
Contents

<i>Preface to the second edition</i>	xvii
<i>Preface to the first edition</i>	xix
1 Introduction and overview	1
1.1 Historical background and overview	1
1.1.1 Case study: Fatigue and the Comet airplane	8
1.2 Different approaches to fatigue	11
1.2.1 Total-life approaches	12
1.2.2 Defect-tolerant approach	13
1.2.3 A comparison of different approaches	14
1.2.4 ‘Safe-life’ and ‘fail-safe’ concepts	14
1.2.5 Case study: Retirement for cause	15
1.3 The need for a mechanistic basis	17
1.4 Continuum mechanics	18
1.4.1 Elements of linear elasticity	20
1.4.2 Stress invariants	21
1.4.3 Elements of plasticity	22
1.4.4 Elements of linear viscoelasticity	26
1.4.5 Viscoplasticity and viscous creep	28
1.5 Deformation of ductile single crystals	29
1.5.1 Resolved shear stress and shear strain	30
Exercises	33
 PART ONE: CYCLIC DEFORMATION AND FATIGUE CRACK INITIATION	
2 Cyclic deformation in ductile single crystals	39
2.1 Cyclic strain hardening in single crystals	40
2.2 Cyclic saturation in single crystals	40
2.2.1 Monotonic versus cyclic plastic strains	45
2.3 Instabilities in cyclic hardening	45
2.3.1 Example problem: Identification of active slip systems	47
2.3.2 Formation of dislocation veins	49
2.3.3 Fundamental length scales for the vein structure	52
2.4 Deformation along persistent slip bands	52
2.5 Dislocation structure of PSBs	53
2.5.1 Composite model	57

2.5.2	Example problem: Dislocation dipoles and cyclic deformation	58
2.6	A constitutive model for the inelastic behavior of PSBs	60
2.6.1	General features	60
2.6.2	Hardening in the PSBs	61
2.6.3	Hardening at sites of PSB intersection with the free surface	61
2.6.4	Unloading and reloading	62
2.6.5	Vacancy generation	62
2.7	Formation of PSBs	63
2.7.1	Electron microscopy observations	63
2.7.2	Static or energetic models	65
2.7.3	Dynamic models of self-organized dislocation structures	68
2.8	Formation of labyrinth and cell structures	69
2.8.1	Example problem: Multiple slip	71
2.9	Effects of crystal orientation and multiple slip	72
2.10	Case study: A commercial FCC alloy crystal	74
2.11	Monotonic versus cyclic deformation in FCC crystals	7
2.12	Cyclic deformation in BCC single crystals	79
2.12.1	Shape changes in fatigued BCC crystals	80
2.13	Cyclic deformation in HCP single crystals	82
2.13.1	Basic characteristics of Ti single crystals	83
2.13.2	Cyclic deformation of Ti single crystals	83
	Exercises	84
3	Cyclic deformation in polycrystalline ductile solids	86
3.1	Effects of grain boundaries and multiple slip	86
3.1.1	Monocrystalline versus polycrystalline FCC metals	87
3.1.2	Effects of texture	89
3.2	Cyclic deformation of FCC bicrystals	89
3.2.1	Example problem: Number of independent slip systems	91
3.3	Cyclic hardening and softening in polycrystals	91
3.4	Effects of alloying, cross slip and stacking fault energy	95
3.5	Effects of precipitation	97
3.6	The Bauschinger effect	97
3.6.1	Terminology	98
3.6.2	Mechanisms	99
3.7	Shakedown	101
3.8	Continuum models for uniaxial and multiaxial fatigue	102
3.8.1	Parallel sub-element model	104
3.8.2	Field of work hardening moduli	106
3.8.3	Two-surface models for cyclic plasticity	110
3.8.4	Other approaches	112
3.9	Cyclic creep or ratchetting	113
3.10	Metal-matrix composites subjected to thermal cycling	115

