Mechanical Behavior of Materials

Engineering Methods for Deformation, Fracture, and Fatigue

Fourth Edition

Norman E. Dowling

Frank Maher Professor of Engineering
Engineering Science and Mechanics Department, and
Materials Science and Engineering Department
Virginia Polytechnic Institute and State University
Blacksburg, Virginia

International Edition contributions by

Katakam Siva Prasad
Assistant Professor
Department of Metallurgical and Materials Engineering
National Institute of Technology
Tiruchirappalli

R. Narayanasamy
Professor
Department of Production Engineering
National Institute of Technology
Tiruchirappalli

PEARSON

Boston Columbus Indianapolis New York San Francisco Upper Saddle River
Amsterdam Cape Town Dubai London Madrid Milan Munich Paris
Montréal Toronto Delhi Mexico City São Paulo Sydney Hong Kong Seoul
Singapore Taipei Tokyo
Contents

PREFACE

ACKNOWLEDGMENTS

1 Introduction

1.1 Introduction
1.2 Types of Material Failure
1.3 Design and Materials Selection
1.4 Technological Challenge
1.5 Economic Importance of Fracture
1.6 Summary

References
Problems and Questions

2 Structure and Deformation in Materials

2.1 Introduction
2.2 Bonding in Solids
2.3 Structure in Crystalline Materials
2.4 Elastic Deformation and Theoretical Strength
2.5 Inelastic Deformation
2.6 Summary

References
Problems and Questions

3 A Survey of Engineering Materials

3.1 Introduction
3.2 Alloying and Processing of Metals
3.3 Irons and Steels
3.4 Nonferrous Metals
3.5 Polymers
<table>
<thead>
<tr>
<th>Section</th>
<th>Title</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>3.6</td>
<td>Ceramics and Glasses</td>
<td>94</td>
</tr>
<tr>
<td>3.7</td>
<td>Composite Materials</td>
<td>100</td>
</tr>
<tr>
<td>3.8</td>
<td>Materials Selection for Engineering Components</td>
<td>105</td>
</tr>
<tr>
<td>3.9</td>
<td>Summary</td>
<td>111</td>
</tr>
<tr>
<td></td>
<td>References</td>
<td>113</td>
</tr>
<tr>
<td></td>
<td>Problems and Questions</td>
<td>114</td>
</tr>
<tr>
<td>4</td>
<td>Mechanical Testing: Tension Test and Other Basic Tests</td>
<td>118</td>
</tr>
<tr>
<td>4.1</td>
<td>Introduction</td>
<td>118</td>
</tr>
<tr>
<td>4.2</td>
<td>Introduction to Tension Test</td>
<td>123</td>
</tr>
<tr>
<td>4.3</td>
<td>Engineering Stress–Strain Properties</td>
<td>128</td>
</tr>
<tr>
<td>4.4</td>
<td>Trends in Tensile Behavior</td>
<td>137</td>
</tr>
<tr>
<td>4.5</td>
<td>True Stress–Strain Interpretation of Tension Test</td>
<td>143</td>
</tr>
<tr>
<td>4.6</td>
<td>Compression Test</td>
<td>151</td>
</tr>
<tr>
<td>4.7</td>
<td>Hardness Tests</td>
<td>157</td>
</tr>
<tr>
<td>4.8</td>
<td>Notch-Impact Tests</td>
<td>164</td>
</tr>
<tr>
<td>4.9</td>
<td>Bending and Torsion Tests</td>
<td>169</td>
</tr>
<tr>
<td>4.10</td>
<td>Summary</td>
<td>175</td>
</tr>
<tr>
<td></td>
<td>References</td>
<td>176</td>
</tr>
<tr>
<td></td>
<td>Problems and Questions</td>
<td>177</td>
</tr>
<tr>
<td>5</td>
<td>Stress–Strain Relationships and Behavior</td>
<td>190</td>
</tr>
<tr>
<td>5.1</td>
<td>Introduction</td>
<td>190</td>
</tr>
<tr>
<td>5.2</td>
<td>Models for Deformation Behavior</td>
<td>191</td>
</tr>
<tr>
<td>5.3</td>
<td>Elastic Deformation</td>
<td>201</td>
</tr>
<tr>
<td>5.4</td>
<td>Anisotropic Materials</td>
<td>214</td>
</tr>
<tr>
<td>5.5</td>
<td>Summary</td>
<td>223</td>
</tr>
<tr>
<td></td>
<td>References</td>
<td>225</td>
</tr>
<tr>
<td></td>
<td>Problems and Questions</td>
<td>225</td>
</tr>
<tr>
<td>6</td>
<td>Review of Complex and Principal States of Stress and Strain</td>
<td>234</td>
</tr>
<tr>
<td>6.1</td>
<td>Introduction</td>
<td>234</td>
</tr>
<tr>
<td>6.2</td>
<td>Plane Stress</td>
<td>235</td>
</tr>
<tr>
<td>6.3</td>
<td>Principal Stresses and the Maximum Shear Stress</td>
<td>245</td>
</tr>
<tr>
<td>6.4</td>
<td>Three-Dimensional States of Stress</td>
<td>253</td>
</tr>
<tr>
<td>6.5</td>
<td>Stresses on the Octahedral Planes</td>
<td>260</td>
</tr>
<tr>
<td>6.6</td>
<td>Complex States of Strain</td>
<td>262</td>
</tr>
<tr>
<td>6.7</td>
<td>Summary</td>
<td>267</td>
</tr>
<tr>
<td></td>
<td>References</td>
<td>269</td>
</tr>
<tr>
<td></td>
<td>Problems and Questions</td>
<td>269</td>
</tr>
</tbody>
</table>
7 Yielding and Fracture under Combined Stresses 275

