

GLOBAL EDITION

Juvinall's **FUNDAMENTALS** OF MACHINE COMPONENT DESIGN

SI VERSION

ROBERT C. JUVINALL
KURT M. MARSHEK

WILEY

JUVINALL'S FUNDAMENTALS OF MACHINE COMPONENT DESIGN

GLOBAL EDITION

SI VERSION

Robert C. Juvinall

*Professor of Mechanical Engineering
University of Michigan*

Kurt M. Marshek

*Professor of Mechanical Engineering
University of Texas at Austin*

WILEY

Copyright © The content provided in this textbook is based on Juvinall and Marshek's Fundamentals Of Machine Component Design, 6th edition [2017]. John Wiley & Sons Singapore Pte. Ltd.

Cover image: ©CHRISTIAN LAGEREK/SCIENCE PHOTO LIBRARY/Getty Images

Founded in 1807, John Wiley & Sons, Inc. has been a valued source of knowledge and understanding for more than 200 years, helping people around the world meet their needs and fulfill their aspirations. Our company is built on a foundation of principles that include responsibility to the communities we serve and where we live and work. In 2008, we launched a Corporate Citizenship Initiative, a global effort to address the environmental, social, economic, and ethical challenges we face in our business. Among the issues we are addressing are carbon impact, paper specifications and procurement, ethical conduct within our business and among our vendors, and community and charitable support. For more information, please visit our website: www.wiley.com/go/citizenship.

All rights reserved. This book is authorized for sale in Europe, Asia, Africa, and the Middle East only and may not be exported outside of these territories. Exportation from or importation of this book to another region without the Publisher's authorization is illegal and is a violation of the Publisher's rights. The Publisher may take legal action to enforce its rights. The Publisher may recover damages and costs, including but not limited to lost profits and attorney's fees, in the event legal action is required.

No part of this publication may be reproduced, stored in a retrieval system, or transmitted in any form or by any means, electronic, mechanical, photocopying, recording, scanning, or otherwise, except as permitted under Section 107 or 108 of the 1976 United States Copyright Act, without either the prior written permission of the Publisher or authorization through payment of the appropriate per-copy fee to the Copyright Clearance Center, Inc., 222 Rosewood Drive, Danvers, MA 01923, website www.copyright.com. Requests to the Publisher for permission should be addressed to the Permissions Department, John Wiley & Sons, Inc., 111 River Street, Hoboken, NJ 07030, (201) 748-6011, fax (201) 748-6008, website <http://www.wiley.com/go/permissions>.

ISBN: 978-1-119-38290-4

Printed in Singapore at Markono Print Media Pte Ltd

10 9 8 7 6 5 4 3 2 1

Appendix A-1a Conversion Factors for British Gravitational, English, and SI Units

Quantity	British Gravitational and English Units ^a	SI Unit ^a	Conversion Factor Equalities
Length	inch (in. or ")	<u>meter</u> (m)	*1 in. = 0.0254 m = 25.4 mm
	foot (ft or')	<u>meter</u> (m)	*1 ft = 0.3048 m = 304.8 mm
	<u>mile</u> (mi U.S. statute)	<u>kilometer</u> (km)	1 mile = 1.609 km = 1609 m
Volume	gallon (gal U.S.)	<u>meter</u> ³ (m ³)	1 gal = 0.003785 m ³ = 3.785 liters
Force (weight)	<u>pound</u> (lb)	<u>newton</u> ^d (N)	1 lb = 4.448 N
Torque	<u>pound-foot</u> (lb·ft)	<u>newton-meter</u> (N·m)	1 lb·ft = 1.356 N·m
Work, Energy	<u>foot-pound</u> (ft·lb)	<u>joule</u> ^e (J)	1 ft·lb = 1.356 J
Power	<u>foot-pound/second</u> (ft·lb/s)	<u>watt</u> ^e (W)	1 ft·lb/s = 1.356 W
	<u>horsepower</u> ^b (hp)	<u>kilowatt</u> (kW)	1 hp = 0.746 kW
Stress,	<u>pounds/in.</u> ² (psi)	<u>pascal</u> ^e (Pa)	1 psi = 6895 Pa
Pressure	<u>thousand pounds/in.</u> ² (ksi)	<u>megapascal</u> (MPa)	1 ksi = 6.895 MPa
Mass (British)	<u>slug</u> ^f	<u>kilogram</u> (kg)	1 slug = 14.59 kg
Mass (English)	<u>lbm</u> ^h	<u>kilogram</u> (kg)	1 lbm = 0.454 kg = 454 grams

^aThe *larger* unit is underlined.

