

Contents

Preface to the Third Edition	page xvii
Preface to the Second Edition	xix
A Note to the Reader	xxi
Chapter 1 Materials: Structure, Properties, and Performance	1
1.1 Introduction	1
1.2 Monolithic, Composite, and Hierarchical Materials	3
1.3 Structure of Materials	10
1.3.1 Crystal Structures	11
1.3.2 Metals	15
1.3.3 Ceramics	21
1.3.4 Glasses	27
1.3.5 Polymers	29
1.3.6 Liquid Crystals	39
1.3.7 Biological Materials and Biomaterials	40
1.3.8 Porous and Cellular Materials	46
1.3.9 Nano- and Microstructures of Biological Materials	48
1.3.10 The Sponge Spicule: An Example of a Biological Material	60
1.3.11 Active (or Smart) Materials	61
1.3.12 Electronic Materials	63
1.3.13 Nanotechnology	64
1.4 Strength of Real Materials	66
Suggested Reading	69
Exercises	71
Chapter 2 Elasticity and Viscoelasticity	77
2.1 Introduction	77
2.2 Longitudinal Stress and Strain	77
2.3 Strain Energy (or Deformation Energy) Density	84
2.4 Shear Stress and Strain	87
2.5 Poisson's Ratio	90
2.6 More Complex States of Stress	93
2.7 Graphical Solution of a Biaxial State of Stress: The Mohr Circle	97

2.8	Volumetric Strain or Dilation	102
2.9	Pure Shear: Relationship between G and E	103
2.10	Anisotropic Effects on Matrix Formulation of Stiffness and Compliance	105
2.10.1	Tensors	105
2.10.2	Transformation of a Second-Rank Tensor	106
2.10.3	Hooke's Law in Tensorial Form	106
2.11	Elastic Properties of Polycrystals	119
2.12	Elastic Properties of Materials	125
2.12.1	Elastic Properties of Metals	125
2.12.2	Elastic Properties of Ceramics	125
2.12.3	Elastic Properties of Polymers	132
2.12.4	Elastic Constants of Unidirectional Fiber-Reinforced Composite	132
2.13	Viscoelasticity	136
2.13.1	Storage and Loss Moduli	139
2.14	Rubber Elasticity	141
2.15	Mooney–Rivlin Equation	147
2.16	Elastic Properties of Biological Materials	150
2.16.1	Blood Vessels	150
2.16.2	Articular Cartilage	153
2.16.3	Mechanical Properties at the Nanometer Level	156
2.17	Elastic Properties of Electronic Materials	160
2.18	Elastic Constants and Bonding	163
	Suggested Reading	178
	Exercises	178

Chapter 3	Plasticity	187
3.1	Introduction	187
3.2	Plastic Deformation in Tension	189
3.2.1	Tensile Curve Parameters	196
3.2.2	Necking	198
3.2.3	Strain Rate Effects	202
3.3	Plastic Deformation in Compression Testing	210
3.4	The Bauschinger Effect	213
3.5	Plastic Deformation of Polymers	214
3.5.1	Stress–Strain Curves	214
3.5.2	Glassy Polymers	216
3.5.3	Semicrystalline Polymers	216
3.5.4	Viscous Flow	218
3.5.5	Adiabatic Heating	218

3.6 Plastic Deformation of Glasses	219
3.6.1 Microscopic Deformation Mechanisms	221
3.6.2 Temperature Dependence and Viscosity	222
3.7 Flow, Yield, and Failure Criteria	225
3.7.1 Maximum-Stress Criterion (Rankine)	226
3.7.2 Maximum-Shear-Stress Criterion (Tresca)	226
3.7.3 Maximum-Distortion-Energy Criterion (von Mises)	227
3.7.4 Graphical Representation and Experimental Verification of Rankine, Tresca, and von Mises Criteria	227
3.7.5 Failure Criteria for Brittle Materials	231
3.7.6 Yield Criteria for Ductile Polymers	235
3.7.7 Failure Criteria for Composite Materials	238
3.7.8 Yield and Failure Criteria for Other Anisotropic Materials	241
3.8 Hardness	242
3.8.1 Macroindentation Tests	243
3.8.2 Microindentation Tests	250
3.8.3 Tabor Equation	252
3.8.4 Nanoindentation	254
3.9 Formability: Important Parameters	258
3.9.1 Plastic Anisotropy	261
3.9.2 Punch-Stretch Tests and Forming-Limit Curves (or Keeler–Goodwin Diagrams)	262
3.10 Euler Buckling or Buckling of a Strut or a Column	266
3.11 Muscle Force	268
3.12 Mechanical Properties of Some Biological Materials	273
Suggested Reading	277
Exercises	277
Chapter 4 Imperfections: Point and Line Defects	286
4.1 Introduction	286
4.2 Theoretical Shear Strength	287
4.3 Atomic or Electronic Point Defects	290
4.3.1 Equilibrium Concentration of Point Defects	291
4.3.2 Production of Point Defects	295
4.3.3 Effect of Point Defects on Mechanical Properties	296
4.3.4 Radiation Damage	297
4.3.5 Ion Implantation	302
4.4 Line Defects	303
4.4.1 Experimental Observation of Dislocations	308
4.4.2 Behavior of Dislocations	310
4.4.3 Stress Field Around Dislocations	314

