic inch (in.^{3})	cubic meter (m^3)	1.638 706	$E-05$
Volume flow rate	cubic inch per minute (in.^{3}/min)	cubic meter per second (m^3/s)	2.731 177	$E-07$
Density	pound per cubic inch (lb/in.^{3})	kilogram per cubic meter (kg/m^3)	2.767 991	$E+04$
Pressure, stress	pound force per square inch (lbf/in.^{2})	newton per square meter (N/m^2)	6.894 757	$E+03$
Energy, work heat	British thermal unit (Btu)	newton-meter (N-m), or joule (J)	1.055 06	$E+03$
Power	horsepower (hp)	joule per second (J/s), or watt (W)	7.457	$E+02$
	foot-pound force per minute (ft-lbf/min)	joule per second (J/s), or watt (W)	2.259 697	$E-02$
Thermal conductivity	Btu in./hr ft^2°F	joule per second meter kelvin (J/smK), or watt per meter kelvin (W/mK)	1.442 279	$E-01$
Specific heat capability	Btu/lb°F	joule per kilogram kelvin (J/kgK)	4.184	$E+03$

[a]Values followed by an asterisk are exact conversions.

INTRODUCTION TO THE INTERNATIONAL (SI) SYSTEM OF UNITS

In 1960 the General Conference of Weights and Measures on the International System of Units formally approved the system of units known as the International (SI) System of Units. This system is now being adopted throughout the world and is currently being adopted by the United States. In practice the system is convenient because it obviates the need for the insertion of conversion factors into equations and eliminates many of the ambiguities present in other systems. The basic SI units encountered in engineering are defined as follows:

1. The unit of length l is the meter, m, which is the length equal to 1, 650, 763.73 wavelengths in vacuo of the radiation corresponding to the transition between the levels $2p_{10}$ and $5d_5$ of the krypton-86 atom.
2. The unit of mass m is the kilogram, kg, which is equal to the mass of the international prototype of the kilogram.
3. The unit of time t is the second, s, which is the duration of 9, 192, 631, 770 periods of the radiation corresponding to the transition between the two hyperfine levels of the ground state of the cesium-133 atom.
4. The unit of temperature T is the kelvin, K, which is 1/273.16 of the thermodynamic temperature of the triple point of water.
5. The unit of electric current I is the ampere, A, which is that constant current which, if maintained in two straight parallel conductors of infinite length, of negligible, circular cross section and placed 1 meter apart in a vacuum, would produce between these conductors a force equal to 2×10^{-7} newton per meter of length.

To encourage the student or reader to become familiar with SI units, most of the problems presented at the end of each chapter are given in SI units without the English equivalents. It is hoped that the student or reader will thereby discover that the new system is considerably easier to work with than the U.S. Customary System (pounds, feet, etc.).

For those not sufficiently familiar with the SI system the tables introduce the basic and derived units and their definitions and recommended symbols. Useful conversions are also given.

Table SI.1 presents a selection of derived units.

The most common prefixes for SI units are listed in Table SI.2. It should be noted that

1. The prefix refers to the whole unit; for example, the m (milli) in $m \cdot N/m^2$ means $m(N/m^2)$, not mN/m^2. The dot is used to indicate multiplication when confusion could arise.
2. Prefixes in denominators are avoided, except for k in kg (kilogram).

Useful conversion factors are given in Table SI.3.

Contents