620.140492 WAC 2nd ed.

CONTENTS

Preface Acknowledgments		xiii	
		XV	
1	Stres	s and Strain	1
	1.1	Introduction	1
	1.2	Tensor Notation for Stress	5
	1.3	Stress in Rotated Coordinate System	8
	1.4	Principal Stress	11
		1.4.1 Principal Stresses in Three Dimensions	15
	1.5	Stress Invariants	16
	1.6	Stress Deviator	16
	1.7	Strain	17
	1.8	True Stress and True Strain	20
		1.8.1 True Strain	21
		1.8.2 True Stress	22
		Problems	23
2	Types of Mechanical Behavior		27
	2.1	Introduction	27
	2.2	Elasticity and Brittle Fracture	28
	2.3	Permanent Deformation	31
3	Elasticity		35
	3.1	Introduction	35
	3.2	Elasticity of Isotropic Bodies	36
	3.3	Reduced Notation for Stresses, Strains,	
		and Elastic Constants	38

vi CONTENTS

	3.4 3.5	Effect of Symmetry on Elastic Constants Orientation Dependence of Elastic Moduli in	41
	2.0	Single Crystals and Composites	43
	3.6	Values of Polycrystalline Moduli in Terms of	11
	37	Variation of Elastic Constants with Lattice Parameter	44
	3.8	Variation of Elastic Constants with Temperature	47
	3.9	Elastic Properties of Porous Ceramics	49
	3.10	Stored Elastic Energy	52
		Problems	53
4	Strength of Defect-Free Solids		55
	4.1	Introduction	55
	4.2	Theoretical Strength in Tension	55
	4.3	Theoretical Strength in Shear	59
		Problems	60
5	Linea	r Elastic Fracture Mechanics	63
	5.1	Introduction	63
	5.2	Stress Concentrations	64
	5.3	Griffith Theory of Fracture of a Brittle Solid	65
	5.4	Stress at Crack Tip: An Estimate	69
	5.5	Crack Shape in Brittle Solids	70
	5.6	Irwin Formulation of Fracture Mechanics:	
		Stress Intensity Factor	71
	5.7	Irwin Formulation of Fracture Mechanics:	75
		Energy Release Rate	15
	5 0	5.7.1 Relationship between G and K_1	76
	5.8 5.0	Some Useful Stress Intensity Factors	/9
	5.10	Creake with Internal Loading	81 82
	5.10	Failure under Multiaxial Stress	85
	5.11	Problems	87
6	Measurements of Elasticity, Strength, and Fracture Toughness		89
	6.1	Introduction	89
	6.2	Tensile Tests	91
	6.3	Flexure Tests	95
		6.3.1 Three-Point Bending	98
		6.3.2 Four-Point Bending	100
		6.3.3 Fracture Toughness Measurement by Bending	101
	6.4	Double-Cantilever-Beam Test	104

	6.5	Double-Torsion Test	106
	6.6	Indentation Test	106
		6.6.1 Direct Method	108
		6.6.2 Indirect Method	109
		6.6.3 Modified Method	111
		6.6.4 Summary of the Three Methods	112
		6.6.5 ASTM Standard C 1421 Method	112
	6.7	Biaxial Flexure Testing	113
	6.8	Elastic Constant Determination Using Vibrational	
		and Ultrasonic Methods	113
		Problems	115
7	Statis	tical Treatment of Strength	119
	7.1	Introduction	119
	7.2	Statistical Distributions	120
	7.3	Strength Distribution Functions	121
		7.3.1 Gaussian, or Normal, Distribution	122
		7.3.2 Weibull Distribution	122
		7.3.3 Comparison of the Normal and Weibull Distributions	124
	7.4	Weakest Link Theory	125
	7.5	Determining Weibull Parameters	128
	7.6	Effect of Specimen Size	129
	7.7	Adaptation to Bend Testing	130
	7.8	Safety Factors	136
	7.9	Example of Safe Stress Calculation	136
	7.10	Proof Testing	138
	7.11	Use of Pooled Fracture Data in Linear Regression	
		Determination of Weibull Parameters	140
	7.12	Method of Maximum Likelihood in Weibull Parameter	1 4 1
	7 1 2	Estimation	141
	7.13	Statistics of Failure under Multiaxial Stress	144
	/.14	en Statistical Distributions of Strength	146
	7 1 5	Surface Flaw Distributions and Multiple Flaw	140
	7.15	Distributions	147
		Problems	140
		110000003	147
8	Subcr	itical Crack Propagation	151
	8.1	Introduction	151
	8.2	Observed Subcritical Crack Propagation	152
	8.3	Crack Velocity Theory and Molecular Mechanism	155

