

Table of Contents

ABOUT THE COVER		xvii
FOREWORD		xix
PREFACE TO THE FIFTH EDITION		xxi
	Objectives	xxi
	Organization	xxi
	New to This Edition	xxii
	End-of-Chapter Problems	xxiv
	Acknowledgments	xxiv
ABOUT THE AUTHORS		xxv
SECTION ONE	RECOVERABLE AND NONRECOVERABLE DEFORMATION	1
CHAPTER 1	ELASTIC RESPONSE OF SOLIDS	3
	1.1 Mechanical Testing	3
	1.2 Definitions of Stress and Strain	4
	1.3 Stress–Strain Curves for Uniaxial Loading	8
	1.3.1 Survey of Tensile Test Curves	8
	1.3.2 Uniaxial Linear Elastic Response	9
	1.3.3 Young’s Modulus and Polymer Structure	13
	1.3.3.1 Thermoplastic Behavior	13
	1.3.3.2 Rigid Thermosets	14
	1.3.3.3 Rubber Elasticity	15
	1.3.4 Compression Testing	17
	1.3.5 Failure by Elastic Buckling	17
	1.3.6 Resilience and Strain Energy Density	19
	1.3.7 Definitions of Strength	19
	1.3.8 Toughness	22
	1.4 Nonaxial Testing	23
	1.4.1 Bend Testing	23
	1.4.2 Shear and Torsion Testing	26
	1.5 Multiaxial Linear Elastic Response	27
	1.5.1 Additional Isotropic Elastic Constants	27
	1.5.2 Multiaxial Loading	28
	1.5.2.1 Thin-Walled Pressure Vessels	30
	1.5.2.2 Special Cases of Multiaxial Loading	32
	1.5.3 Instrumented Indentation	33
	1.6 Elastic Anisotropy	34

1.6.1	Stiffness and Compliance Matrices	34
1.6.1.1	Symmetry Classes	36
1.6.1.2	Loading Along an Arbitrary Axis	37
1.6.2	Composite Materials	40
1.6.3	Isostrain Analysis	41
1.6.4	Isostress Analysis	43
1.6.5	Aligned Short Fibers	44
1.6.6	Strength of Composites	47
1.6.6.1	Effects of Matrix Behavior	47
1.6.6.2	Effects of Fiber Orientation	48
1.7	Thermal Stresses and Thermal Shock-Induced Failure	50
1.7.1	Upper Bound Thermal Stress	50
1.7.2	Cooling Rate and Thermal Stress	54
	References	55
	Further Readings	56
	Problems	56
	Review	56
	Practice	57
	Design	59
	Extend	60

CHAPTER 2**YIELDING AND PLASTIC FLOW****63**

2.1	Dislocations in Metals and Ceramics	63
2.1.1	Strength of a Perfect Crystal	63
2.1.2	The Need for Lattice Imperfections: Dislocations	65
2.1.3	Observation of Dislocations	67
2.1.4	Lattice Resistance to Dislocation Movement: The Peierls Stress	69
2.1.4.1	Peierls Stress Temperature Sensitivity	70
2.1.4.2	Effect of Dislocation Orientation on Peierls Stress	71
2.1.5	Characteristics of Dislocations	72
2.1.6	Elastic Properties of Dislocations	75
2.1.7	Partial Dislocations	78
2.1.7.1	Movement of Partial Dislocations	80
2.2	Slip	81
2.2.1	Crystallography of Slip	81
2.2.2	Geometry of Slip	84
2.2.3	Slip in Polycrystals	87
2.3	Yield Criteria for Metals and Ceramics	88
2.4	Post-Yield Plastic Deformation	90
2.4.1	Strain Hardening	90
2.4.2	Plastic Instability and Necking	93
2.4.2.1	Strain Distribution in a Tensile Specimen	94
2.4.2.2	Extent of Uniform Strain	95
2.4.2.3	True Stress Correction	95
2.4.2.4	Failure of the Necked Region	96
2.4.3	Upper Yield Point Behavior	99
2.4.4	Temperature and Strain-Rate Effects in Tension	100
2.5	Slip in Single Crystals and Textured Materials	102
2.5.1	Geometric Hardening and Softening	103
2.5.2	Crystallographic Textures (Preferred Orientations)	105
2.5.3	Plastic Anisotropy	108