^b 1 hp = 550 ft·lb/s; ^c 1 J = 1 N·m; ^d 1 N = 1 kg·m/s²; ^e 1 Pa = 1 N/m²; ^f 1 slug = 1 lb·s²/ft; ^g 1 W = 1 J/s; ^h 1 slug = 32.2 lbm.

* An exact definition.

Appendix C-1 Physical Properties of Common Metals

Metal	Modulus of Elasticity, E		Modulus of Rigidity, G		Poisson's Ratio, ν	Unit Weight, w (lb/in. ³)	Density, ρ (Mg/m ³)	Coefficient of Thermal Expansion, α		Thermal Conductivity		Specific Heat	
	Mpsi	GPa	Mpsi	GPa				10 ⁻⁶ /°F	10 ⁻⁶ /°C	Btu/h-ft-°F	W/m-°C	Btu/lbm-°F	J/kg-°C
Aluminum alloy	10.4 ^a	72	3.9	27	0.32	0.10	2.8	12.0	22	100	173	0.22	920
Beryl. copper	18.5	127	7.2	50	0.29	0.30	8.3	9.3	17	85	147	0.10	420
Brass, Bronze	16	110	6.0	41	0.33	0.31	8.7	10.5	19	45	78	0.10	420
Copper	17.5	121	6.6	46	0.33	0.32	8.9	9.4	17	220	381	0.10	420
Iron, gray cast ^b	15	103	6.0	41	0.26	0.26	7.2	6.4	12	29	50	0.13	540
Magnesium alloy	6.5	45	2.4	17	0.35	0.065	1.8	14.5	26	55	95	0.28	1170
Nickel alloy	30	207	11.5	79	0.30	0.30	8.3	7.0	13	12	21	0.12	500
Steel, carbon	30	207	11.5	79	0.30	0.28	7.7	6.7	12	27	47	0.11	460
Steel, alloy	30	207	11.5	79	0.30	0.28	7.7	6.3	11	22	38	0.11	460
Steel, stainless	27.5	190	10.6	73	0.30	0.28	7.7	8.0	14	12	21	0.11	460
Titanium alloy	16.5	114	6.2	43	0.33	0.16	4.4	4.9	9	7	12	0.12	500
Zinc alloy	12	83	4.5	31	0.33	0.24	6.6	15.0	27	64	111	0.11	460

^aValues given are representative. Exact values may vary with composition and processing, sometimes greatly.

^bSee Appendix C-3 for more detailed elastic properties of cast irons.

Note: See Appendix C-18 for physical properties of some plastics.

**JUVINALL'S
FUNDAMENTALS OF MACHINE
COMPONENT DESIGN**

PREFACE

This book is intended as a text for first courses in Mechanical Engineering Design and as a reference for practicing engineers. It is assumed that the user has had basic courses in Mechanics, Strength of Materials, and Materials Properties. However, the first nine chapters of the book (Part I) serve to review as well as extend this basic background. The remaining chapters (Part II) deal with the application of these fundamentals to specific machine components.

Features of the Global Edition of the text include:

- **Homework problems**—A large number of new problems are added that help the student focus on introductory concepts and definitions.
- **Safety considerations**—The textbook continues to focus on real world safety issues adapted from actual case studies. For example, presented are an analysis of truck pick up tailgate cable failures, an unguarded in-running nip point of a treadmill belt drive, the sudden collapse of a cantilevered section of a walkway under demolition, the unexpected release of a hack squat machine carriage, the exposed shaft of an industrial finger jointer, and the safety of a two-wheeled, self-balancing electric personal transport.
- **Engineering material selection**—New charts from Professor Ashby’s material selection procedure form the basis for introducing the student to selection and use of common engineering materials.
- **Elastic stability**—A design study presents an introduction to a captive cap that has two elastically stable positions: “opened” and “closed.” The study references a patent and an exercise, the solution of which reveals a method of patent analysis.
- **Abrasive wear**—A device for screening seal materials is studied. An associated homework problem introduces the student to a patented test apparatus used to select the best materials for tricone drilling bits.
- **Impact absorber**—The concept of reducing impact forces and dissipating and dispersing impact loads is expanded to footwear with the introduction of a design study and homework problem involving a high heel shoe impact absorber.
- **Fasteners**—A design case study introduces a fastening device that is comprised of multiple components. A flexible slotted circular binding band in effect acts like a worm gear, and a thread screw member acts like a worm in driving the joined ends of the circular band. A new related homework problem provides the student with an opportunity to fully understand a related patent.
- **Suspension system**—A design study gives the student an opportunity to better understand a patented front and rear vehicle suspension system, and suspension related vehicle components.
- **Microscale and nanoscale machine elements**—A chapter contributed by Professor Cullinan presents a detailed study of micro–nano machine elements, such as mechanical sensors, actuators, and bearings that are used in microelectromechanical (MEMS) and nanoelectromechanical systems (NEMS).
- **Remote control racecars**—A design project case study authored by Professor Cullinan introduces readers to an exciting design-and-build racecar experience that involves design, analysis, experimentation, and evaluation, culminating with a student RC car race.
- **Appendix**—The appendices have been edited and condensed to focus on supplemental material that is most necessary for reference work with the textbook.

Part I

Although much of Part I of the text is a review of earlier courses, we would like to call attention to several particular sections.

- Sections 1.2, 1.3, and 1.4 deal with three of the broadest aspects of engineering—safety, ecology, and social significance. These are concerns to which today’s students are particularly responsive.
- Section 1.7 presents a methodology for solving machine component problems. Embodied in this methodology is a sample problem format that includes a restatement, solution, and comments for the problem under the headings: known, find, schematic, decisions, assumptions, analysis, and comments. *Decisions* are choices made by the designer. Since design is an iterative decision-making process of synthesis, whenever the heading “decisions” is utilized, a design problem is presented. If a solution is presented without decisions being made, the problem is one of analysis. The inclusion of the category “decisions” allows the student to see clearly the difference between design and analysis. Once appropriate decisions have been made, analysis can follow. *Assumptions*, which are used in solving a problem, are statements about beliefs; for example, the material is homogeneous throughout. The design engineer and the student need to understand what assumptions are made in solving a problem. The listing of assumptions provides more opportunities for students of machine design to “think before doing.” *Comments* present key aspects of the solution and discuss how better results might be obtained by making different design decisions, relaxing certain assumptions, and so on.
- Sections 1.8, 1.9, and 1.10 review fundamental energy relationships. Most students at this level need to gain insight and understanding concerning such basic matters as the relationship between work input to a rotating camshaft and work output at a translating follower, and the relationship between engine power, vehicle speed, and fuel consumption.
- Most teachers of Mechanical Engineering Design lament the weakness of their students in the area of free-body diagram analysis of loads. Unless the loading on a machine component is properly established, subsequent design or analysis is of little value. Section 2.2 is directed toward helping relieve this common deficiency and its associated problems.
- References are often an invaluable resource for the student as they provide in depth coverage of topics to which the text may only be able to devote a single paragraph. As such, *MIL-HDBK-17* is introduced to the student in Chapter 3 and *MIL-HDBK-5J* in Appendix F. These two references provide a wealth of pragmatic engineering knowledge regarding engineering materials and composites. The use of these volumes, along with the chapter references, has the ability to dramatically enhance a student’s knowledge base.
- An elementary treatment of residual stresses is included in Chapter 4. An understanding of the basic concepts involved is vital to modern stress analysis, particularly when fatigue is present.
- Castigliano’s method for determining elastic deflections and redundant reactions is included in Chapter 5. This method permits a ready solution to many problems not amenable to traditional elementary methods.
- Chapter 6 on Failure Theories, Safety Factors, Stress Intensity Factors, and Reliability includes introductory treatments of fracture mechanics and interference theory of statistical reliability prediction.
- Chapter 7 focuses on impact, which is also called shock, sudden, or impulsive loading.
- Chapter 8 contains a simplified, condensed, and introductory version of Fatigue Design and Fatigue Crack Growth. This chapter is particularly important, and represents primarily new material for most students.
- Chapter 9 deals with the various kinds of surface deterioration experienced by machine components. This is of great importance because more machine parts “fail” (cease to be suitable for performing their intended function) because of surface damage than from actual breakage.