viii CONTENTS

	8.4	Time to Failure under Constant Stress	158
	8.5	Failure under Constant Stress Rate	162
	8.6	Comparison of Times to Failure under Constant Stress	
		and Constant Stress Rate	164
	8.7	Relation of Weibull Statistical Parameters with	
		and without Subcritical Crack Growth	164
	8.8	Construction of Strength-Probability-Time Diagrams	166
	8.9	Proof Testing to Guarantee Minimum Life	171
	8.10	Subcritical Crack Growth and Failure from Flaws	
		Originating from Residual Stress Concentrations	172
	8.11	Slow Crack Propagation at High Temperature	173
		Problems	175
9	Stable	Crack Propagation and <i>R</i> -Curve Behavior	177
	9.1	Introduction	177
	9.2	<i>R</i> -Curve (<i>T</i> -Curve) Concept	179
	9.3	<i>R</i> -Curve Effects of Strength Distributions	185
	9.4	Effect of R Curve on Subcritical Crack Growth	186
		Problems	186
10	Overview of Toughening Mechanisms in Ceramics		189
	10.1	Introduction	189
	10.1	Toughening by Crack Deflection	107
	10.2	Toughening by Crack Bowing	193
	10.4	General Remarks on Crack Tip Shielding	194
11	Effec	t of Microstructure on Toughness and Strength	199
	11 1	Introduction	100
	11.1	Fracture Modes in Polycrystalline Ceramics	200
	11.2	Crystalline Anisotropy in Polycrystalline Ceramics	200
	11.5	Effect of Grain Size on Toughness	204
	11.4	Natural Flaws in Polycrystalline Ceramics	210
	11.6	Effect of Grain Size on Fracture Strength	212
	11.7	Effect of Second-Phase Particles on Fracture Strength	217
	11.8	Relationship between Strength and Toughness	219
	11.9	Effect of Porosity on Toughness and Strength	220
	11.10	Fracture of Traditional Ceramics	222
		Problems	224
12	Toug	hening by Transformation	227
	12.1	Introduction	227
	12.2	Basic Facts of Transformation Toughening	228
			0

12.3	Theory of Transformation Toughening	230
12.4	Shear-Dilatant Transformation Theory	233
12.5	Grain-Size-Dependent Transformation Behavior	233
12.6	Application of Theory to Ca-Stabilized Zirconia	242
	Problems	245
13 Mec	hanical Properties of Continuous-Fiber-Reinforced	
Cera	mic Matrix Composites	249
13.1	Introduction	249
13.2	Elastic Behavior of Composites	250
13.3	Fracture Behavior of Composites with Continuous,	
	Aligned Fibers	253
13.4	Complete Matrix Cracking of Composites	
	with Continuous, Aligned Fibers	255
13.5	Propagation of Short, Fully Bridged Cracks	260
13.6	Propagation of Partially Bridged Cracks	264
13.7	Additional Treatment of Crack-Bridging Effects	267
13.8	Additional Statistical Treatments	269
13.9	Summary of Fiber-Toughening Mechanisms	270
13.10	Other Failure Mechanisms in Continuous,	
	Aligned-Fiber Composites	270
13.11	Tensile Stress-Strain Curve of Continuous,	
	Aligned-Fiber Composites	271
13.12	Laminated Composites	273
	Problems	274
14 Mec	nanical Properties of Whisker-, Ligament-, and	
Plate	let-Reinforced Ceramic Matrix Composites	277
14.1	Introduction	277
14.2	Model for Whisker Toughening	278
14.3	Combined Toughening Mechanisms in	
	Whisker-Reinforced Composites	288
14.4	Ligament-Reinforced Ceramic Matrix Composites	288
14.5	Platelet-Reinforced Ceramic Matrix Composites	289
	Problems	289
15 Cycl	c Fatigue of Ceramics	291
15.1	Introduction	291
15.2	Cyclic Fatigue of Metals	292
15.3	Cyclic Fatigue of Ceramics	295
15.4	Mechanisms of Cyclic Fatigue of Ceramics	298
15.5	Cyclic Fatigue by Degradation of Crack Bridges	298
15.6	Short-Crack Fatigue of Ceramics	298
	-	