4.4.4	Energy of Dislocations	316
4.4.5	Force Required to Bow a Dislocation	321
4.4.6	Dislocations in Various Structures	323
4.4.7	Dislocations in Ceramics	335
4.4.8	Sources of Dislocations	339
4.4.9	Dislocation Pileups	345
4.4.10	Intersection of Dislocations	346
4.4.11	Deformation Produced by Motion of Dislocations (Orowan's Equation)	348
4.4.12	The Peierls–Nabarro Stress	351
4.4.13	The Movement of Dislocations: Temperature and Strain Rate Effects	354
4.4.14	Dislocations in Electronic Materials	357
	Suggested Reading	360
	Exercises	361
Chapter 5	Imperfections: Interfacial and Volumetric Defects	369
5.1	Introduction	369
5.2	Grain Boundaries	369
5.2.1	Tilt and Twist Boundaries	374
5.2.2	Energy of a Grain Boundary	376
5.2.3	Variation of Grain-Boundary Energy with Misorientation	379
5.2.4	Coincidence Site Lattice (CSL) Boundaries	383
5.2.5	Grain-Boundary Triple Junctions	383
5.2.6	Grain-Boundary Dislocations and Ledges	384
5.2.7	Electron Backscattered Diffraction (EBSD)	384
5.2.8	Grain Boundaries as a Packing of Polyhedral Units	386
5.3	Twinning and Twin Boundaries	388
5.3.1	Crystallography and Morphology	388
5.3.2	Mechanical Effects	393
5.4	Grain Boundaries in Plastic Deformation (Grain-Size Strengthening)	396
5.4.1	Hall–Petch Theory	400
5.4.2	Cottrell's Theory	401
5.4.3	Li's Theory	402
5.4.4	Meyers–Ashworth Theory	403
5.5	Other Internal Obstacles	405
5.6	Nanocrystalline Materials	408
5.7	Volumetric or Tridimensional Defects	411
5.8	Imperfections in Polymers	414
5.9	Micrometer and Submicrometer Compression (Pillar) Testing	416
	Suggested Reading	417
	Exercises	418

Chapter 6 Geometry of Deformation and Work-Hardening	424
6.1 Introduction	424
6.2 Geometry of Deformation	428
6.2.1 Stereographic Projections	428
6.2.2 Stress Required for Slip	430
6.2.3 Shear Deformation	436
6.2.4 Slip in Systems and Work-Hardening	437
6.2.5 Independent Slip Systems in Polycrystals	440
6.3 Work-Hardening in Polycrystals	441
6.3.1 Taylor's Theory	443
6.3.2 Seeger's Theory	444
6.3.3 Kuhlmann-Wilsdorf's Theory	445
6.4 Softening Mechanisms	448
6.5 Texture Strengthening	452
Suggested Reading	455
Exercises	455
Chapter 7 Fracture: Macroscopic Aspects	462
7.1 Introduction	462
7.2 Theoretical Tensile Strength	465
7.3 Stress Concentration and Griffith Criterion of Fracture	468
7.3.1 Stress Concentrations	469
7.3.2 Stress Concentration Factor	469
7.4 Griffith Criterion	476
7.5 Crack Propagation with Plasticity	481
7.6 Linear Elastic Fracture Mechanics	483
7.6.1 Fracture Toughness	483
7.6.2 Hypotheses of LEFM	485
7.6.3 Crack-Tip Separation Modes	485
7.6.4 Stress Field in an Isotropic Material in the Vicinity of a Crack Tip	485
7.6.5 Details of the Crack-Tip Stress Field in Mode I	487
7.6.6 Plastic-Zone Size Correction	491
7.6.7 Variation in Fracture Toughness with Thickness	493
7.7 Fracture Toughness Parameters	497
7.7.1 Crack Extension Force	497
7.7.2 Crack Opening Displacement	500
7.7.3 J -Integral	503
7.7.4 R Curve	506
7.7.5 Relationships among Different Fracture Toughness Parameters	507
7.8 Importance of K_{Ic} in Practice	508
7.9 Post-Yield Fracture Mechanics	510

