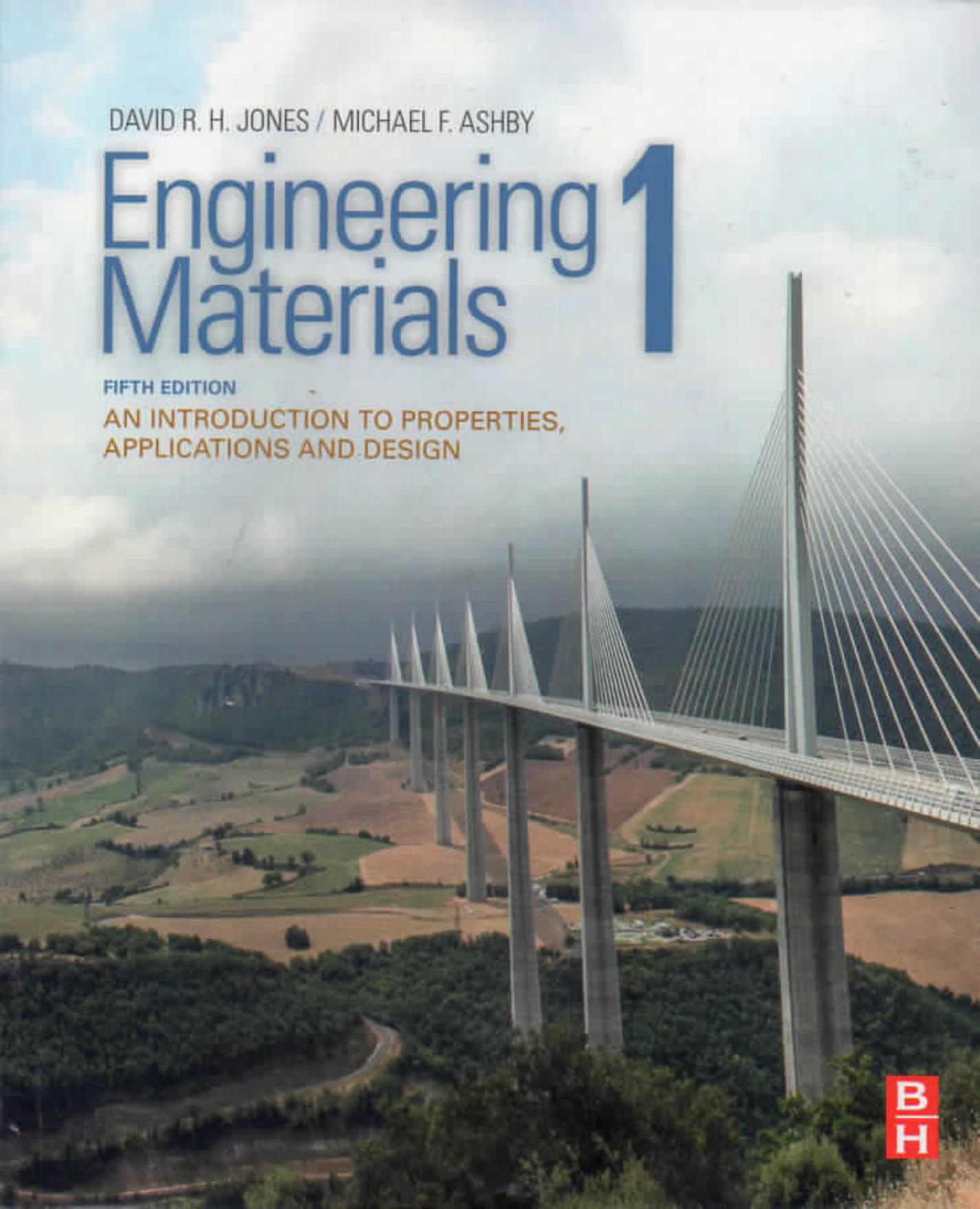


DAVID R. H. JONES / MICHAEL F. ASHBY

# Engineering Materials 1

FIFTH EDITION

AN INTRODUCTION TO PROPERTIES,  
APPLICATIONS AND DESIGN



B  
H

# **Engineering Materials 1**

**An Introduction to Properties,  
Applications and Design**

**Fifth Edition**

**David R. H. Jones**

Former President, Christ's College  
Cambridge

**Michael F. Ashby**

Royal Society Research Professor Emeritus,  
University of Cambridge and Former Visiting  
Professor of Design at the Royal college  
of Art, London



Butterworth-Heinemann  
An imprint of Elsevier

# Contents

<b>PREFACE TO FIFTH EDITION .....</b>	xv	
<b>ACKNOWLEDGMENTS .....</b>	xvii	
<b>GENERAL INTRODUCTION .....</b>	xix	
<b>CHAPTER 1</b>	<b>Engineering Materials and Their Properties .....</b>	<b>1</b>
1.1	Introduction .....	1
1.2	Examples of Materials Selection .....	2
<b>PART A</b>	<b>Price and Availability</b>	
<b>CHAPTER 2</b>	<b>Price and Availability of Materials .....</b>	<b>15</b>
2.1	Introduction .....	15
2.2	Data for Material Prices .....	15
2.3	Use-pattern of Materials .....	18
2.4	Ubiquitous Materials .....	19
2.5	Exponential Growth and Doubling-Time .....	20
2.6	Resource Availability .....	22
2.7	The future .....	23
2.8	Conclusion .....	24
Worked Example .....	25	
Examples .....	26	
Answers .....	27	
<b>PART B</b>	<b>Elastic Moduli</b>	
<b>CHAPTER 3</b>	<b>Elastic Moduli .....</b>	<b>31</b>
3.1	Introduction .....	31
3.2	Definition of Stress .....	33
3.3	Definition of Strain .....	36
3.4	Hooke's Law .....	38
3.5	Measurement of Young's Modulus .....	38
3.6	Data for Young's Modulus .....	39

