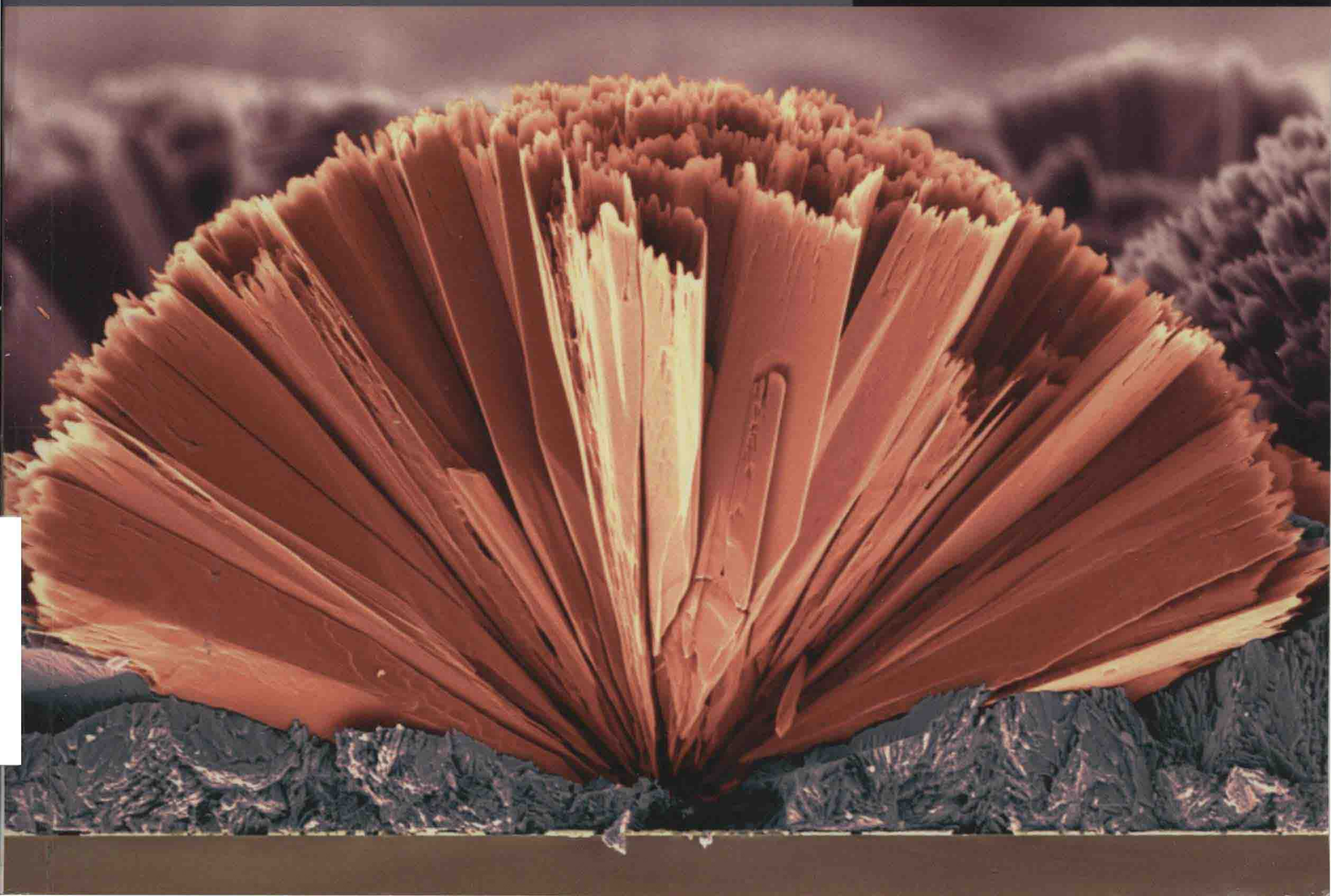
SI EDITION

SEVENTH EDITION

THE SCIENCE AND ENGINEERING OF MATERIALS

DONALD R. ASKELAND

WENDELIN J. WRIGHT



The Science and Engineering of Materials

Seventh Edition, SI

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Donald R. Askeland and Wendelin J. Wright