3.10.1 Thermoelastic deformation	115
3.10.2 Characteristic temperatures for thermal fatigue	117
3.10.3 Plastic strain accumulation during thermal cycling	119
3.10.4 Effects of matrix strain hardening	120
3.10.5 Example problem: Critical temperatures for thermal fatigue in a metal-matrix composite	122
3.11 Layered composites subjected to thermal cycling	123
3.11.1 Thermoelastic deformation of a bilayer	124
3.11.2 Thin-film limit: the Stoney formula	127
3.11.3 Characteristic temperatures for thermal fatigue	128
Exercises	129
4 Fatigue crack initiation in ductile solids	132
4.1	132
4.1.1 Earlier observations and viewpoints	133
4.1.2 Electron microscopy observations	134
4.2	137
4.3 Crack initiation along PSBs	141
4.4 Role of surfaces in crack initiation	143
4.5 Computational models for crack initiation	143
4.5.2	145
4.5.3 Example problem: Effects of vacancies	146
4.6 Environmental effects on crack initiation	147
4.7	148
4.8 Crack initiation along grain and twin boundaries	149
4.9 Crack initiation in commercial alloys	152
4.9.1	152
4.9.2 Micromechanical models	155
4.10 Environmental effects in commercial alloys	156
4.11	157
4.11.1 Crack initiation under far-field cyclic compression	158
Exercises	162
5 Cyclic deformation and crack initiation in brittle solids	165
5.1 Degrees of brittleness	166
5.2	167
5.3 Highly brittle solids	169
5.3.2 Constitutive models	170
5.3.3	175
5.3.4 Elevated temperature behavior	176
5.4 Semi-brittle solids	179
5.4.1 Crack nucleation by dislocation pile-up	179

5.4.2	Example problem: Cottrell mechanism for sessile dislocation formation	180
5.4.3	Cyclic deformation	182
5.5	*Transformation-toughened ceramics	184
5.5.1	Phenomenology	185
5.5.2	Constitutive models	187
5.6	Fatigue crack initiation under far-field cyclic compression	191
5.6.1	Example problem: Crack initiation under far-field cyclic compression	196
	Exercises	197
6	Cyclic deformation and crack initiation in noncrystalline solids	200
6.1	Deformation features of semi-/noncrystalline solids	200
6.1.1	Basic deformation characteristics	200
6.1.2	Crazing and shear banding	201
6.1.3	Cyclic deformation: crystalline versus noncrystalline materials	203
6.2	Cyclic stress-strain response	205
6.2.1	Cyclic softening	205
6.2.2	Thermal effects	207
6.2.3	Example problem: Hysteretic heating	207
6.2.4	Experimental observations of temperature rise	209
6.2.5	Effects of failure modes	210
6.3	Fatigue crack initiation at stress concentrations	211
6.4	Case study: Compression fatigue in total knee replacements	213
	Exercises	217
PART TWO: TOTAL-LIFE APPROACHES		219
7	Stress-life approach	221
7.1	The fatigue limit	222
7.2	Mean stress effects on fatigue life	224
7.3	Cumulative damage	227
7.4	Effects of surface treatments	228
7.5	Statistical considerations	231
7.6	Practical applications	235
7.6.1	Example problem: Effects of surface treatments	235
7.6.2	Case study: HCF in aircraft turbine engines	236
7.7	Stress-life response of polymers	237
7.7.1	General characterization	237
7.7.2	Mechanisms	238
7.8	Fatigue of organic composites	239
7.8.1	Discontinuously reinforced composites	240
7.8.2	Continuous-fiber composites	240
7.9	Effects of stress concentrations	242
7.9.1	Fully reversed cyclic loading	242

7.9.2	Combined effects of notches and mean stresses	243
7.9.3	Nonpropagating tensile fatigue cracks	244
7.9.4	Example problem: Effects of notches	244
7.10	Multiaxial cyclic stresses	246
7.10.1	Proportional and nonproportional loading	246
7.10.2	Effective stresses in multiaxial fatigue loading	247
7.10.3	Stress-life approach for tension and torsion	248
7.10.4	The critical plane approach	250
	Exercises	254
8	Strain-life approach	256
8.1	Strain-based approach to total life	256
8.1.1	Separation of low-cycle and high-cycle fatigue lives	256
		257
8.1.3		260
8.1.3	composite	260
8.2	Local strain approach for notched members	262
		263
8.3	Variable amplitude cyclic strains and cycle counting	265
8.3.1		265
8.4	Multiaxial fatigue	268
8.4.1	Measures of effective strain	268
8.4.2		269
8.4.3	Different cracking patterns in multiaxial fatigue	271
8.4.4	Example problem: Critical planes of failure in multiaxial loading	273
8.5		276
	Exercises	278
I PART THREE: DAMAGE-TOLERANT APPROACH		281
9	Fracture mechanics and its implications for fatigue	283
9.1	Griffith fracture theory	283
9.2	Energy release rate and crack driving force	285
9.3	Linear elastic fracture mechanics	288
9.3.1		288
9.3.2	The plane problem	289
9.3.3	Conditions of K-dominance	295
9.3.4	Fracture toughness	296
9.3.5	Characterization of fatigue crack growth	296
9.4	Equivalence of G and K	297
9.4.1	Example problem: G and K for the DCB specimen	298
9.4.2	Example problem: Stress intensity factor for a blister test	300
9.5	Plastic zone size in monotonic loading	302
9.5.1	The Irwin approximation	302
9.5.2	The Dugdale model	303