Part II

Part II is concerned with the application of the fundamentals to specific machine components. In engineering practice, problems involving the design, analysis, or application of machine members can seldom be solved by applying the

fundamentals alone. As critically important as a knowledge of the underlying sciences is, it is seldom sufficient. Almost always some empirical information must be used, and good engineering judgment brought to bear. Actual engineering design problems seldom have only one correct answer. For example, engineering staffs of competing companies arrive at different product designs as solutions to the same problem. And these solutions change as new technology, new materials, new manufacturing methods, and new marketing conditions prevail. For many students, the course based on this text will provide their first experience in dealing with these kinds of professional engineering problems.

Most engineers find that this aspect of engineering adds to the interest and excitement of their profession. There is a close parallel between engineers and medical doctors in this respect: Both must solve real-life problems *now*, making full use of the best available scientific information. Engineers must design engines and build electronic apparatus even though scientists are still seeking a more complete knowledge of combustion and electricity. Similarly, medical doctors cannot tell their patients to await treatment until more research has been completed.

Even though the fundamentals treated in Part I are seldom *sufficient* for solving engineering problems relating to machine components, it is important that they be applied fully and consistently. In particular, a special effort has been made in Part II to deal with fatigue and surface considerations in a manner consistent with the treatment given in Chapters 8 and 9. This sometimes results in the development of procedures that vary in detail from those given in the specialized literature, but this discrepancy is not of major importance. What *is* of major importance is helping the student learn to approach engineering problems by applying the fundamentals and other scientific knowledge as extensively as possible, and then supplementing these with empirical data and judgment as required to get good solutions within available time limitations.

Few engineering schools allot sufficient time to cover all the machine components treated in Part II. In addition, many components are not treated in the book, and even more are not yet in existence. For these reasons, each component is treated not only as an end in itself, but also as a representative example of applying basic fundamentals and necessary empirical information to solve practical engineering problems.

Throughout Part II, the reader will find numerous instances in which ingenuity, insight, and imagination are called for in order to deal effectively with engineering problems associated with an individual machine component. The next step in the study of Mechanical Engineering Design usually involves the conception and design of a complete machine. As an introduction to this next step, the final two chapters of the book (Chapters 21 and 22), present (1) a case study of the design of the first commercially successful automotive automatic transmission, and (2) a case study of the design of remote control vehicles. These chapters can be found on the website for this text, <http://www.wiley.com/college/juvinall>. Here, as with numerous other designs of complete machines, one cannot help being impressed and inspired by the insights, ingenuity, and imagination (as well as the prolonged diligent effort) displayed by engineers and engineering students. Also illustrated in these case studies is the way that the design of any one component is often influenced by the design of related parts.

Because engineers will inevitably need to continue to deal with SI, British gravitational, and English engineering units, all three systems are used in the text and problems. Recalling the NASA/JPL Mars Climate Orbiter, where the root cause of the loss of the Orbiter spacecraft was the failed translation of English units into metric units in a segment of ground-base, navigation-related mission software, should help to remind the student just how important it is to understand and apply units properly.

ROBERT C. JUVINALL
KURT M. MARSHEK

ACKNOWLEDGMENTS

It is impossible to give adequate recognition to the many individuals who have contributed substantially to our own professional thinking reflected in this book. Five of the earliest of this distinguished group are Professor Robert R. Slaymaker and Professor Daniel K. Wright of Case Western Reserve University, Professor Ralph I. Stephens of the University of Iowa, Professor Ali Seireg of the University of Wisconsin–Madison, and Professor Walter L. Starkey of Ohio State University. We have often wondered how strongly our gravitating to the area of mechanical engineering design was influenced by the fact that we first studied the subject under outstanding engineers, superb teachers, and gentlemen whom we greatly admired. (Those of us in engineering education easily forget how much students are influenced by the character and the professional attitudes and practices of their instructors.)