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CONVERSIONS BETWEEN U.S. CUSTOMARY UNITS AND SI UNITS

U.S. Customary unit		Times conversion factor		Equals SI unit	
		Accurate	Practical		
Acceleration (linear)					
foot per second squared	ft/s^2	0.3048*	0.305	meter per second squared	m/s^2
inch per second squared	$in./s^2$	0.0254*	0.0254	meter per second squared	m/s^2
Area					
square foot	ft^2	0.09290304*	0.0929	square meter	m^2
square inch	$in.^2$	645.16*	645	square millimeter	mm^2
Density (mass)					
slug per cubic foot	$slug/ft^3$	515.379	515	kilogram per cubic meter	kg/m^3
Density (weight)					
pound per cubic foot	lb/ft^3	157.087	157	newton per cubic meter	N/m^3
pound per cubic inch	$lb/in.^3$	271.447	271	kilonewton per cubic meter	kN/m^3
Energy; work					
foot-pound	ft-lb	1.35582	1.36	joule (N·m)	J
inch-pound	in.-lb	0.112985	0.113	joule	J
kilowatt-hour	kWh	3.6*	3.6	megajoule	MJ
British thermal unit	Btu	1055.06	1055	joule	J
Force					
pound	lb	4.44822	4.45	newton ($kg \cdot m/s^2$)	N
kip (1000 pounds)	k	4.44822	4.45	kilonewton	kN
Force per unit length					
pound per foot	lb/ft	14.5939	14.6	newton per meter	N/m
pound per inch	lb/in.	175.127	175	newton per meter	N/m
kip per foot	k/ft	14.5939	14.6	kilonewton per meter	kN/m
kip per inch	k/in.	175.127	175	kilonewton per meter	kN/m
Length					
foot	ft	0.3048*	0.305	meter	m
inch	in.	25.4*	25.4	millimeter	mm
mile	mi	1.609344*	1.61	kilometer	km
Mass					
slug	$lb\text{-}s^2/ft$	14.5939	14.6	kilogram	kg
Moment of a force; torque					
pound-foot	lb-ft	1.35582	1.36	newton meter	N·m
pound-inch	lb-in.	0.112985	0.113	newton meter	N·m
kip-foot	k-ft	1.35582	1.36	kilonewton meter	kN·m
kip-inch	k-in.	0.112985	0.113	kilonewton meter	kN·m

CONVERSIONS BETWEEN U.S. CUSTOMARY UNITS AND SI UNITS (Continued)

U.S. Customary unit		Times conversion factor		Equals SI unit	
		Accurate	Practical		
Moment of inertia (area)					
inch to fourth power	in.^{4}	416,231	416,000	millimeter to fourth power	mm^4
inch to fourth power	in.^{4}	0.416231×10^{-6}	0.416×10^{-6}	meter to fourth power	m^4
Moment of inertia (mass)					
slug foot squared	slug-ft^2	1.35582	1.36	kilogram meter squared	kg·m^2
Power					
foot-pound per second	ft-lb/s	1.35582	1.36	watt (J/s or N·m/s)	W
foot-pound per minute	ft-lb/min	0.0225970	0.0226	watt	W
horsepower (550 ft-lb/s)	hp	745.701	746	watt	W
Pressure; stress					
pound per square foot	psf	47.8803	47.9	pascal (N/m^2)	Pa
pound per square inch	psi	6894.76	6890	pascal	Pa
kip per square foot	ksf	47.8803	47.9	kilopascal	kPa
kip per square inch	ksi	6.89476	6.89	megapascal	MPa
Section modulus					
inch to third power	in.^{3}	16,387.1	16,400	millimeter to third power	mm^3
inch to third power	in.^{3}	16.3871×10^{-6}	16.4×10^{-6}	meter to third power	m^3
Velocity (linear)					
foot per second	ft/s	0.3048*	0.305	meter per second	m/s
inch per second	in./s	0.0254*	0.0254	meter per second	m/s
mile per hour	mph	0.44704*	0.447	meter per second	m/s
mile per hour	mph	1.609344*	1.61	kilometer per hour	km/h
Volume					
cubic foot	ft^3	0.0283168	0.0283	cubic meter	m^3
cubic inch	in.^{3}	16.3871×10^{-6}	16.4×10^{-6}	cubic meter	m^3
cubic inch	in.^{3}	16.3871	16.4	cubic centimeter (cc)	cm^3
gallon (231 in.^{3})	gal.	3.78541	3.79	liter	L
gallon (231 in.^{3})	gal.	0.00378541	0.00379	cubic meter	m^3