Worked Example 1.....	43
Worked Example 2.....	44
Examples.....	45
Answers.....	46
<b>CHAPTER 4</b>	
Bonding between Atoms.....	49
4.1 Introduction.....	49
4.2 Primary Bonds .....	50
4.3 Secondary Bonds .....	55
4.4 Condensed States of Matter.....	56
4.5 Interatomic Forces .....	57
Examples.....	58
Answers.....	60
<b>CHAPTER 5</b>	
Packing of Atoms in Solids.....	63
5.1 Introduction.....	63
5.2 Atom Packing in Crystals .....	63
5.3 Close-Packed Structures and Crystal Energies.....	64
5.4 Crystallography.....	66
5.5 Plane Indices.....	68
5.6 Direction Indices .....	69
Worked Example 1 .....	70
5.7 Other Crystal Structures .....	71
Worked Example 2 .....	71
5.8 Atom Packing in Polymers .....	73
5.9 Atom Packing in Inorganic Glasses.....	74
5.10 Density of Solids .....	76
Examples.....	78
Answers.....	79
<b>CHAPTER 6</b>	
Physical Basis of Young's Modulus.....	83
6.1 Introduction.....	83
6.2 Moduli of Crystals.....	83
6.3 Rubbers and Glass Transition Temperature .....	86
6.4 Composites .....	87
Worked Example .....	90
Examples.....	92
Answers.....	93
<b>CHAPTER 7</b>	
Applications of Elastic Deformation.....	95
7.1 Introduction.....	95
7.2 Bending .....	96
Worked Example 1 .....	97
7.3 Vibration .....	98

	Worked Example 2 .....	99
<b>7.4</b>	Buckling .....	99
	Worked Example 3 .....	100
<b>7.5</b>	Stress and Strain in Three Dimensions .....	100
	Examples .....	103
	Answers .....	106
	Bending of Beams .....	108
	Second Moments of Area .....	109
	Vibration of Beams .....	111
	Buckling of Beams .....	112
<b>CHAPTER 8</b>	Case Studies in Modulus-Limited Design .....	115
<b>8.1</b>	Case Study 1: Selecting Materials for Racing Yacht Masts .....	115
<b>8.2</b>	Case Study 2: Designing a Mirror for a Large Reflecting Telescope .....	118
<b>8.3</b>	Case Study 3: The Challenger Space Shuttle Disaster .....	122
	Worked example .....	128
	Examples .....	129
	Answers .....	131
<b>PART C</b>	<b>Yield Strength, Tensile Strength, and Ductility</b>	
<b>CHAPTER 9</b>	Yield Strength, Tensile Strength, and Ductility .....	137
<b>9.1</b>	Introduction .....	137
<b>9.2</b>	Linear and Nonlinear Elasticity .....	138
<b>9.3</b>	Load-Extension Curves for Nonelastic (Plastic) Behavior .....	139
<b>9.4</b>	True Stress-Strain Curves for Plastic Flow .....	141
<b>9.5</b>	Plastic Work .....	143
<b>9.6</b>	Tensile Testing .....	143
<b>9.7</b>	Data .....	145
	Worked Example .....	145
	Examples .....	149
	Answers .....	151
	Revision of Terms and Useful Relations .....	153
<b>CHAPTER 10</b>	Dislocations and Yielding in Crystals .....	157
<b>10.1</b>	Introduction .....	157
<b>10.2</b>	Strength of a Perfect Crystal .....	157
<b>10.3</b>	Dislocations in Crystals .....	159
<b>10.4</b>	Force Acting on a Dislocation .....	162
<b>10.5</b>	Other Properties of Dislocations .....	165
	Examples .....	167
	Answers .....	167

<b>CHAPTER 11</b>	Strengthening and Plasticity of Polycrystals .....	169
11.1	Introduction .....	169
11.2	Strengthening Mechanisms .....	170
11.3	Solid Solution Hardening .....	170
11.4	Precipitate and Dispersion Strengthening .....	170
11.5	Work-Hardening .....	172
11.6	Dislocation Yield Strength .....	173
11.7	Yield in Polycrystals .....	173
11.8	Final Remarks .....	176
	Examples .....	177
	Answers .....	177
<b>CHAPTER 12</b>	Continuum Aspects of Plastic Flow .....	179
12.1	Introduction .....	179
12.2	Onset of Yielding and Shear Yield Strength, $K$ .....	180
12.3	Analyzing the Hardness Test .....	182
12.4	Plastic Instability: Necking in Tensile Loading .....	183
	Worked Example .....	187
	Examples .....	188
	Answers .....	190
	Plastic Bending of Beams, Torsion of Shafts,	
	Buckling of Struts .....	191
<b>CHAPTER 13</b>	Case Studies in Yield-Limited Design .....	195
13.1	Introduction .....	195
13.2	Case Study 1: Elastic Design—Materials for Springs .....	195
	Worked Example .....	198
13.3	Case Study 2: Plastic Design—Materials for Pressure	
	Vessels .....	200
13.4	Case Study 3: Large-Strain Plasticity—Metal Rolling .....	202
	Examples .....	203
	Answers .....	206
<b>PART D</b>	<b>Fast Fracture, Brittle Fracture, and Toughness</b>	
<b>CHAPTER 14</b>	Fast Fracture and Toughness .....	211
14.1	Introduction .....	211
14.2	Energy Criterion for Fast Fracture .....	211
	Worked example .....	212
14.3	Data for $G_c$ and $K_c$ .....	218
	Examples .....	221
	Answers .....	224
	$Y$ Values .....	225
	$K$ Conversions .....	230