We would like to recognize with sincere thanks the several engineering authorities who reviewed individual chapters of the first edition and offered valuable suggestions. Among these are Joseph Datsko (University of Michigan), Robert J. Finkelston (Standard Pressed Steel Co.), Robert Frayer (Federal Mogul Corp.), Alex Gomza (Grumman Aerospace Corp.), Evan L. Jones (Chrysler Corp.), Vern A. Phelps (University of Michigan), Robert R. Slaymaker (Case Western Reserve University), Gus S. Tayeh (New Departure Hyatt Bearings), Paul R. Trumpler (Trumpler Associates), Lew Wallace (Gleason Machine Div.), James E. West (FAG Bearings Corp.), Charles Williams (Federal Mogul Corp.), Ward O. Winer (Georgia Institute of Technology), and William Wood (Associated Spring Barnes Group). In addition to expressing our deep gratitude to these individuals, we would like to state clearly that the responsibility for each chapter is solely ours. If the reader finds errors, or points of view with which he or she disagrees, there should be no inference that these are due to anyone except the authors. Moreover, we would like to state that, while every effort has been made to ensure the accuracy and conformity with good engineering practice of all the material contained in this book, there is no guarantee, stated or implied, that mechanical components designed on the basis of this text will in all instances be proper and safe. Mechanical engineering design is sufficiently complex that its actual practice should always take advantage of the specialized literature in the area involved, the background of experience with related components, and, most importantly, appropriate tests to establish proper and safe performance in critical cases.

We would also like to express appreciation to Professors James Barber, Panos Papalambros, and Mohammed Zarrugh at the University of Michigan who made valuable suggestions as a result of teaching from preliminary versions of the first edition. Our thanks go as well to their students and to our students, who contributed important improvements. We would like to express particular thanks to Professor Emeritus Herbert H. Alvord of the University of Michigan who generously permitted us the use of his extensive collection of problems, which he developed for his own classes. We also thank Professors J. Darrell Gibson (Rose Hulman Institute of Technology), Donald A. Smith (University of Wyoming), and Petru-Aurelian Simionescu (Texas A&M—CC), and Professors Michael D. Bryant, Eric P. Fahrenthold, Kristin L. Wood, and Rui Huang at the University of Texas who offered valuable suggestions.

Appreciation is expressed to those who have reviewed this and previous editions: Kuang-Hua Chang, University of Oklahoma, Tim Dalrymple, University of Florida, Hamid Davoodi, North Carolina State University, Thomas Grimm, Michigan Technological University, Thomas Haas, Virginia Commonwealth University, Liwei Lin, University of California at Berkeley, Frank Owen, California Polytechnic State University, San Luis Obispo, Wendy Reffeor, Grand Valley State University, John Schueller, University of Florida, William Semke, University of North Dakota, Albert Shih, University of Michigan, Donald Smith, University of Wyoming, John Thacker, University of Virginia, and Raymond Yee, San Jose State University, Steve Daniewicz, Mississippi State University, Richard Englund, Penn State University, Ernst Kiesling, Texas Tech University, Edward R. Evans Jr., Penn State Erie, The Behrend College, Thomson R. Grimm, Michigan Technological University, Dennis Hong, Virginia Polytechnic Institute and State University, E. William Jones, Mississippi State University, Gloria Starns, Iowa State University, and Andreas Polycarpou, University of Illinois at Urbana–Champaign.

We would like to personally thank Professor Roger Bradshaw, University of Louisville, for contributing Appendix F as well as related sets of homework problems and solutions for Chapter 3 and Chapter 8, and Professor Krishnan Suresh, University of Wisconsin–Madison, for contributing Appendices G, H, I, and J.

Special thanks also to Professor Michael Cullian, the University of Texas at Austin, for authoring Chapter 20 and Chapter 22.

We deeply appreciate the understanding and encouragement of our wives, Arleene and Linda, during the preparation of this book, which preempted time belonging, by all reasonable standards, to important family and social activities.