7.1 Introduction 275
7.2 General Form of Failure Criteria 277
7.3 Maximum Normal Stress Fracture Criterion 279
7.4 Maximum Shear Stress Yield Criterion 282
7.5 Octahedral Shear Stress Yield Criterion 288
7.6 Discussion of the Basic Failure Criteria 295
7.7 Coulomb–Mohr Fracture Criterion 301
7.8 Modified Mohr Fracture Criterion 311
7.9 Additional Comments on Failure Criteria 318
7.10 Summary 321
References 322
Problems and Questions 323

8 Fracture of Cracked Members 334

8.1 Introduction 334
8.2 Preliminary Discussion 337
8.3 Mathematical Concepts 344
8.4 Application of $K$ to Design and Analysis 348
8.5 Additional Topics on Application of $K$ 359
8.6 Fracture Toughness Values and Trends 371
8.7 Plastic Zone Size, and Plasticity Limitations on LEFM 381
8.8 Discussion of Fracture Toughness Testing 390
8.9 Extensions of Fracture Mechanics Beyond Linear Elasticity 391
8.10 Summary 398
References 401
Problems and Questions 402

9 Fatigue of Materials: Introduction and Stress-Based Approach 416

9.1 Introduction 416
9.2 Definitions and Concepts 418
9.3 Sources of Cyclic Loading 429
9.4 Fatigue Testing 430
9.5 The Physical Nature of Fatigue Damage 435
9.6 Trends in $S-N$ Curves 441
9.7 Mean Stresses 451
9.8 Multiaxial Stresses 463
9.9 Variable Amplitude Loading 468
9.10 Summary 478
References 479
Problems and Questions 481
10. Stress-Based Approach to Fatigue: Notched Members

10.1 Introduction 491
10.2 Notch Effects 493
10.3 Notch Sensitivity and Empirical Estimates of $k_f$ 497
10.4 Estimating Long-Life Fatigue Strengths (Fatigue Limits) 501
10.5 Notch Effects at Intermediate and Short Lives 506
10.6 Combined Effects of Notches and Mean Stress 510
10.7 Estimating S-N Curves 520
10.8 Use of Component S-N Data 527
10.9 Designing to Avoid Fatigue Failure 536
10.10 Discussion 541
10.11 Summary 542
References 544
Problems and Questions 545

11. Fatigue Crack Growth

11.1 Introduction 560
11.2 Preliminary Discussion 561
11.3 Fatigue Crack Growth Rate Testing 569
11.4 Effects of $R = S_{min}/S_{max}$ on Fatigue Crack Growth 574
11.5 Trends in Fatigue Crack Growth Behavior 584
11.6 Life Estimates for Constant Amplitude Loading 590
11.7 Life Estimates for Variable Amplitude Loading 601
11.8 Design Considerations 607
11.9 Plasticity Aspects and Limitations of LEFM for Fatigue Crack Growth 609
11.10 Environmental Crack Growth 616
11.11 Summary 621
References 623
Problems and Questions 624


12.1 Introduction 638
12.2 Stress–Strain Curves 641
12.3 Three-Dimensional Stress–Strain Relationships 649
12.4 Unloading and Cyclic Loading Behavior from Rheological Models 659
12.5 Cyclic Stress–Strain Behavior of Real Materials 668
12.6 Summary 681
References 683
Problems and Questions 684
13 Stress–Strain Analysis of Plastically Deforming Members 693

13.1 Introduction 693
13.2 Plasticity in Bending 694
13.3 Residual Stresses and Strains for Bending 703
13.4 Plasticity of Circular Shafts in Torsion 707
13.5 Notched Members 710
13.6 Cyclic Loading 722
13.7 Summary 733
    References 734
    Problems and Questions 735

14 Strain-Based Approach to Fatigue 745

14.1 Introduction 745
14.2 Strain Versus Life Curves 748
14.3 Mean Stress Effects 758
14.4 Multiaxial Stress Effects 767
14.5 Life Estimates for Structural Components 771
14.6 Discussion 781
14.7 Summary 789
    References 790
    Problems and Questions 791

15 Time-Dependent Behavior: Creep and Damping 802

15.1 Introduction 802
15.2 Creep Testing 804
15.3 Physical Mechanisms of Creep 809
15.4 Time–Temperature Parameters and Life Estimates 821
15.5 Creep Failure under Varying Stress 833
15.6 Stress–Strain–Time Relationships 836
15.7 Creep Deformation under Varying Stress 841
15.8 Creep Deformation under Multiaxial Stress 848
15.9 Component Stress–Strain Analysis 850
15.10 Energy Dissipation (Damping) in Materials 855
15.11 Summary 864
    References 867
    Problems and Questions 868

Appendix A Review of Selected Topics from Mechanics of Materials 880

A.1 Introduction 880
A.2 Basic Formulas for Stresses and Deflections 880