<b>CHAPTER 15</b>	Micromechanisms of Fast Fracture.....	231
15.1	Introduction.....	231
15.2	Mechanisms of Crack Propagation 1: Ductile Tearing.....	232
15.3	Mechanisms of Crack Propagation 2: Cleavage .....	234
15.4	Composites, Including Wood .....	236
15.5	Avoiding Brittle Alloys .....	237
Worked Example.....	238	
Examples.....	239	
Answers .....	244	
<b>CHAPTER 16</b>	Fracture Probability of Brittle Materials .....	247
16.1	Introduction.....	247
16.2	Statistics of Strength .....	248
16.3	Weibull Distribution .....	250
Worked Example 1.....	252	
Worked Example 2.....	253	
16.4	Modulus of Rupture .....	254
Worked Example 3.....	255	
Worked Example 4.....	256	
Examples.....	257	
Answers .....	259	
<b>CHAPTER 17</b>	Case Studies in Fracture.....	261
17.1	Introduction.....	261
17.2	Case Study 1: Fast Fracture of an Ammonia Tank.....	261
17.3	Case Study 2: Explosion of a Perspex Pressure Window during Hydrostatic Testing .....	265
17.4	Case Study 3: Cracking of a Foam Jacket on a Liquid Methane Tank .....	267
Worked Example .....	272	
Examples.....	276	
Answers .....	278	
<b>PART E</b>	<b>Fatigue Failure</b>	
<b>CHAPTER 18</b>	Fatigue Failure.....	283
18.1	Introduction.....	283
18.2	Fatigue of Uncracked Components.....	283
18.3	Fatigue of Cracked Components.....	288
18.4	Fatigue Mechanisms.....	290
Worked Example 1.....	293	
Worked Example 2.....	294	
Examples.....	295	
Answers .....	298	

<b>CHAPTER 19</b>	Fatigue Design .....	301
19.1	Introduction .....	301
19.2	Fatigue Data for Uncracked Components .....	302
19.3	Stress Concentrations .....	302
19.4	Notch Sensitivity Factor .....	303
19.5	Fatigue Data for Welded Joints .....	305
19.6	Fatigue Improvement Techniques .....	307
19.7	Designing Out Fatigue Cycles .....	307
	Worked Example .....	310
	Examples .....	312
	Answers .....	322
<b>CHAPTER 20</b>	Case Studies in Fatigue Failure .....	325
20.1	Case Study 1: The Comet Air Disasters .....	325
20.2	Case Study 2: The Eschede Railway Disaster .....	331
20.3	Case Study 3: Safety of the Streatham Engine .....	336
	Examples .....	339
	Answers .....	345
<b>PART F Creep Deformation and Fracture</b>		
<b>CHAPTER 21</b>	Creep and Creep Fracture .....	351
21.1	Introduction .....	351
21.2	Creep Testing and Creep Curves .....	355
21.3	Creep Relaxation .....	358
21.4	Creep Damage and Creep Fracture .....	360
21.5	Creep-Resistant Materials .....	361
	Worked Example .....	362
	Examples .....	363
	Answers .....	365
<b>CHAPTER 22</b>	Kinetic Theory of Diffusion .....	367
22.1	Introduction .....	367
22.2	Diffusion and Fick's Law .....	368
22.3	Data for Diffusion Coefficients .....	374
22.4	Mechanisms of Diffusion .....	375
	Worked Example .....	377
	Examples .....	378
	Answers .....	379
<b>CHAPTER 23</b>	Mechanisms of Creep, and Creep-Resistant Materials .....	381
23.1	Introduction .....	381
23.2	Creep Mechanisms: Metals and Ceramics .....	382
23.3	Creep Mechanisms: Polymers .....	387
23.4	Selecting Materials to Resist Creep .....	389

Worked Example .....	389	
Examples .....	393	
Answers .....	394	
<b>CHAPTER 24</b>	<b>The Turbine Blade—A Case Study in Creep-Limited Design .....</b>	<b>395</b>
24.1	Introduction .....	395
24.2	Properties Required of a Turbine Blade .....	396
24.3	Nickel-Based Super-Alloys .....	398
24.4	Engineering Developments—Blade Cooling .....	402
24.5	Future Developments: High-Temperature Ceramics .....	403
24.6	Cost Effectiveness .....	403
	Worked Example .....	405
	Examples .....	407
	Answers .....	407
<b>PART G</b>	<b>Oxidation and Corrosion</b>	
<b>CHAPTER 25</b>	<b>Oxidation of Materials .....</b>	<b>411</b>
25.1	Introduction .....	411
25.2	Energy of Oxidation .....	412
25.3	Rates of Oxidation .....	412
25.4	Data .....	415
25.5	Micromechanisms .....	416
	Examples .....	419
	Answers .....	420
<b>CHAPTER 26</b>	<b>Case Studies in Dry Oxidation .....</b>	<b>421</b>
26.1	Introduction .....	421
26.2	Case Study 1: Making Stainless Alloys .....	421
26.3	Case Study 2: Protecting Turbine Blades .....	422
26.4	Case study 3: Joining Metals by Soldering and Brazing ..	426
	Examples .....	429
	Answers .....	430
<b>CHAPTER 27</b>	<b>Wet Corrosion of Materials .....</b>	<b>431</b>
27.1	Introduction .....	431
27.2	Wet Corrosion .....	432
27.3	Voltage Differences as the Driving Force for Wet Oxidation .....	433
27.4	Pourbaix [Electrochemical Equilibrium] Diagrams .....	434
27.5	Some Examples .....	436
27.6	Standard Electrode Potentials .....	440
27.7	Localized Attack .....	441
	Examples .....	443