2.6	Deformation Twinning	111
2.6.1	Comparison of Slip and Twinning Deformations	111
2.6.2	Heterogeneous Plastic Tensile Behavior	113
2.6.3	Stress Requirements for Twinning	113
2.6.4	Geometry of Twin Formation	114
2.6.5	Elongation Potential of Twin Deformation	116
2.6.6	Twin Shape	116
2.6.7	Twinning in HCP Crystals	117
2.6.8	Twinning in BCC and FCC Crystals	120
2.7	Plasticity in Polymers	120
2.7.1	Polymer Structure: General Remarks	120
2.7.1.1	Side Groups and Chain Mobility	121
2.7.1.2	Side Groups and Crystallinity	123
2.7.1.3	Morphology of Amorphous and Crystalline Polymers	124
2.7.1.4	Polymer Additions	127
2.7.2	Plasticity Mechanisms	128
2.7.2.1	Amorphous Polymers	128
2.7.2.2	Semi-crystalline Polymers	130
2.7.3	Macroscopic Response of Ductile Polymers	131
2.7.4	Yield Criteria	133
	References	136
	Problems	139
	Review	139
	Practice	140
	Design	141
	Extend	141

CHAPTER 3**CONTROLLING STRENGTH****143**

3.1	Strengthening: A Definition	143
3.2	Strengthening of Metals	143
3.2.1	Dislocation Multiplication	143
3.2.2	Dislocation–Dislocation Interactions	146
3.3	Strain (Work) Hardening	151
3.4	Boundary Strengthening	155
3.4.1	Strength of Nanocrystalline and Multilayer Metals	156
3.5	Solid Solution Strengthening	158
3.5.1	Yield-Point Phenomenon and Strain Aging	161
3.6	Precipitation Hardening	164
3.6.1	Microstructural Characteristics	164
3.6.2	Dislocation–Particle Interactions	167
3.7	Dispersion Strengthening	170
3.8	Strengthening of Steel Alloys by Multiple Mechanisms	172
3.9	Metal-Matrix Composite Strengthening	175
3.9.1	Whisker-Reinforced Composites	175
3.9.2	Laminated Composites	176
3.10	Strengthening of Polymers	177
3.11	Polymer-Matrix Composites	182
	References	184
	Further Reading	185
	Problems	186
	Review	186
	Practice	186

Design 187
 Extend 188

CHAPTER 4 TIME-DEPENDENT DEFORMATION 189

4.1 Time-Dependent Mechanical Behavior of Solids 189
 4.2 Creep of Crystalline Solids: An Overview 191
 4.3 Temperature–Stress–Strain-Rate Relations 195
 4.4 Deformation Mechanisms 202
 4.5 Superplasticity 205
 4.6 Deformation-Mechanism Maps 208
 4.7 Parametric Relations: Extrapolation Procedures for Creep Rupture Data 215
 4.8 Materials for Elevated Temperature Use 220
 4.9 Viscoelastic Response of Polymers and the Role of Structure 227
 4.9.1 Polymer Creep and Stress Relaxation 229
 4.9.2 Mechanical Analogs 235
 4.9.3 Dynamic Mechanical Testing and Energy-Damping Spectra 239
 References 243
 Problems 245
 Review 245
 Practice 246
 Design 247
 Extend 248

SECTION TWO FRACTURE MECHANICS OF ENGINEERING MATERIALS 249

CHAPTER 5 FRACTURE: AN OVERVIEW 251

5.1 Introduction 251
 5.2 Theoretical Cohesive Strength 253
 5.3 Defect Population in Solids 254
 5.3.1 Statistical Nature of Fracture: Weibull Analysis 255
 5.3.1.1 Effect of Size on the Statistical Nature of Fracture 258
 5.4 The Stress-Concentration Factor 260
 5.5 Notch Strengthening 264
 5.6 External Variables Affecting Fracture 265
 5.7 Characterizing the Fracture Process 266
 5.8 Macroscopic Fracture Characteristics 269
 5.8.1 Fractures of Metals 269
 5.8.2 Fractures of Polymers 271
 5.8.3 Fractures of Glasses and Ceramics 273
 5.8.4 Fractures of Engineering Composites 277
 5.9 Microscopic Fracture Mechanisms 278
 5.9.1 Microscopic Fracture Mechanisms: Metals 279
 5.9.2 Microscopic Fracture Mechanisms: Polymers 282
 5.9.3 Microscopic Fracture Mechanisms: Glasses and Ceramics 287
 5.9.4 Microscopic Fracture Mechanisms: Engineering Composites 289
 5.9.5 Microscopic Fracture Mechanisms: Metal Creep Fracture 291
 References 294
 Problems 295
 Review 295
 Practice 296