7.10 Statistical Analysis of Failure Strength	512
Appendix: Stress Singularity at Crack Tip	522
Suggested Reading	525
Exercises	525
Chapter 8 Fracture: Microscopic Aspects	532
8.1 Introduction	532
8.2 Fracture in Metals	534
8.2.1 Crack Nucleation	534
8.2.2 Ductile Fracture	535
8.2.3 Brittle, or Cleavage, Fracture	547
8.3 Fracture in Ceramics	554
8.3.1 Microstructural Aspects	554
8.3.2 Effect of Grain Size on Strength of Ceramics	562
8.3.3 Fracture of Ceramics in Tension	563
8.3.4 Fracture in Ceramics Under Compression	566
8.3.5 Thermally Induced Fracture in Ceramics	572
8.4 Fracture in Polymers	575
8.4.1 Brittle Fracture	576
8.4.2 Crazing and Shear Yielding	577
8.4.3 Fracture in Semicrystalline and Crystalline Polymers	581
8.4.4 Toughness of Polymers	582
8.5 Fracture and Toughness of Biological Materials	586
8.6 Fracture Mechanism Maps	591
Suggested Reading	592
Exercises	592
Chapter 9 Fracture Testing	598
9.1 Introduction	598
9.2 Impact Testing	598
9.2.1 Charpy Impact Test	599
9.2.2 Drop-Weight Test	603
9.2.3 Instrumented Charpy Impact Test	604
9.4 Plane-Strain Fracture Toughness Test	606
9.5 Crack Opening Displacement Testing	611
9.6 J -Integral Testing	612
9.7 Flexure Test	614
9.7.1 Three-Point Bend Test	615
9.7.2 Four-Point Bending	616
9.7.3 Interlaminar Shear Strength Test	618
9.8 Fracture Toughness Testing of Brittle Materials	620
9.8.1 Chevron Notch Test	621
9.8.2 Indentation Methods for Determining Toughness	623

9.9 Adhesion of Thin Films to Substrates	627
Suggested Reading	629
Exercises	629
Chapter 10 Solid Solution, Precipitation, and Dispersion Strengthening	637
10.1 Introduction	637
10.2 Solid-Solution Strengthening	638
10.2.1 Elastic Interaction	639
10.2.2 Other Interactions	643
10.3 Mechanical Effects Associated with Solid Solutions	644
10.3.1 Well-Defined Yield Point in the Stress–Strain Curves	645
10.3.2 Plateau in the Stress–Strain Curve and Lüders Band	646
10.3.3 Strain Aging	647
10.3.4 Serrated Stress–Strain Curve	648
10.3.5 Snoek Effect	649
10.3.6 Blue Brittleness	650
10.4 Precipitation- and Dispersion-Hardening	650
10.5 Dislocation–Precipitate Interaction	659
10.6 Precipitation in Microalloyed Steels	666
10.7 Advanced Steels	671
Suggested Reading	676
Exercises	676
Chapter 11 Martensitic Transformation	682
11.1 Introduction	682
11.2 Structures and Morphologies of Martensite	682
11.3 Strength of Martensite	688
11.4 Mechanical Effects	692
11.5 Shape-Memory Effect	697
11.5.1 Shape-Memory Effect in Polymers	702
11.6 Martensitic Transformation in Ceramics	703
Suggested Reading	707
Exercises	708
Chapter 12 Special Materials: Intermetallics and Foams	711
12.1 Introduction	711
12.2 Silicides	711
12.3 Ordered Intermetallics	712
12.3.1 Dislocation Structures in Ordered Intermetallics	714
12.3.2 Effect of Ordering on Mechanical Properties	717
12.3.3 Ductility of Intermetallics	724