Worked Example .....	389	
Examples .....	393	
Answers .....	394	
<b>CHAPTER 24</b>	<b>The Turbine Blade—A Case Study in Creep-Limited Design .....</b>	<b>395</b>
24.1	Introduction .....	395
24.2	Properties Required of a Turbine Blade .....	396
24.3	Nickel-Based Super-Alloys .....	398
24.4	Engineering Developments—Blade Cooling .....	402
24.5	Future Developments: High-Temperature Ceramics .....	403
24.6	Cost Effectiveness .....	403
	Worked Example .....	405
	Examples .....	407
	Answers .....	407
<b>PART G</b>	<b>Oxidation and Corrosion</b>	
<b>CHAPTER 25</b>	<b>Oxidation of Materials .....</b>	<b>411</b>
25.1	Introduction .....	411
25.2	Energy of Oxidation .....	412
25.3	Rates of Oxidation .....	412
25.4	Data .....	415
25.5	Micromechanisms .....	416
	Examples .....	419
	Answers .....	420
<b>CHAPTER 26</b>	<b>Case Studies in Dry Oxidation .....</b>	<b>421</b>
26.1	Introduction .....	421
26.2	Case Study 1: Making Stainless Alloys .....	421
26.3	Case Study 2: Protecting Turbine Blades .....	422
26.4	Case study 3: Joining Metals by Soldering and Brazing ..	426
	Examples .....	429
	Answers .....	430
<b>CHAPTER 27</b>	<b>Wet Corrosion of Materials .....</b>	<b>431</b>
27.1	Introduction .....	431
27.2	Wet Corrosion .....	432
27.3	Voltage Differences as the Driving Force for Wet Oxidation .....	433
27.4	Pourbaix (Electrochemical Equilibrium) Diagrams .....	434
27.5	Some Examples .....	436
27.6	Standard Electrode Potentials .....	440
27.7	Localized Attack .....	441
	Examples .....	443

	Answers .....	445
	Rates of Uniform Metal Loss .....	446
<b>CHAPTER 28</b>	<b>Case Studies in Wet Corrosion.....</b>	<b>449</b>
28.1	Case Study 1: Protecting Ships' Hulls from Corrosion .....	449
28.2	Case Study 2: Rusting of a Stainless Steel Water Filter .....	453
28.3	Case Study 3: Corrosion in Reinforced Concrete .....	456
28.4	Small Anodes and Large Cathodes .....	458
	Worked Example 1 .....	459
	Worked Example 2 .....	460
	Examples .....	462
	Answers .....	464
<b>PART H</b>	<b>Friction and Wear</b>	
<b>CHAPTER 29</b>	<b>Friction and Wear .....</b>	<b>469</b>
29.1	Introduction .....	469
29.2	Friction Between Materials .....	470
29.3	Coefficients of Friction .....	472
29.4	Lubrication .....	474
29.5	Wear of Materials .....	475
29.6	Surface and Bulk Properties .....	477
	Worked Example .....	478
	Examples .....	479
	Answers .....	483
<b>CHAPTER 30</b>	<b>Case Studies in Friction and Wear .....</b>	<b>485</b>
30.1	Introduction .....	485
30.2	Case Study 1: Design of Journal Bearings .....	485
30.3	Case Study 2: Materials for Skis and Sledge Runners .....	491
30.4	Case Study 3: High-Friction Rubber .....	492
	Examples .....	494
	Answers .....	497
<b>PART I</b>	<b>Thermal Properties</b>	
<b>CHAPTER 31</b>	<b>Thermal Expansion .....</b>	<b>501</b>
31.1	Introduction .....	501
	Worked Example 1 .....	502
31.2	Coefficients of Thermal Expansion .....	503
31.3	Physical Basis of Thermal Expansion .....	503
	Worked Example 2 .....	506
31.4	Thermal Expansion of Composites .....	508
31.5	Case Studies .....	508

Examples .....	513
Answers .....	513
<b>CHAPTER 32 Thermal Conductivity and Specific Heat .....</b>	<b>515</b>
<b>32.1 Introduction .....</b>	<b>515</b>
Worked Example 1 .....	517
<b>32.2 Thermal Conductivities and Specific Heats .....</b>	<b>518</b>
<b>32.3 Physical Basis of Specific Heat .....</b>	<b>518</b>
<b>32.4 Physical Basis of Thermal Conductivity .....</b>	<b>522</b>
Worked Example 2 .....	522
Worked Example 3 .....	522
Worked Example 4 .....	523
<b>32.5 Case Studies .....</b>	<b>524</b>
Worked Example 5 .....	528
Examples .....	529
Answers .....	529
<b>CHAPTER 33 Final Case Study: Materials and Energy in Car Design .....</b>	<b>531</b>
<b>33.1 Introduction .....</b>	<b>531</b>
<b>33.2 Energy and Carbon Emissions .....</b>	<b>531</b>
<b>33.3 Achieving Energy Economy .....</b>	<b>532</b>
<b>33.4 Material Content of a Car .....</b>	<b>533</b>
<b>33.5 Alternative Materials .....</b>	<b>533</b>
<b>33.6 Production Methods .....</b>	<b>539</b>
<b>33.7 Conclusions .....</b>	<b>541</b>
<b>APPENDIX Symbols and Formulae .....</b>	<b>543</b>
Principal Symbols .....	543
Other Symbols .....	544
Principal Formulae .....	547
Magnitude of Properties .....	555
<b>REFERENCES .....</b>	<b>557</b>
<b>INDEX .....</b>	<b>559</b>

# Index

Note: Page numbers followed by "f" indicate figures, and "t" indicate tables.