x CONTENTS

	15.7	Implications of Cyclic Fatigue in Design of Ceramics	301
		Problems	301
16	Ther	mal Stress and Thermal Shock in Ceramics	303
	16.1	Introduction	303
	16.2	Magnitude of Thermal Stresses	304
	16.3	Figure of Merit for Various Thermal Stress Conditions	304
	16.4	Crack Propagation under Thermal Stress	306
		Problems	313
17	Frac	tography	317
	17.1	Introduction	317
	17.2	Qualitative Features of Fracture Surfaces	318
	17.3	Quantitative Fractography	325
	17.4	Fractal Concepts in Fractography	328
	17.5	Fractography of Single Crystals and Polycrystals	328
		Problems	330
18	Dislo	cations and Plastic Deformation in Ductile Crystals	333
	18.1	Introduction	333
	18.2	Definition of Dislocations	334
	18.3	Glide and Climb of Dislocations	337
	18.4	Force on a Dislocation	337
	18.5	Stress Field and Energy of a Dislocation	339
	18.6	Force Required to Move a Dislocation	340
	18.7	Line Tension of a Dislocation	341
	18.8	Dislocation Multiplication	342
	18.9	Forces between Dislocations	343
	18.10	Dislocation Pileups	345
	18.11	Orowan's Equation for Strain Rate	346
	18.12	Dislocation Velocity	347
	18.13	Hardening by Solid Solution and Precipitation	348
	18.14	Slip Systems	349
	18.15	Partial Dislocations	351
	18.10	Deformation Twinning	555
		Problems	356
19	Dislo	cations and Plastic Deformation in Ceramics	357
	19.1	Introduction	357
	19.2	Slip Systems in Ceramics	358
	19.3	Independent Slip Systems	359
	19.4	Plastic Deformation in Single-Crystal Alumina	360
	19.5	Twinning in Aluminum Oxide	366

	19.6	Plastic Deformation of Single-Crystal Magnesium Oxide	368
	19.7	Problems	369
20	Cree	p in Ceramics	371
	20.1	Introduction	371
	20.2	Nabarro-Herring Creep	373
	20.3	Combined Diffusional Creep Mechanisms	374
	20.4	Power Law Creep	376
	20.5	Combined Diffusional and Power Law Creep	3/8
	20.0	Deformation and Eailure	270
	20.7	Demage-Enhanced Creen	380
	20.7	Superplasticity	382
	20.0	Deformation Mechanism Maps	388
	20.7	Problems	388
	~		
21	Cree	p Rupture at High Temperatures and Safe Life Design	391
	21.1	Introduction	391
	21.2	General Process of Creep Damage and Failure in Ceramics	391
	21.3	Monkman–Grant Technique of Life Prediction	395
	21.4	Two-Stage Strain Projection Technique	397
	21.5	Fracture Mechanism Maps	399
		Problems	403
22	Hard	ness and Wear	405
	22.1	Introduction	405
	22.2	Spherical Indenters versus Sharp Indenters	406
	22.3	Methods of Hardness Measurement	408
	22.4	Deformation around Indentation	410
	22.5	Cracking around Indentation	412
	22.6	Indentation Size Effect	413
	22.7	Wear Resistance	416
		Problems	421
23	Mech	anical Properties of Glass and Glass Ceramics	423
	23.1	Introduction	423
	23.2	Typical Inorganic Glasses	423
	23.3	Viscosity of Glass	424
	23.4	Elasticity of Inorganic Glasses	425
	23.5	Strength and Fracture Surface Energy of Inorganic Glasses	426
	23.6	Achieving High Strength in Bulk Glasses	427
	23.7	Glass Ceramics	429
		Problems	429

xii CONTENTS

24	Mechanical Properties of Polycrystalline Ceramics		
	in General and Design Considerations	431	
	24.1 Introduction	431	
	24.2 Mechanical Properties of Polycrystalline Ceramics in General	432	
	24.3 Design Involving Mechanical Properties	436	
Ref	erences	439	
Inde	Index		