SYMBOLS

A	area, cross-sectional area, arm of planetary gear	C_R	reliability factor
A	point A	c_p	volumetric specific heat
A_0	original unloaded cross-sectional area	C_{req}	required value of C
a	influence coefficient	C_s	surface factor
a, a	acceleration	D	diameter, mean coil diameter, velocity factor
a	crack depth, radius of contact area of two spheres	d	diameter, major diameter, nominal diameter, wire diameter
A_c	effective clamped area	d_{av}	average diameter
a_{cr}	critical crack depth	d_b	diameter of base circle
A_f	final area	d_c	collar (or bearing) diameter
A_r	area reduction	dc/dN	crack propagation rate
A_t	tensile stress area, tensile stress area of the thread	$(dc/dN)_o$	crack propagation rate at $(\Delta K)_o$
\bar{B}	actual backlash	d_g	pitch diameter of gear
b	section width, half width of contact area measured perpendicular to axes of two parallel contacting cylinders, gear face width, band width	d_i	minor diameter of the internal thread
C	spring index, overall heat transfer coefficient, rated load capacity, heat transfer coefficient, constant (material property)	d_m	mean diameter
C	specific heat	d_p	pitch diameter, pitch diameter of pinion
c	distance from the neutral axis to the extreme fiber, half of crack length, radial clearance, center distance, distance between shafts, crack length	d_r	root (or minor) diameter
\bar{c}	distance from the centroidal axis to the extreme inner fiber, actual distance between gear and pinion centers	E	modulus of elasticity, elastic proportionality constant, tensile elastic modulus
c_{cr}	critical crack length	E	modulus of elasticity (tension)
\overline{CR}	contact ratio	E_p	plastic strain
\overline{CR}	actual contact ratio	e	distance between the neutral axis and the centroidal axis, efficiency, eccentricity, train value, edge distance for joint, percent elongation at break
CG	center of gravity	e/D	edge margin
C_G	gradient factor or gradient constant	E_b	Young's modulus for the bolt
c_i	distance from the neutral axis to the extreme inner fiber	E_c	Young's modulus for clamped member, compression modulus of elasticity
C_L	load factor	E_s	secant modulus
C_{Li}	life factor	E_t	tangent modulus
c_o	distance from the neutral axis to the extreme outer fiber	F	force, compressive force between the surfaces
CP	center of aerodynamic pressure	f	relative hardenability effectiveness, coefficient of friction
C_p	elastic coefficient	\mathbf{F}, F	force
		F_a	axial force
		F_b	bolt axial load
		F_{bru}	bearing ultimate strength
		F_{bry}	bearing yield strength
		F_c	clamping force
		f_c	collar (or bearing) coefficient of friction
		F_d	drag force, dynamic load

F_{cy}	compression yield strength	K_{Ic}	critical stress intensity factor for tensile loading (mode I)
F_e	equivalent radial load, equivalent static force, external force	K_a	application factor
\mathbf{F}_{ext}	external force vector applied on a member	K_B	constant of proportionality
F_{ga}	gear axial force	k_b	spring constant for the bolt
F_{gr}	gear radial force	K_c	fracture toughness or critical stress intensity factor
F_{gt}	gear tangential force	k_c	spring constant for clamped members
F_i	initial tensile force, initial clamping force	KE	kinetic energy
\mathbf{F}_{int}	internal force vector at a cross-section	K_f	fatigue stress concentration factor
F_n	normal force	K_i	curvature factor for inner fiber, effective stress concentration factor for impact loading, constant used for calculating initial bolt-tightening force
f_n	natural frequency	K_m	mounting factor
F_r	radial load, radial force	K_{max}	stress intensity factor at σ_{max}
F_s	strength capacity	K_{min}	stress intensity factor at σ_{min}
F_{solid}	force when solid	k_{ms}	mean stress factor
F_{su}	shear ultimate strength	K_o	curvature factor for outer fiber, overload factor, critical stress intensity factor for infinite plate with central crack in uniaxial tension
F_t	thrust force, tendon force, tangential force, thrust load	K_r	life adjustment reliability factor
F_{tu}	tensile ultimate strength	k_r	reliability factor
F_{ty}	tensile yield strength	K_s	stress concentration factor for static loading
F_w	wear capacity	K_t	theoretical or geometric stress concentration factor
F_{wa}	worm axial force	k_t	temperature factor
F_{wr}	worm radial force	K_v	velocity or dynamic factor
F_{wt}	worm tangential force	K_w	Wahl factor, material and geometry factor
G	torsional or shear modulus of elasticity	L	length, contact length measured parallel to the axis of contacting cylinder, lead, length of weld, life corresponding to radial load F_r , or life required by the application, pitch cone length
g	gravitational acceleration or acceleration of gravity, grip length	L_0	original unloaded length
g_c	constant of proportionality, 32.2 lbfm-ft/lb-s ²	L_e	equivalent length
H	surface hardness, time rate of heat dissipation	L_f	final length, free length
h	section depth, height of fall, leg length, weld size, film thickness, height	L_R	life corresponding to rated capacity
h_0	minimum film thickness	L_s	solid height
H_B	Brinell hardness number	L, ST, LT	longitudinal direction, short transverse direction, long transverse direction
I	polar moment of inertia, moment of inertia, geometry factor, stress invariant	M	moment, internal bending moment, bending moment
i	integer	M_0	redundant moment
I_x	moment of inertia about x axis	m	mass, strain-hardening exponent, module (used only with SI or metric units)
J	polar moment of inertia, spur gear geometry factor	m'	mass per unit length of belt
K	curvature factor, spring rate for angular deflection, stress intensity factor, wear coefficient	\mathbf{M}_{ext}	external moment vector applied on a member
k	spring rate, thermal conductivity, spring rate for linear deflection, number of standard deviations, shaft spring rate	M_f	moment of friction forces
K	thermal conductivity		
K'	section property		
K_I	stress intensity factor for tensile loading (mode I)		