## A

- Abrasive wear, 476–477, 477f
- Abundance of elements, 19, 20t
- Adhesive wear, 475, 486
- Ammonia tank
  - critical stress, 263–264, 264f
  - fracture toughness, 264
  - geometry of failure, 262, 263f
  - material properties, 262–263
  - pressure vessel, 261–262, 262f
- Amorphous polymers, 73–74, 75f
- Anelasticity, 493
- Anisotropy composites, 89–90
- Arrhenius's law, 367, 368f
- Atomic level materials, 49
- Atom packing, 49, 50f
  - in crystals (*see Crystals, atom packing*)
  - density of solids, 76–78, 76–77t, 78f
  - in inorganic glasses, 74–75, 75f
  - in polymers, 73–74, 75f
- Availability of materials, 15

## B

- Bending moment, 96–97
- Bending of beams, 97–98, 108–109
- Biaxial tension, 34, 35f
- Bimetals
  - beam, 508–510, 509f
  - snap-through bimetal disc, 508–510, 510f
- Bond-angle, 50f
- Bonding, atoms
  - atom packing, 49, 50f
  - condensed states of matter, 56, 57t
  - interatomic bonds, 49, 50f

interatomic forces, 57–58, 58f

primary bonds, 49–55, 51–54f

secondary bonds, 49, 55–56, 55–56f

Bond stiffness, 83–86, 84f, 85t

Boundary lubrication, 474, 475f

Brazing, 426–429

Brittle cracking, 234, 235f, 238

Brittle materials

alloys, 237–238

design strength, 248

failure probability, 248–249

modulus of rupture, 254–257, 255f

statistics of strength, 248–249, 249–250f

strength of ceramic, 252–253

survival probability, 250, 253

tensile strength, 248

Weibull distribution, 250–252, 250f

Buckling, 512

Buckling of beams, 99–100, 112–113

Bulk diffusion, 376, 382

Bulk modulus, 38

Burgers vector, 160–161

## C

Carbon emissions, 531–532

Carbon-fiber reinforced polymers (CFRP), 5, 88, 117–118

Car design

aluminum alloys, 539, 540f, 541

carbon emissions, 531–532

compression molding, 539–540, 541f

energy, 531

energy economy, 532, 532t, 533f

GFRP, 539–541, 540–541f

high-strength steel, 539, 541

material content, 533, 534f, 534t  
primary mechanical properties, 533–537

secondary properties, 537–539

Challenger space shuttle disaster

circumstances, 122–123

hoop strain, 125, 129

hoop stress, 129

joint rotation, 125, 126f

O ring, 125–128, 126f

party balloon and rubber band, 125, 127f

Poisson's ratio, 129

solid rocket booster casing joint, 123–125, 124f, 128–129

Close-packed hexagonal structures, 65, 66f, 68, 68f, 70–71

Close-packed plane, 64

Coefficient of kinetic friction, 470, 470f

Coefficient of static friction, 470, 470f, 473f, 474

Comet air disasters, 325–331

Composites

fast fracture, 236–237, 236–237f

modulus, 87–90

thermal expansion, 508, 509f

Compression, 34, 35f, 139

Compression molding, 539–540, 541f

Concentration gradient, 515

Condensed states of matter, 56, 57t

Continuous welded railroad track, 510–512, 511f

Corrosion design error, 458–459

Covalent bonding, 52–54, 53–54f

Crack-growth rate, 288

Crack propagation, 271  
 cleavage, 234–236, 235/  
 ductile tearing, 232–234, 232–233f  
**C** Creep, 538  
 ceramics, 382–387  
 damage, 360–361, 360f, 400  
 fracture, 360–361, 385–386  
 metals, 382–387  
 polymers, 387–389  
 relaxation, 358–360  
 tests, 355–358, 357f  
**C** Creep-resistant materials, 361  
**C** Creep-rupture diagram, 361, 361f  
**C** Crystal energies, 64–66  
**C** Crystallography, 66–68  
**C** Crystals  
 atom packing  
 body-centered cubic structure, 71, 71f  
 close-packed structures and  
 crystal energies, 64–66, 65–66f  
 direction indices, 69–70, 70f  
 grain boundaries, 63–64  
 hard spheres, 63–64  
 nondirectional bonding, 63–64  
 plane indices, 68, 69f  
 three-dimensional packing  
 pattern, 64  
 bond stiffness, 83–86, 84f, 85f  
 dislocation of (*see* Dislocations)  
 strength, 157–158, 158–159f

**D** Debonding, 236–237  
**D** Defect-sensitive materials, 247  
**D** Deformation mechanism diagrams, 385  
**D** Density of solids, 76–78, 76–77t, 78f  
**D** Diffusional flow, 386–387  
**D** Diffusion coefficients, 374, 515  
**D** Diffusion creep, 384  
**D** Dilatation, 36  
**D** Directional covalent bonding, 53–54, 54f  
**D** Direction indices, 69–70, 70f  
**D** Dislocation-core diffusion, 376–377, 377f  
**D** Dislocations  
 creep, 382–383  
 edge dislocation, 159–161, 160f, 162–163f  
 electron microscope, stainless steel, 161, 165f

force acting, 162–165, 166f  
 glide on crystallographic planes, 166  
 line tension, 166, 166f  
 motion, 160–161  
 plastic strain, 160–161  
 screw dislocation, 161, 163–164f  
 yield strength, 169, 173  
**D** Doubling-time, 21  
**D** Dry oxidation  
 metals joining, 426–429  
 stainless alloys, making of, 421–422  
 turbine blades, 422–426  
**D** Ductile tearing, 233–234, 233f  
**D** Ductile-to-brittle transition, 235–236  
**D** Ductility, of aluminum alloys, 539