*An asterisk denotes an *exact* conversion factor

***Note:* To convert from SI units to USCS units, *divide* by the conversion factor**

Temperature Conversion Formulas

$$T(°C) = \frac{5}{9}[T(°F) - 32] = T(K) - 273.15$$

$$T(K) = \frac{5}{9}[T(°F) - 32] + 273.15 = T(°C) + 273.15$$

$$T(°F) = \frac{9}{5}T(°C) + 32 = \frac{9}{5}T(K) - 459.67$$

To Mary Sue and Tyler
–Donald R. Askeland

To John, my love
–Wendelin J. Wright

PREFACE

The copper age, the iron age, the silicon age . . . eras defined by the materials found in nature, but manipulated by the engineers of their day. The fundamental principles of structure, defects, kinetics, and processing are generally applicable to all materials, while over time our understanding has advanced and incorporated new ideas. As a result, the observable and macroscopic behavior of materials, spanning such varied characteristics as mechanical strength and toughness, electrical conductivity, refractive index, and corrosion resistance, is both understood more deeply and related more directly to underlying atomic-level phenomena.

Our tools for characterizing and manipulating materials have also grown vastly more sophisticated, allowing for deeper insights into materials structures and phenomena. At the edge of innovation we find the discovery—or even the creation—of entirely new materials, often made possible by new processing techniques, by circumventing equilibrium to cause materials to exist in metastable states, and by developing the tools to assemble, form, and study materials at the nanoscale. It is now routine, for instance, to examine materials at the near-atomic level for both structure and composition, using techniques such as high resolution transmission electron microscopy, grazing incidence x-ray diffraction, and electron energy loss spectroscopy. At the same time, materials processing has advanced to the point where thin films just a few atomic layers thick can in many instances be grown or deposited, while three-dimensional structures with dimensions of only a few tens of nanometers or less can also be manufactured. The entire electronics industry, for instance, is based on these types of advances. Flat screen televisions, high-speed wireless data systems, portable computation and telecommunication devices, automobiles and other transportation systems . . . these and countless other technologies are all dependent on our contemporary understanding of materials.

While not all students who study materials science will be practicing materials engineers, most engineers will in fact work with a diverse materials set, comprising metals, ceramics, plastics, composites, and semiconductors, and across lengths scales from the nanoscale to the macroscale, all within a context of myriad and diverse applications. Materials are an enabling component of what engineers imagine, design, and build. The ability to *innovate* and to incorporate materials *safely* in a design is rooted in an understanding of how to manipulate materials properties and functionality through the control of materials structure and processing techniques. The objective of this textbook, then, is to describe the foundations and applications of materials science for college-level engineering students as predicated upon the structure-processing-properties paradigm.

The challenge of any textbook is to provide the proper balance of breadth and depth for the subject at hand, to provide rigor at the appropriate level, to provide meaningful examples and up to date content, and to stimulate the intellectual excitement of the reader. Our goal here is to provide enough *science* so that the reader may understand basic materials phenomena, and enough *engineering* to prepare a wide range of students for competent professional practice.

Cover Art

The cover art for the seventh edition of the text is a scanning electron microscope image showing two-dimensional (2-D) layers of Ti_3C_2, which were formed by selectively extracting Al from Ti_3AlC_2. Ti_3C_2 is a member of a new family of 2-D materials called MXenes, which was first discovered at Drexel University in 2011. Single and multilayer MXenes show attractive properties, such as a combination of metallic conductivity within the carbide layer and hydrophilicity of the oxygen terminated surface. MXenes comprise a growing family of 2-D materials with great promise in many applications, such as batteries and supercapacitor electrodes, transparent conducting coatings, and composite reinforcement. The width of the image is about 20 μm. The color is false; it has been added for artistic effect. The image is titled "The Cliff of the Two-Dimensional World" by Babak Anasori, Michael Naguib, Yury Gogotsi, and Michel W. Barsoum from the Department of Materials Science and Engineering and A. J. Drexel Nanotechnology Institute at Drexel University.

Audience and Prerequisites

This text is intended for an introductory science of materials class taught at the sophomore or junior level. A first course in college level chemistry is assumed, as is some coverage of first year college physics. A calculus course is helpful, but certainly not required. The text does not presume that students have taken other introductory engineering courses such as statics, dynamics, or mechanics of materials.