9.5.3	The Barenblatt model	304
9.6	Plastic zone size in cyclic loading	304
9.7	Elastic-plastic fracture mechanics	307
9.7.1	The J-integral	307
9.7.2	Hutchinson-Rice-Rosengren (HRR) singular fields	308
9.7.3	Crack tip opening displacement	309
9.7.4	Conditions of J-dominance	310
9.7.5	Example problem: Specimen size requirements	312
9.7.6	Characterization of fatigue crack growth	313
9.8	Two-parameter representation of crack-tip fields	316
9.8.1	Small-scale yielding	318
9.8.2	Large-scale yielding	318
9.9	Mixed-mode fracture mechanics	319
9.10	Combined mode I-mode II fracture in ductile solids	320
9.11	Crack deflection	322
9.11.1	Branched elastic cracks	324
9.11.2	Multiaxial fracture due to crack deflection	326
9.12	Case study: Damage-tolerant design of aircraft fuselage	327
	Exercises	328
10	Fatigue crack growth in ductile solids	331
10.1	Characterization of crack growth	331
10.1.1	Fracture mechanics approach	332
10.1.2	Fatigue life calculations	334
10.2	Microscopic stages of fatigue crack growth	335
10.2.1	Stage I fatigue crack growth	335
10.2.2	Stage II crack growth and fatigue striations	335
10.2.3	Models for striation formation	337
10.2.4	Environmental effects on stage II fatigue	340
10.3	Different regimes of fatigue crack growth	341
10.4	Near-threshold fatigue crack growth	343
10.4.1	Models for fatigue thresholds	345
10.4.2	Effects of microstructural size scale	346
10.4.3	Effects of slip characteristics	347
10.4.4	Example problem: Issues of length scales	351
10.4.5	On the determination of fatigue thresholds	352
10.5	Intermediate region of crack growth	354
10.6	High growth rate regime	357
10.7	Case study: Fatigue failure of aircraft structures	358
10.8	Case study: Fatigue failure of total hip components	364
10.9	Combined mode I-mode II fatigue crack growth	368
10.9.1	Mixed-mode fatigue fracture envelopes	369
10.9.2	Path of the mixed-mode crack	370
10.9.3	Some general observations	372
10.10	Combined mode I-mode III fatigue crack growth	373

10.10.1 Crack growth characteristics	374
10.10.2 Estimation of intrinsic growth resistance	378
Exercises	379
11 Fatigue crack growth in brittle solids	383
11.1 Some general effects of cyclic loading on crack growth	384
11.2 Characterization of crack growth in brittle solids	385
11.2.1 Crack growth under static loads	385
11.2.2 Crack growth under cyclic loads	386
11.3 Crack growth resistance and toughening of brittle solids	388
11.3.1 Example problem: Fracture resistance and stability of crack growth	389
11.4 Cyclic damage zone ahead of tensile fatigue crack	392
11.5 Fatigue crack growth at low temperatures	393
11.6 Case study: Fatigue cracking in heart valve prostheses	396
11.7 Fatigue crack growth at elevated temperatures	399
11.7.1 Micromechanisms of deformation and damage due to intergranular/interfacial glassy films	399
11.7.2 Crack growth characteristics at high temperatures	402
11.7.3 Role of viscous films and ligaments	403
Exercises	406
12 Fatigue crack growth in noncrystalline solids	408
12.1 Fatigue crack growth characteristics	408
12.2 Mechanisms of fatigue crack growth	411
12.2.2 Discontinuous growth bands	413
12.2.3	417
12.2.4 Shear bands	419
12.2.5 Some general observations	420
	422
12.3 Fatigue of metallic glasses	424
12.4 Exercises	426
	430
	433
13 Contact fatigue: sliding, rolling and fretting	435
13.1 Basic terminology and definitions	435
13.2 Mechanics of stationary contact under normal loading	439
13.2.1 Elastic indentation of a planar surface	440
13.2.2 Plastic deformation	442
13.2.3 Residual stresses during unloading	443
13.2.4 Example problem: Beneficial effects of surface compressive stresses	444