**E**

Edge dislocation, 159–161, 160f, 162–163f  
**E** Elastic bending, 96–98, 96–97f  
**E** Elastic deflection, 95–98, 97f, 535–538  
**E** Elastic deformation  
 bending, 96–98, 96–97f  
 buckling, 99–100  
 elastic limit, 95  
 strain, 102–103, 103f  
 stress, 100–102, 101–102f  
 vibration, 98–99  
**E** Elastic design, springs  
 energy density, 196  
 leaf springs (*see* Leaf springs)  
 materials, 195–196, 196t  
 primary function, 196  
 types, 195–196  
**E** Elastic limit, 137  
**E** Elastic moduli  
 deck hangers, Sydney Harbour Bridge, 31, 32f  
 floppy materials, 31  
 Hooke's law, 38  
 rubber band, 31, 32f  
 strain, 36–37, 37f  
 stress, 33–35  
 Young moduli (*see* Young's modulus)  
**E** Electrochemical equilibrium diagram.  
*See* Pourbaix diagram  
**E** Electropolishing, 455  
**E** Energies of formation, of oxides, 412, 413f, 414t  
**E** Energy costs, 24–25  
**E** Engineering materials  
 for bridges  
 cast-iron bridges, Magdalene Bridge, 8, 10f  
 Clare Bridge, 8, 9f  
 mild-steel bridge, St George footbridge, 10, 11f  
 reinforced concrete footbridge in Garret Hostel Lane, 10, 11f  
 wooden bridge at Queens' College, 8, 9f  
**E** ceramics, 1–2  
**E** classes of materials, 1–2, 3t, 4f  
**E** composites, 1–2  
**E** engineering design considerations, 10, 12f  
**E** material prices, breakdown of, 7–8, 8t  
**E** metals and alloys, 1–2  
**E** natural materials, 1–2  
**E** precious metals and gemstones, 8 properties  
 classes of property, 1, 2t  
 fatigue strength, 1  
 fracture toughness, 1  
 sailing cruiser, 6, 7f  
**E** screwdriver  
 fracture toughness, 4  
 friction coefficient, 4  
 modulus, steel, 2–3  
**E** PMMA handle, 4–5  
**E** with steel shaft and polymer (plastic) handle, 2–3, 4f  
**E** yield strength, 2–3  
**E** structure cost, 7–8  
**E** turbofan aero-engine  
 cross-section, 5, 5f  
**E** insulation, 6  
**E** petrol engine spark plug, 6, 6f  
**E** turbine blades, 5–6  
**E** turbofan blades, 5  
**E** Environmental impact, 25  
**E** Epoxy resin, 522–523  
**E** Eschede railway disaster  
 broken tire  
 circumferential tensile stress, 333–335, 334f  
 fatigue fracture surface, 332, 333f  
**E** rubber-sprung wheel  
 circumferential tensile stress, 332, 332f  
**E** Exponential growth  
 doubling-time, 21  
 law, 20–21, 21f

**F**

Face-centered cubic structures, 65–67, 67f, 70–71, 72f  
**Fast fracture**  
 ammonia tank, 261–264  
 brittle alloys, 237–238  
 cleavage (brittle), 234–236, 235f, 238  
 composites, 236–237, 236–237f  
 condition, 217–218  
 ductile tearing, 232–234, 232–233f, 238  
 energy criterion, 211–212  
 failure criteria, 231–232  
 at fixed displacements, 215–216, 215–216f  
 at fixed loads, 216–217, 217f  
 fracture toughness ( $K_C$ ), 217–221, 219f, 220t  
 $G_C$  and  $K_C$  data, 218–221, 218–219f, 220t  
 leak before break, 213  
 loading conditions, 232  
 material property, 232  
 stress intensity factor, 221  
 thermal fatigue, 213  
 toughness ( $G_C$ ), 214–215, 214f, 218–221, 218f, 220t  
**Fatigue**, 538  
 Comet air disasters, 325–331  
 cracked components, 288–289  
 cycles, designing out, 307–310  
 Eschede railway disaster, 331–335  
 high-cycle, 286–287, 291f  
 human tooth, 291, 292f  
 low-cycle, 286, 290, 291f  
 mechanisms, 290–292  
 metals and alloys, 302, 302t  
 precracked components, 288, 289f  
 steel plate, 291, 292f  
 strength improvement techniques, 307, 308f  
 Stretham steam pumping engine, 336–339  
 tests, 283–284, 284f  
 uncracked components, 283–288, 302  
 welded joints, 305–307, 305–306f  
**Fatigue strength**, 1  
**Fiber-reinforced composites**, 88–90, 89–90f  
 Fick's law, 368–374, 382  
**Filled polymers**, 88, 90

**Floppy materials**, 31, 39  
**Foam jacket cracking**, liquid methane tank  
 polyurethane (PUR), 268  
 schematic half-section, 267, 268f  
 thermal stresses in foam, 269–271, 269f, 271f  
**Forging**, 202  
**Fossil fuels**, 25  
**Fracture**  
 ammonia tank, 261–264  
 foam jacket cracking, liquid methane tank, 267–271  
 perspex pressure window explosion, 265–267  
 Tay Bridge collapse, 272–276, 272–276f  
**Fracture toughness ( $K_C$ )**, 217–221, 219f, 220t  
 ammonia tank, 264  
 ceramics and rigid polymers, 247  
 PUR foam, 271  
 steel, 1  
**Friction**  
 high-friction rubber, 492–493  
 journal bearings, 485–490  
 skis and sledge runners, 491–492  
**Frictional heat**, 526–527

**G**

**Galvanizing**, 459–460  
**Glass-fiber reinforced polymers (GFRP)**, 87, 539–541, 540–541f  
**Glass–rubber transition**, 236  
**Glass temperature**, 86  
**Grain-boundary diffusion**, 376–377, 377f  
**Gross yield strength**, 174

**H**

**Hall–Petch effect**, 175–176, 176f  
**Hardness test**, 145–147, 148f  
**Heat exchanger**  
 heat distortion, 524–525, 524f  
 thermal fatigue cracking, 525, 525f  
**Heat flow distances**, 528–529  
**High-cycle fatigue**, 286–287, 291f  
**High-friction rubber**, 492–493  
**High-loss/high-hysteresis rubbers**, 493  
**Hooke's law**, 38  
**Hydrodynamic lubrication**, 474