New to this Edition

The beginning of each chapter includes learning objectives to guide students in their studies. New problems have been added to the end of each chapter to increase the number of problems by 15%. The breadth of Chapter 15 on ceramic materials has been extended to include crystalline ceramics, silica and silicate compounds, and other topics of interest to provide a more comprehensive view of this important class of engineering materials. Other portions of the chapter have been revised for clarity. The cost of common engineering materials in Chapter 14 has been updated. As always, we have taken great care to provide the most error-free text possible.

Knovel™ Problems

At the conclusion of the end of chapter problems, you will find a special section with problems that require the use of Knovel (**www.knovel.com**). Knovel is an online aggregator of engineering references including handbooks, encyclopedias, dictionaries, textbooks, and databases from leading technical publishers and engineering societies such as the American Society of Mechanical Engineers (ASME) and the American Institute of Chemical Engineers (AIChE).

The Knovel problems build on material found in the textbook and require familiarity with online information retrieval. The problems are also available online at **www.cengage.com/engineering.** In addition, the solutions are accessible by registered instructors. If your institution does not have a subscription to Knovel or if you have any questions about Knovel, please contact

support@knovel.com
(210) 340-1944
(866) 324-5163

The Knovel problems were created by a team of engineers led by Sasha Gurke, senior vice president and co-founder of Knovel.

Supplements for the Instructor

Supplements to the text include the Instructor's Solutions Manual that provides complete solutions to selected problems and annotated Powerpoint™ slides.

MindTap

This textbook is also available online through Cengage Learning's MindTap, a personalized learning program. Students who purchase the MindTap version have access to the book's MindTap Reader and are able to complete homework and assessment material online, through their desktop, laptop, or iPad. If you are using a Learning Management System (such as Blackboard or Moodle) for tracking course content, assignments, and grading, you can seamlessly access the MindTap suite of content and assessments for this course.

In MindTap, instructors can:

- Personalize the Learning Path to match the course syllabus by rearranging content or appending original material to the online content.
- Connect a Learning Management System portal to the online course and Reader
- Customize online assessments and assignments
- Track student progress and comprehension
- Promote student engagement through interactivity and exercises

Additionally, students can listen to the text through ReadSpeaker, take notes, create their own flashcards, highlight content for easy reference, and check their understanding of the material through practice quizzes and homework.

Acknowledgments

We thank all those who have contributed to the success of past editions and also the reviewers who provided detailed and constructive feedback on the sixth edition:

Cynthia W. Barnicki, Milwaukeee School of Engineering

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Stephen W. Stafford, University of Texas, El Paso

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We are grateful to the team at Cengage Learning who has carefully guided this seventh edition through all stages of the publishing process. In particular, we thank Timothy Anderson, publisher for Global Engineering; Eavan Cully and Hilda Gowans, development editors; Rose Kernan, production editor; Kristiina Paul, permissions and photo researcher; Ashley Kaupert, media assistant; and Sam Roth, team assistant. We also thank Stephen Stafford and Keith McIver for new end of chapter problems in this edition.

Wendelin Wright thanks Briana King and Joanne Mowen for their assistance during the revision process as well as John Bravman of Bucknell University for his feedback, contributed illustrations, patience, and constant support.

Donald R. Askeland
University of Missouri — Rolla, Emeritus

Wendelin J. Wright
Bucknell University

PREFACE TO THE SI EDITION

This edition of *The Science and Engineering of Materials* has been adapted to incorporate the International System of Units (*Le Système International d'Unités* or SI) throughout the book.

Le Système International d'Unités

The United States Customary System (USCS) of units uses FPS (foot–pound–second) units (also called English or Imperial units). SI units are primarily the units of the MKS (meter–kilogram–second) system. However, CGS (centimeter–gram–second) units are often accepted as SI units, especially in textbooks.

Using SI Units in this Book

In this book, we have used both MKS and CGS units. USCS units or FPS units used in the US Edition of the book have been converted to SI units throughout the text and problems. However, in case of data sourced from handbooks, government standards, and product manuals, it is not only extremely difficult to convert all values to SI, it also encroaches upon the intellectual property of the source. Some data in figures, tables, and references, therefore, remains in FPS units. For readers unfamiliar with the relationship between the FPS and the SI systems, a conversion table has been provided inside the front cover.