13.3	Mechanics of sliding contact fatigue	445
13.3.1	Sliding of a sphere on a planar surface	446
13.3.2	Partial slip and complete sliding of a cylinder on a planar surface	447
13.3.3	Partial slip of a sphere on a planar surface	448
13.3.4	Cyclic variations in tangential force	449
13.4	Rolling contact fatigue	451
13.4.1	Hysteretic energy dissipation in rolling contact fatigue	452
13.4.2	Shakedown limits for rolling and sliding contact fatigue	453
13.5	Mechanisms of contact fatigue damage	457
13.5.1	Types of microscopic damage	457
13.5.2		457
13.6	Fretting fatigue	462
13.6.1		462
13.6.2	Fretting fatigue damage	463
13.6.3		466
13.6.4	Example problem: Fracture mechanics methodology for fretting fatigue fracture	469
13.7		474
13.7.1	Design details and geometry	474
13.7.2		474
	Exercises	481
14	Retardation and transients in fatigue crack growth	483
14.1	Fatigue crack closure	484
14.2	Plasticity-induced crack closure	486
14.2.1	Mechanisms	486
14.2.2	Analytical models	490
14.2.3	Numerical models	493
14.2.4	Effects of load ratio on fatigue thresholds	494
14.3	Oxide-induced crack closure	496
14.3.1	Mechanism	496
14.3.2	Implications for environmental effects	497
14.4	Roughness-induced crack closure	500
14.4.1	Mechanism	500
14.4.2	Implications for microstructural effects on threshold fatigue	501
14.5	Viscous fluid-induced crack closure	503
14.5.1	Mechanism	503
14.6	Phase transformation-induced crack closure	504
14.7	Some basic features of fatigue crack closure	505
14.8	Issues and difficulties in the quantification of crack closure	506
14.9	Fatigue crack deflection	507
14.9.1	Linear elastic analyses	508
14.9.2	Experimental observations	511

14.9.3 Example problem: Possible benefits of deflection	512
14.10 Additional retardation mechanisms	515
14.10.1 Crack-bridging and trapping in composite materials	515
14.10.2 On crack retardation in advanced metallic systems	518
14.11 Case study: Variable amplitude spectrum loads	519
14.12 Retardation following tensile overloads	520
14.12.1 Plasticity-induced crack closure	521
14.12.2 Crack tip blunting	522
14.12.3 Residual compressive stresses	523
14.12.4 Deflection or bifurcation of the crack	523
14.12.5 Near-threshold mechanisms	524
14.13 Transient effects following compressive overloads	526
14.13.1 Compressive overloads applied to notched materials	529
14.14 Load sequence effects	529
14.14.1 Block tensile load sequences	530
14.14.2 Tension-compression load sequences	533
14.15 Life prediction models	534
14.15.1 Yield zone models	534
14.15.2 Numerical models of crack closure	535
14.15.3 Engineering approaches	536
14.15.4 The characteristic approach	536
Exercises	537
15 Small fatigue cracks	541
15.1 Definitions of small cracks	543
15.2 Similitude	543
15.3 Microstructural aspects of small flaw growth	544
15.4 Threshold conditions for small flaws	545
15.4.1 Transition crack size	545
15.4.2 Critical size of cyclic plastic zone	547
15.4.3 Slip band models	548
15.5 Fracture mechanics for small cracks at notches	550
15.5.1 Threshold for crack nucleation	551
15.5.2 Example problem: Crack growth from notches	552
15.6 Continuum aspects of small flaw growth	554
15.6.1 Two-parameter characterization of short fatigue cracks	554
15.6.2 Near-tip plasticity	556
15.6.3 Notch-tip plasticity	556
15.7 Effects of physical smallness of fatigue flaws	559
15.7.1 Mechanical effects	559
15.7.2 Environmental effects	561
15.8 On the origins of ‘short crack problem’	562
15.9 Case study: Small fatigue cracks in surface’coatings	564
15.9.1 Theoretical background for cracks approaching interfaces perpendicularly	564

15.9.2 Application to fatigue at surface coatings	566
Exercises	568
16 Environmental interactions: corrosion-fatigue and creep-fatigue	570
16.1 Mechanisms of corrosion-fatigue	570
16.1.1 Hydrogenous gases	571
16.1.2 Aqueous media	572
16.1.3 Metal embrittlement	574
16.2 Nucleation of corrosion-fatigue cracks	574
16.2.1 Gaseous environments	575
16.2.2 Aqueous environments	575
16.3 Growth of corrosion-fatigue cracks	577
16.3.1 Types of corrosion-fatigue crack growth	579
16.3.2 Formation of brittle striations	581
16.3.3 Effects of mechanical variables	583
16.3.4 Models of corrosion-fatigue	585
16.4 Case study: Fatigue design of exhaust valves for cars	586
16.5 Fatigue at low temperatures	588
16.6 Damage and crack initiation at high temperatures	589
16.6.1 Micromechanisms of damage	590
16.6.2 Life prediction models	594
16.7 Fatigue crack growth at high temperatures	598
16.7.1 Fracture mechanics characterization	598
16.7.2 Characterization of creep-fatigue crack growth	601
16.7.3 Summary and some general observations	603
16.8 Case study: Creep-fatigue in steam-power generators	604
Exercises	608
Appendix	609
References	614
Author index	659
Subject index	669