12.4 Cellular Materials	730
12.4.1 Structure	730
12.4.2 Modeling of the Mechanical Response	732
12.4.3 Comparison of Predictions and Experimental Results	736
12.4.4 Syntactic Foam	736
12.4.5 Plastic Behavior of Porous Materials	737
Suggested Reading	741
Exercises	741
Chapter 13 Creep and Superplasticity	745
13.1 Introduction	745
13.2 Correlation and Extrapolation Methods	751
13.3 Fundamental Mechanisms Responsible for Creep	758
13.4 Diffusion Creep	759
13.5 Dislocation (or Power Law) Weertman Creep	764
13.6 Dislocation Glide	767
13.7 Grain-Boundary Sliding	768
13.8 Deformation-Mechanism (Weertman–Ashby) Maps	770
13.9 Creep-Induced Fracture	772
13.10 Heat-Resistant Materials	775
13.11 Creep in Polymers	782
13.12 Diffusion-Related Phenomena in Electronic Materials	791
13.13 Superplasticity	793
Suggested Reading	799
Exercises	800
Chapter 14 Fatigue	811
14.1 Introduction	811
14.2 Fatigue Parameters and S – N (Wöhler) Curves	812
14.3 Fatigue Strength or Fatigue Life	814
14.4 Effect of Mean Stress on Fatigue Life	817
14.5 Effect of Frequency	820
14.6 Cumulative Damage and Life Exhaustion	820
14.7 Mechanisms of Fatigue	824
14.7.1 Fatigue Crack Nucleation	824
14.7.2 Fatigue Crack Propagation	829
14.8 Linear Elastic Fracture Mechanics Applied to Fatigue	834
14.8.1 Fatigue of Biomaterials	845
14.9 Hysteretic Heating in Fatigue	847
14.10 Environmental Effects in Fatigue	849
14.11 Fatigue Crack Closure	849
14.12 The Two-Parameter Approach	850
14.13 The Short-Crack Problem in Fatigue	851

14.14 Fatigue Testing	853
14.14.1 Conventional Fatigue Tests	853
14.14.2 Rotating Bending Machine	854
14.14.3 Statistical Analysis of S – N Curves	854
14.14.4 Nonconventional Fatigue Testing	855
14.14.5 Servohydraulic Machines	857
14.14.6 Low-Cycle Fatigue Tests	858
14.14.7 Fatigue Crack Propagation Testing	859
Suggested Reading	860
Exercises	861
Chapter 15 Composite Materials	870
15.1 Introduction	870
15.2 Types of Composites	870
15.3 Important Reinforcements and Matrix Materials	873
15.4 Microstructural Aspects and Importance of the Matrix	874
15.5 Interfaces in Composites	875
15.5.1 Crystallographic Nature of the Fiber– Matrix Interface	876
15.5.2 Interfacial Bonding in Composites	877
15.5.3 Interfacial Interactions	878
15.6 Properties of Composites	879
15.6.1 Density and Heat Capacity	880
15.6.2 Elastic Moduli	880
15.6.3 Strength	885
15.6.4 Anisotropic Nature of Fiber- Reinforced Composites	888
15.6.5 Aging Response of Matrix in MMCs	889
15.6.6 Toughness	889
15.7 Load Transfer from Matrix to Fiber	892
15.7.1 Fiber and Matrix Elastic	893
15.7.2 Fiber Elastic and Matrix Plastic	897
15.8 Fracture in Composites	899
15.8.1 Single and Multiple Fracture	899
15.8.2 Failure Modes in Composites	900
15.9 Some Fundamental Characteristics of Composites	903
15.9.1 Heterogeneity	904
15.9.2 Anisotropy	904
15.9.3 Shear Coupling	905
15.9.4 Statistical Variation in Strength	907
15.10 Functionally Graded Materials	907
15.11 Applications	908
15.11.1 Aerospace Applications	908
15.11.2 Nonaerospace Applications	909

15.12 Laminated Composites	912
Suggested Reading	915
Exercises	915
Chapter 16 Environmental Effects	921
16.1 Introduction	921
16.2 Electrochemical Nature of Corrosion in Metals	921
16.2.1 Galvanic Corrosion	922
16.2.2 Uniform Corrosion	923
16.2.3 Crevice Corrosion	923
16.2.4 Pitting Corrosion	924
16.2.5 Intergranular Corrosion	924
16.2.6 Selective Leaching	924
16.2.7 Erosion-Corrosion	924
16.2.8 Radiation Damage	924
16.2.9 Stress Corrosion	925
16.3 Oxidation of Metals	925
16.4 Environmentally Assisted Fracture in Metals	926
16.4.1 Stress Corrosion Cracking (SCC)	926
16.4.2 Hydrogen Damage in Metals	931
16.4.3 Liquid and Solid Metal Embrittlement	938
16.5 Environmental Effects in Polymers	939
16.5.1 Chemical or Solvent Attack	940
16.5.2 Swelling	940
16.5.3 Oxidation	941
16.5.4 Radiation Damage	942
16.5.5 Environmental Crazeing	942
16.5.6 Alleviating the Environmental Damage in Polymers	943
16.6 Environmental Effects in Ceramics	944
16.6.1 Oxidation of Ceramics	948
Suggested Reading	948
Exercises	948
Appendixes	951
Index	959