Design 297
 Extend 297

CHAPTER 6**ELEMENTS OF FRACTURE MECHANICS****299**

- 6.1 Griffith Crack Theory 299
 - 6.1.1 Verification of the Griffith Relation 301
 - 6.1.2 Griffith Theory and Propagation-Controlled Thermal Fracture 301
 - 6.1.3 Adapting the Griffith Theory to Ductile Materials 304
 - 6.1.4 Energy Release Rate Analysis 305
- 6.2 Charpy Impact Fracture Testing 307
- 6.3 Related Polymer Fracture Test Methods 311
- 6.4 Limitations of the Transition Temperature Philosophy 312
- 6.5 Stress Analysis of Cracks 315
 - 6.5.1 Multiplicity of Y Calibration Factors 323
 - 6.5.2 The Role of K 326
 FAILURE ANALYSIS CASE STUDY 6.1: Fracture Toughness of Manatee Bones in Impact 327
- 6.6 Design Philosophy 328
- 6.7 Relation Between Energy Rate and Stress Field Approaches 330
- 6.8 Crack-Tip Plastic-Zone Size Estimation 332
 - 6.8.1 Dugdale Plastic Strip Model 335
- 6.9 Fracture-Mode Transition: Plane Stress Versus Plane Strain 336
 - FAILURE ANALYSIS CASE STUDY 6.2: Analysis of Crack Development during Structural Fatigue Test 339
- 6.10 Plane-Strain Fracture-Toughness Testing of Metals and Ceramics 341
- 6.11 Fracture Toughness of Engineering Alloys 344
 - 6.11.1 Impact Energy—Fracture-Toughness Correlations 347
 - FAILURE ANALYSIS CASE STUDY 6.3: Failure of Arizona Generator Rotor Forging 354
- 6.12 Plane-Stress Fracture-Toughness Testing 355
- 6.13 Toughness Determination from Crack-Opening Displacement Measurement 358
- 6.14 Fracture-Toughness Determination and Elastic-Plastic Analysis with the J Integral 360
 - 6.14.1 Determination of J_{IC} 362
- 6.15 Other Fracture Models 368
- 6.16 Fracture Mechanics and Adhesion Measurements 371
- References 375
- Further Readings 378
- Problems 378
 - Review 378
 - Practice 379
 - Design 380
 - Extend 381

CHAPTER 7**FRACTURE TOUGHNESS****383**

- 7.1 Some Useful Generalities 383
 - 7.1.1 Toughness and Strength 383
 - 7.1.2 Intrinsic Toughness 385
 - 7.1.3 Extrinsic Toughening 387
- 7.2 Intrinsic Toughness of Metals and Alloys 389
 - 7.2.1 Improved Alloy Cleanliness 389

7.2.1.1	Cleaning up Ferrous Alloys	390
7.2.1.2	Cleaning up Aluminum Alloys	394
7.2.2	Microstructural Refinement	398
7.3	Toughening of Metals and Alloys Through Microstructural Anisotropy	402
7.3.1	Mechanical Fiberling	402
	MICROSTRUCTURAL TOUGHENING CASE STUDY 7.1: The <i>Titanic</i>	404
7.3.2	Internal Interfaces and Crack Growth	406
7.3.3	Fracture Toughness Anisotropy	410
7.4	Optimizing Toughness of Specific Alloy Systems	411
7.4.1	Ferrous Alloys	411
7.4.2	Nonferrous Alloys	414
7.5	Toughness of Ceramics, Glasses, and Their Composites	416
7.5.1	Ceramics and Ceramic-Matrix Composites	416
7.5.2	Glass	422
7.6	Toughness of Polymers and Polymer-Matrix Composites	426
7.6.1	Intrinsic Polymer Toughness	426
7.6.2	Particle-Toughened Polymers	427
7.6.3	Fiber Reinforced Polymer Composites	432
7.7	Natural and Biomimetic Materials	434
7.7.1	Mollusk Shells	434
7.7.2	Bone	437
7.7.3	Tough Biomimetic Materials	438
7.8	Metallurgical Embrittlement of Ferrous Alloys	440
7.8.1	300 to 350°C or Tempered Martensite Embrittlement	441
7.8.2	Temper Embrittlement	442
7.8.3	Neutron-Irradiation Embrittlement	444
7.9	Additional Data	449
	References	453
	Problems	459
	Review	459
	Practice	460
	Design	461
	Extend	461