**Hydrogen bonds**, 56, 56f  
**Hydrostatic pressure**, 34, 35f  
**Hydrostatic testing**, 265–267

**I**

**Indentation hardness**, 149  
**Inorganic glasses**, atom packing, 74–75, 75f  
**Interatomic bonds**, 49, 50f  
**Interatomic force–distance curve**, 157–158  
**Interatomic forces**, 57–58, 58f, 157–158  
**Intergranular attack**, 442f, 443  
**Interstitial diffusion**, 376, 376f  
**Intrinsic lattice resistance**, 170  
**Investment casting**, 398  
**Ionic bond**, 50–52, 51–52f  
**Isotropic composite**, 90

**J**

**Journal bearing**  
 adhesive wear, 486  
 boundary lubrication, 486  
 conformability, 487, 488f  
 crankshafts, 486  
 embeddability, 487, 488f  
 hydrodynamic lubrication, 485–486, 486f  
 replaceable bearing shells, 486, 487f  
 seizure prevention, 488–490, 490–491f  
 standard alloys, 486, 487f  
**Jumping jack firework**, 73–74

**K**

**Kevlar-fiber reinforced polymers (KFRP)**, 88

**L**

**Large reflecting telescope**, mirror design  
 British infrared telescope, 118, 119f  
 candidate materials, 121, 121f  
 distortion of mirror, 121–122, 122f  
 Keck telescopes, 122  
 mass of mirror, 120–121  
 quasi isotropic laminate, 121  
 scaling laws, 120  
 telescope mirror, elastic deflection, 120–121, 120f  
 vapour-deposited aluminum, 119

Large-strain plasticity, 195, 202–203, 202f  
 Leaf springs  
     for centrifugal clutch, 198, 198f  
     elastic energy stored, 196–197  
     under load, 196, 197f  
     mechanics, 198–199  
     metallic materials, clutch springs, 199, 200f  
     nonmetallic materials, 199–200  
     stresses in, 197, 197f  
 Lignin, 88  
 Linear elasticity, 38, 138–139  
 Linear oxidation  
     breakdown of oxide films, 418, 419f  
     definition, 413  
 Linear-viscous creep. *See* Diffusion creep  
 Low-cycle fatigue, 286, 290, 291f  
 Lubrication, 474–475  
 Lüders band, 186

## M

Material-efficient design, 24  
 Material prices  
     copper and rubber, price fluctuations, 17, 17f  
     inflation, 17–18  
     long-term changes, 17–18  
     raw commodity prices, 15–17  
     relative cost per unit weight, 15–17, 16–17f  
     use-pattern, 18–19, 18t  
 Mega-newton per squaremeter, 34  
 Metallic bond, 54–55, 54f  
 Metals  
     rolling, 195, 202–203, 202f  
     standard electrode potentials, 440–441, 441f  
 Miller indices, 68–70, 69f  
 Modulus-limited design  
     large reflecting telescope (*see* Large reflecting telescope, mirror design)  
     racing yacht mast, selecting material (*see* Racing yacht mast material selection)  
     space shuttle disaster  
         (*see* Challenger space shuttle disaster)  
 Multi-leaf springs, 199, 200f

## N

Necking, tensile loading  
     aluminum alloy, 185, 186f  
     condition, 184–185, 185f  
     mild steel, 185–186, 186–187f  
     neck formation, 183, 183f  
     nominal stress-strain curve, 184  
     polythene, 185–188, 187f  
     rate of work-hardening, 184–185  
 Negative thermal expansion, 507–508, 507f

Noncrystalline polymers, 73–74  
 Nonelastic (plastic) behavior  
     load-extension curve, 139, 139f  
     necking, 139–140  
     permanent plastic deformation, 139, 140f  
     squashing, 140, 140f  
 Nonlinear elasticity, 138–139  
 Notch sensitivity factor, 303–305, 304f

## O

One-dimensional heat flow  
     nonsteady-state conditions, 516–517, 517f  
     steady-state conditions, 516–517  
 Oxidation  
     energy, 412, 413f, 414t  
     micromechanisms, 416–419  
     rates, 412–415, 414–415f

## P

Parabolic oxidation  
     definition, 413–415  
     mechanism, 416, 417f  
 Partial lubrication, 474  
 Particulate composites, 90  
 Perspex pressure window explosion  
     design data, 265–266  
     experimental rig arrangement, 265, 265f  
     failure analysis, 266–267, 266f  
 Phonons, 522  
 Photons, 522  
 Pitting corrosion, 441, 442f  
 Plane indices, 68, 69f  
 Plastic deflection, 538  
 Plastic deformation, 139, 140f  
 Plastic design  
     materials for pressure vessels, 201, 201f

thin-walled spherical pressure vessel, 200–201, 201f  
 Plastic flow, 535  
     hardness test analysis, 182–183, 182f  
     instability (*see* Necking, tensile loading)  
     onset of yielding, 180–181  
     shear yield strength, 179–181, 180–181f  
     tensile yield strength, 179  
     true stress-strain curves, 141–143, 141–142f

Plastic instability. *See* Necking, tensile loading

Plasticity, 195  
 Plastic strain, 160–161  
 Plastic work, 143  
 Plastic yielding, 536  
 Poisson's ratio effect, 36  
 Polycrystal strengthening and plasticity  
     ball-bearing model, 173, 174f  
     dislocation yield strength, 169, 173  
     grain-boundary strengthening, 175–176, 176f  
     gross yield strength, 174  
     precipitate and dispersion, 170–171, 172f  
     progressive nature of yielding, 173–174, 175f  
     solid solution hardening, 170, 171f  
     strengthening mechanisms, 170  
     tensile yield strength, 174–175  
     work-hardening, 172, 173f

Pourbaix diagram

    aluminum, 439, 440f  
     copper, 434–436, 435f  
     iron, 436–439, 438f

Pourbaix diagrams, 452–453f

Power-law creep, 382–383, 386

Primary bonds, 49  
     covalent bonding, 52–54, 53–54f  
     ionic bond, 50–52, 51–52f  
     metallic bond, 54–55, 54f