To solve problems that require the use of sourced data, the sourced values can be converted from FPS units to SI units just before they are to be used in a calculation. To obtain standardized quantities and manufacturers' data in SI units, the readers may contact the appropriate government agencies or authorities in their countries/regions.

Instructor Resources

The Instructors' Solution Manual in SI units is available through your Sales Representative or online through the book website at **www.login.cengage.com**. A digital version of the ISM and PowerPoint slides of figures, tables, and examples and equations from the SI text are available for instructors registering on the book website.

Feedback from users of this SI Edition will be greatly appreciated and will help us improve subsequent editions.

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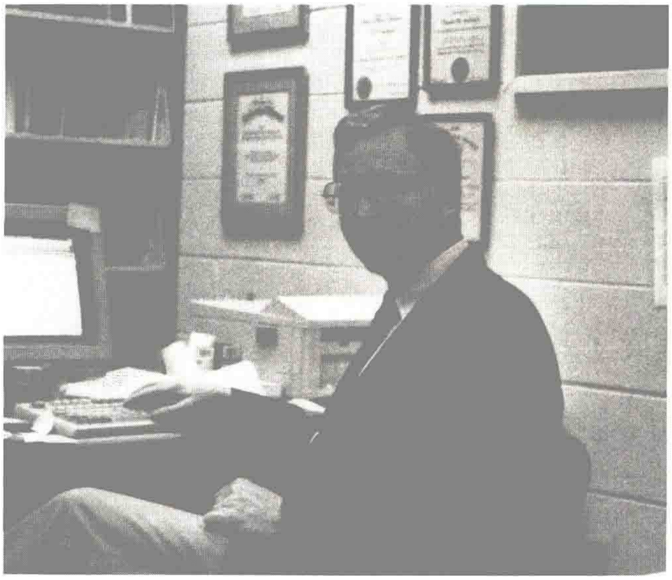
ABOUT THE AUTHORS



Donald R. Askeland is a Distinguished Teaching Professor Emeritus of Metallurgical Engineering at the University of Missouri–Rolla. He received his degrees from the Thayer School of Engineering at Dartmouth College and the University of Michigan prior to joining the faculty at the University of Missouri–Rolla in 1970. Dr. Askeland taught a number of courses in materials and manufacturing engineering to students in a variety of engineering and science curricula. He received a number of awards for excellence in teaching and advising at UMR. He served as a Key Professor for the Foundry Educational Foundation and received several awards for his service to that organization. His teaching and research were directed primarily to metals casting and joining, in particular lost foam casting, and resulted in over 50 publications and a number of awards for service and best papers from the American Foundry Society.

Wendelin Wright is an associate professor at Bucknell University with a joint appointment in the departments of Mechanical Engineering and Chemical Engineering. She received her B.S., M.S., and Ph.D. in Materials Science and Engineering from Stanford University. Following graduation, she served a post–doctoral term at the Lawrence Livermore National Laboratory in the Manufacturing and Materials Engineering Division and then returned to Stanford as an Acting Assistant Professor in 2005. She joined the Santa Clara University faculty in 2006 as a tenure-track assistant professor and assumed her position at Bucknell in the fall of 2010.

Professor Wright's research interests focus on the mechanical behavior of materials, particularly of metallic glasses. She is the recipient of the 2003 Walter J. Gores Award for Excellence in Teaching, which is Stanford University's highest teaching honor, a 2005 Presidential Early Career Award for Scientists and Engineers, and a 2010 National Science Foundation CAREER Award. Professor Wright is a licensed professional engineer in metallurgy in California. She is married to John Bravman and is the mother of two young sons, Cole and Cooper.

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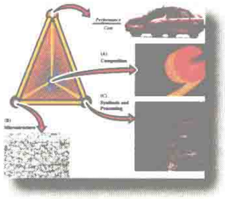

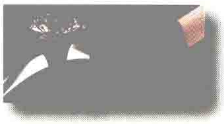

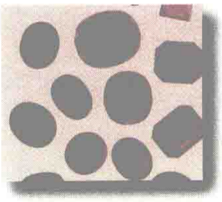

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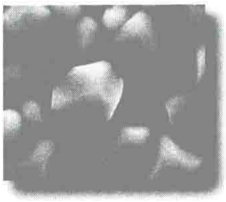

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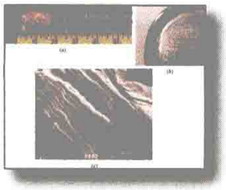

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