CHAPTER 8**ENVIRONMENT-ASSISTED CRACKING****463**

8.1	Embrittlement Models	465
8.1.1	Hydrogen Embrittlement Models	465
8.1.2	Stress Corrosion Cracking Models	468
8.1.2.1	SCC of Specific Material–Environment Systems	470
8.1.3	Liquid-Metal Embrittlement	471
8.1.4	Dynamic Embrittlement	472
8.2	Fracture Mechanics Test Methods	472
8.2.1	Major Variables Affecting Environment-Assisted Cracking	480
8.2.1.1	Alloy Chemistry and Thermomechanical Treatment	480
8.2.1.2	Environment	483
8.2.1.3	Temperature and Pressure	485
8.2.2	Environment-Assisted Cracking in Plastics	487
8.2.3	Environment-Assisted Cracking in Ceramics and Glasses	489
8.3	Life and Crack-Length Calculations	492
	References	493
	Problems	496

Review	496
Practice	497
Design	497
Extend	497

CHAPTER 9 **CYCLIC STRESS AND STRAIN FATIGUE** **499**

9.1	Macrofractography of Fatigue Failures	499
9.2	Cyclic Stress-Controlled Fatigue	503
9.2.1	Effect of Mean Stress on Fatigue Life	506
9.2.2	Stress Fluctuation, Cumulative Damage, and Safe-Life Design	508
9.2.3	Notch Effects and Fatigue Initiation	511
9.2.4	Material Behavior: Metal Alloys	516
9.2.4.1	Surface Treatment	520
9.2.5	Material Behavior: Polymers	523
9.2.6	Material Behavior: Composites	526
9.2.6.1	Particulate Composites	526
9.2.6.2	Fiber Composites	527
9.3	Cyclic Strain-Controlled Fatigue	529
9.3.1	Cycle-Dependent Material Response	531
9.3.2	Strain Life Curves	538
9.4	Fatigue Life Estimations for Notched Components	541
9.5	Fatigue Crack Initiation Mechanisms	545
9.6	Avoidance of Fatigue Damage	547
9.6.1	Favorable Residual Compressive Stresses	547
9.6.2	Pretensioning of Load-Bearing Members	550
	References	554
	Problems	556
Review	556	
Practice	556	
Design	557	
Extend	557	

CHAPTER 10 **FATIGUE CRACK PROPAGATION** **559**

10.1	Stress and Crack Length Correlations with FCP	559
10.1.1	Fatigue Life Calculations	563
10.1.2	Fail-Safe Design and Retirement for Cause	567
10.2	Macroscopic Fracture Modes in Fatigue	568
	FATIGUE FAILURE ANALYSIS CASE STUDY 10.1: Stress Intensity Factor Estimate Based on Fatigue Growth Bands	571
10.3	Microscopic Fracture Mechanisms	572
10.3.1	Correlations with the Stress Intensity Factor	575
10.4	Crack Growth Behavior at ΔK Extremes	578
10.4.1	High ΔK Levels	578
10.4.2	Low ΔK Levels	583
10.4.2.1	Estimation of Short-Crack Growth Behavior	590
10.5	Influence of Load Interactions	592
10.5.1	Load Interaction Macroscopic Appearance	596
10.6	Environmentally Enhanced FCP (Corrosion Fatigue)	600
10.6.1	Corrosion Fatigue Superposition Model	605
10.7	Microstructural Aspects of FCP in Metal Alloys	606
10.7.1	Normalization and Calculation of FCP Data	615

- 10.8 Fatigue Crack Propagation in Engineering Plastics 618
 - 10.8.1 Polymer FCP Frequency Sensitivity 620
 - 10.8.2 Fracture Surface Micromorphology 625
- 10.9 Fatigue Crack Propagation in Ceramics 628
- 10.10 Fatigue Crack Propagation in Composites 632
- References 635
- Further Reading 641
- Problems 641
 - Review 641
 - Practice 642
 - Design 643
 - Extend 644