\mathbf{M}_{int}	generalized internal moment vector at a cross-section	r	radius, reliability
M_n	moment of normal forces	\bar{r}	radial distance to the centroidal axis
N	fatigue life, total normal load, number of active coil turns, number of teeth, number of friction interfaces, number of cycles	$r_{a(\text{max})}$	maximum noninterfering addendum circle radius of pinion or gear
n	rotating speed, number of cycles, normal force, number of equally spaced planet gears, index (subscript), Ramberg-Osgood parameter	$r_{\text{ag}}^{\text{max}}$	maximum allowable addendum radius on the gear to avoid interference
N'	virtual number of teeth	$r_{\text{ap}}^{\text{max}}$	maximum allowable addendum radius on the pinion to avoid interference
N.A.	neutral axis	$r_{\text{ap}}, r_{\text{ag}}$	addendum radii of the mating pinion and gear
n_c	critical speed	r_b	base circle radius, back cone radius
N_e	number of teeth	$r_{\text{bp}}, r_{\text{bg}}$	base circle radii of the mating pinion and gear
N_t	total number of turns, number of teeth in the sprocket	r_c	chordal radius
P	load, cumulative probability of failure, bearing unit load, average film pressure, radial load per unit of projected bearing area, pitch point, diametral pitch (used only with English units), diameter or number of teeth of planet, band force, load (force), uniform load	r_f	friction radius
\bar{P}	actual pitch	\bar{r}_g	actual pitch radius of gear
p	frequency of occurrence, probability of failure, surface interface pressure, pitch, film pressure, circular pitch, uniform level of interface pressure, pressure	r_i	inner radius
\bar{p}	actual circular pitch	\bar{r}_p	actual pitch radius of pinion
p_0	maximum contact pressure	R_m	modulus of resilience
p_a	axial pitch	r_n	radial distance to the neutral axis
p_b	base pitch	r_o	outer radius
P_c	tension created by centrifugal force	S	linear displacement, total rubbing distance, Saybolt viscometer measurement in seconds, bearing characteristic number or Sommerfeld variable, diameter or number of teeth of sun gear, slip
P_{cr}	critical load	S_{cr}	critical unit load
PE	potential energy	S_e	elastic limit
p_{max}	allowable pressure, maximum normal pressure	S_{eq}	equivalent stress—see Table F.4
p_n	circular pitch measured in a plane normal to the teeth	SF	safety factor
Q	heat energy transferred to the system, load, total tangential force, flow rate, mass flow rate	S_{fe}	surface fatigue strength
q	number of revolutions, notch sensitivity factor, tangential force	S_H	surface endurance strength
Q_f	volume of lubricant per-unit time flowing across	S–N	fatigue stress versus cycles
Q_s	side leakage rate	S_{max}	maximum fatigue cycle stress—see Table F.4
R	radius, transmission speed ratio, area ratio, radius of curvature, diameter or number of teeth of ring or annulus gear, ratio of gear and pinion diameter, load ratio, fatigue cycle stress ratio	S_n	endurance limit
		S'_n	standard fatigue strength for rotating bending proof load (strength)
		S_p	shear yield strength
		S_{sy}	shear yield strength
		S_u	ultimate strength, ultimate tensile strength
		S_{uc}	ultimate strength in compression
		S_{us}	ultimate shear strength, ultimate torsional shear strength
		S_{ut}	ultimate strength in tension
		S_y	yield strength
		S_{yc}	yield strength in compression
		S_{yt}	yield strength in tension
		T	torque, brake torque, band brake torque
		t	time, thickness, nut thickness, throat length
		T_a	alternating torque
		t_a	air temperature, ambient air temperature
		T_e	equivalent static torque