Primary creep, 355

Principal directions, 102

Principal planes, 102

Principal stresses, 102

**R**

Racing yacht mast material selection  
aluminum alloys, 117–118  
bamboo scaffolding, 117–118, 118f  
bending stiffness, 117  
candidate materials, 117, 117f  
cantilever beam, elastic deflection, 115–117, 116f  
CFRP, 115, 116f, 117–118  
mass of beam, 117  
Random substitutional solid solution, 170  
Recycling, 24–26  
Reinforced concrete corrosion, 456–458, 456–458f  
Resource availability, 22–23, 22f  
Rolling torque, 202–203  
Rubbers  
modulus, 86–87, 87f  
stress-strain curve, 138–139, 138f  
Rubber-sprung wheels, 332, 332f  
Rubber-toughened polymers, 237, 237f

**S**

Screw dislocation, 161, 163–164f  
Secondary bonds, 49  
hydrogen bonds, 56, 56f  
Van der Waals bonding, 55–56, 55f  
Secondary creep, 355  
Second moment of area, 96–97, 109–110  
bending of beams, 97–98  
buckling of beams, 100  
vibration of beams, 99  
Shear modulus, 38  
Shear strain, 36  
Shear stress, 34, 35f, 180, 180–181f  
Shear yield strength, 179–181, 180–181f  
Sheet drawing, 202  
Silica glass, 74, 75f  
Simple tension, 34, 35f  
Skis and sledge runners, 491–492  
Sodium atom, 50  
Soldering, 426–429  
Solid solution hardening, 170, 171f  
Specific heat  
data, 518, 519–520f  
frictional heat, 526–527  
physical basis, 518–522, 521f

**S**tainless steel water filter

corrosion, 453–456, 454f

Strain, 36–37, 37f, 102–103, 103f

**S**tress

common states, 34–35, 35f

distribution in cargo ship, 100–101

inside solid, 101, 101f

intensity, 33

shear stress, 33, 33f, 101–102

SI metric system, 34, 43–45

stress tensor, 101–102

tenile stress, 33, 33f, 101–102

Stress corrosion cracking (SCC), 442f, 443

Stress intensity factor, 221

**S**tress-strain behavior

linear elastic solid, 138, 138f

nonlinear elastic solid, 138–139, 138f

Stretham steam pumping engine

crank shaft stress, 337

engine part, 336f

failure by fast fracture, 338

failure by fatigue, 338–339, 338f

mechanics, 337–338

safety, 337

schematic diagram, 337f

Substitution, 24

Surface treatment, 478

Survival probability, 250

**T**

Taylor factor, 174–175

Temperature gradient, 515–517

Temperature switches, 508–510, 509–510f

Tensile ductility, 145, 146–147f, 148f

Tensile strain, 36

Tensile strength

data, 145, 146–147f, 148f

hardness, 149

Tensile stress, 180, 180f

polycrystals, 174–175

Tensile testing, 143–145, 144f

Tensile yield strength, 174–175, 179

Thermal conductivity, 516

data, 518, 519–520f

IACS, 523–524

phonon transport, 522–523

physical basis, 522

warm and cold seats, 527–528,

527–528f

Thermal diffusivity, 516–518, 519–520f

Thermal expansion

bond stiffness, 506

coefficients, 503, 504–505f

composites, 508, 509f

continuous welded railroad track, 510–512, 511f

glass-to-metal seals, 512–513

linear coefficient of thermal

expansion, 501

negative thermal expansion, 507f

rubber, 507–508, 507f

physical basis, 503–506, 505f

temperature switches, 508–510, 509–510f

thermal strain, 501–502

thermal stress in PUR foam, 502

volume strain, 501–502

Young's modulus, 506

Thermal fatigue, 397

Toughness ( $G_C$ ), 214–215, 214f, 218–221, 218f, 220f

fiber composites, 237

Turbine-blade materials

alloy requirements, 396, 397f

blade cooling, 402–403, 402f

development costs, 405f

dry oxidation, 422–426

high-temperature ceramics, 403, 404f

investment casting, 398, 400f

nickel-based super-alloys, 398–401, 399f

turbofan efficiency, 396, 396f

**U**

Ubiquitous materials, 19–20, 20f

U.K.'s infrared telescope (UKIRT), 118, 119f

Unit cell, 67–68, 70–71

**V**

Vacancy diffusion, 376, 376f

Vacuum brazing, 428

Van der Waals bonds, 55–56, 55f, 86–88

Vibration of beams, 98–99, 111–112

**W**

Wear

abrasive, 476–477

**Wear (Continued)**

- adhesive, 475
- high-friction rubber, 492–493
- journal bearings, 485–490
- skis and sledge runners, 491–492
- Weibull distribution, 250–252, 250f
- Weibull modulus, 251, 253
- Welded joints, 305–307, 305–306f
- Wet corrosion, 432–433, 433f
  - reinforced concrete, 456–458
  - stainless steel water filter, 453–456
  - voltage differences, 433–434
- Whirling, 130
- Wood, 4–5
- Work-hardening, 170, 172, 173f

**Y**

Yielding, car-body panel, 536, 536f

Yield-limited design

- materials for pressure vessels

(*see* Plastic design)

- materials for springs (*see* Elastic design, springs)

- metal rolling (*see* Large-strain plasticity)

Yield strength

- bar chart, 158, 159f

- data, 145, 146–147t, 148f

- hardness test, 145–147, 149

Young's modulus, 38, 129

- aluminum, 83

- bar chart, 42, 42f

- calculation method, 84f

cement and concrete, 83

ceramics and metals, 83

composites, 87–90

crystals, 83–86

data, 39–43, 40–41t

measurement, 38–39

oboe reed, 90–92

polymers, 83

rubbers and glass transition

temperature, 86–87

steels, 83

thermal expansion, 506

**Z**

Zero-stress temperature, 512