CHAPTER 11

ANALYSES OF ENGINEERING FAILURES

645

- 11.1 Typical Defects 647
- 11.2 Macroscopic Fracture Surface Examination 647
- 11.3 Metallographic and Fractographic Examination 651
- 11.4 Component Failure Analysis Data 652
- 11.5 Case Histories 652
- CASE 1: Shotgun Barrel Failures 653
 - Overview of Failure Events and Background Information 653
 - Proposed Causation Theories 654
 - Fractographic Evidence of Failed Gun Barrels 655
 - Estimation of the Material's Fatigue Endurance Limit 655
 - Microfractography of Fatigue Fracture in Gun Barrel Material 656
 - The Verdicts 658
- CASE 2: Analysis of Aileron Power Control Cylinder Service Failure 658
- CASE 3: Failure of Pittsburgh Station Generator Rotor Forging 660
- CASE 4: Stress Corrosion Cracking Failure of the Point Pleasant Bridge 661
- CASE 5: Weld Cold Crack-Induced Failure of Kings Bridge, Melbourne, Australia 664
- CASE 6: Failure Analysis of 175-mm Gun Tube 665
- CASE 7: Hydrotest Failure of a 660-cm-Diameter Rocket Motor Casing 670
- CASE 8: Premature Fracture of Powder-Pressing Die 673
- CASE 9: A Laboratory Analysis of a Lavatory Failure 674
- 11.6 Additional Comments Regarding Welded Bridges 676
- References 680
- Further Reading 681

CHAPTER 12

CONSEQUENCES OF PRODUCT FAILURE

683

- 12.1 Introduction to Product Liability 683
- 12.2 History of Product Liability 684
 - 12.2.1 Caveat Emptor and Express Liability 685
 - 12.2.2 Implied Warranty 685
 - 12.2.3 Privity of Contract 686
 - 12.2.4 Assault on Privity Protection 687
 - 12.2.5 Negligence 691
 - 12.2.6 Strict Liability 694
 - 12.2.7 Attempts to Codify Product Liability Case Law 696
- 12.3 Product Recall 697
 - 12.3.1 Regulatory Requirements and Considerations 698
 - 12.3.1.1 Consumer Product Safety Commission 698

	12.3.1.1.1 Defect	699
	12.3.1.1.2 Substantial Product Hazard	700
	12.3.1.1.3 Unreasonable Risk	700
	12.3.1.2 International Governmental Landscape	701
12.3.2	Technical Considerations Regarding Potential Recalls	701
	12.3.2.1 Determination of the Failure Process	702
	12.3.2.2 Identification of the Affected Product Population	704
	12.3.2.3 Assessment of Risk Association with Product Failure	705
	12.3.2.4 Generation of an Appropriate Corrective Action Plan	707
12.3.3	Proactive Considerations	707
	12.3.3.1 Think Like a Consumer	707
	12.3.3.1 Test Products Thoroughly	707
	12.3.3.3 Ensure Adequate Traceability	708
	12.3.3.4 Manage Change Carefully	708
	RECALL CASE STUDY: The "Unstable" Ladder	708
	References	710
	Problems	712
	Review	712
	Extend	712
APPENDIX A	FRACTURE SURFACE PRESERVATION, CLEANING AND REPLICATION TECHNIQUES, AND IMAGE INTERPRETATION	713
	A.1 Fracture Surface Preservation	713
	A.2 Fracture Surface Cleaning	713
	A.3 Replica Preparation and Image Interpretation	715
	References	717
APPENDIX B	K CALIBRATIONS FOR TYPICAL FRACTURE TOUGHNESS AND FATIGUE CRACK PROPAGATION TEST SPECIMENS	719
APPENDIX C	Y CALIBRATION FACTORS FOR ELLIPTICAL AND SEMI-CIRCULAR SURFACE FLAWS	723
APPENDIX D	SUGGESTED CHECKLIST OF DATA DESIRABLE FOR COMPLETE FAILURE ANALYSIS	725
AUTHOR INDEX		729
MATERIALS INDEX		741
SUBJECT INDEX		747