T_f	friction torque	α_2	normalized crack size at c_2
T_m	modulus of toughness, mean torque	α_n	thread angle measured in the normal plane
t_o	average oil film temperature, oil temperature	Δ	deflection, material parameter important in computing contact stress
t_s	average temperature of heat-dissipating surfaces	δ, δ	deflection
U	stored elastic energy, impact kinetic energy, laminar flow velocity	δ	linear deflection, wear depth
U'	complementary energy	ΔA	change in area
V	internal transverse shear force, shear force, volume	ΔE	change in total energy of the system
V, V	linear velocity, gear pitch line velocity	ΔKE	change in kinetic energy of the system
v	velocity at impact, sliding velocity	ΔK	stress intensity range
V_{60}	cutting speed in feet per minute for 60-min tool life under standard cutting conditions	ΔK_o	stress intensity range at the point o
V_{av}	average velocity	ΔL	change in length
V_g	gear tangential velocity, pitch line velocity of the gear	ΔPE	change in gravitational potential energy of the system
V_{gt}	velocity of gear at contact point in tangent direction	ΔN_{12}	number of cycles during crack growth from c_1 to c_2
V_{pt}	velocity of pinion at contact point in tangent direction	δ_s	solid deflection
V_{gn}	velocity of gear at contact point in normal direction	δ_{st}	deflection caused by static loading (static deflection)
V_{pn}	velocity of pinion at contact point in normal direction	ΔT	temperature change
V_s	sliding velocity	ΔU	change in internal energy of the system
V_w	worm tangential velocity	λ	lead angle, helix angle, ratio of actual to ideal distance between gear and pinion centers
W	work done, weight, volume of material worn away, total axial load	ϕ	angle between the principal axes and the x and y axes, angle giving position of minimum film thickness, pressure angle, angle of wrap
\dot{W}	power	ϕ_n	pressure angle measured in a plane normal to the teeth
w	load, load intensity, gravitational force, width	$\bar{\phi}$	actual pressure angle
Y	Lewis form factor based on diametral pitch or module, configuration factor	γ	pitch cone angle
y	distance from the neutral axis, Lewis form factor	$\gamma_{xy}, \gamma_{xz}, \gamma_{yz}$	shear strains
Y_{cr}	configuration factor at critical crack size	μ	mean, viscosity
Z	section modulus	μ	Poisson's ratio—see Appendix F
		ν	Poisson's ratio
		ϵ	normal strain
		$\epsilon_1, \epsilon_2, \epsilon_3$	principal strains
		ϵ_f	strain at fracture
		ϵ_p	plastic strain
		ϵ_T	"true" normal strain
		ϵ_{Tf}	true normal strain at fracture
		$\epsilon_x, \epsilon_y, \epsilon_z$	normal strains
		θ	angular displacement, angular deflection, slope
		$\theta_{p_{max}}$	position of maximum film pressure
		ρ	mass density, radial distance
		σ	normal stress, standard deviation, uniform uniaxial tensile stress

Greek Letters

α	angular acceleration, coefficient of thermal expansion, angles measured clockwise positive from the 0° gage to the principal strain axes numbers 1 and 2, factor by which the compressive strength is reduced through buckling tendencies, thread angle, contact angle, cone angle, normalized crack size
α_{cr}	normalized critical crack size
α_1	normalized crack size at c_1