

Contents

I	Introduction and Theory	1
1	Introduction	3
2	Transformation Toughening Materials	9
2.1	General	9
2.2	Modern Zirconia-Based Ceramics	10
2.3	Martensitic Transformation	11
2.3.1	Retention of the t -phase	15
2.4	Fabrication and Microstructure of PSZ	17
2.5	Microstructural Development	18
2.5.1	Ca-PSZ	18
2.5.2	Mg-PSZ	21
2.5.3	Y-PSZ	27
2.6	Fabrication and Microstructure of TZP	28
2.6.1	Y-TZP	29
2.6.2	Ce-TZP	30
3	Constitutive Modelling	35
3.1	Introduction	35
3.2	Constitutive Model for Dilatant Transformation Behaviour	36
3.3	Constitutive Model for Shear and Dilatant Transformation Behaviour	43
3.3.1	Stress-Strain Relations during Transformation . . .	44
3.3.2	Transformation Criterion and Transformed Fraction of Material	47
3.3.3	Comparison between the Two Constitutive Models	54
3.3.4	Comparison with Experiment	56

3.4	Constitutive Model for ZTC	58
3.4.1	Equivalent Inclusion Method for Inhomogeneity Problem	59
3.4.2	Transformation Yielding and Twinning of a Single Zirconia Particle	62
3.4.3	Overall Properties and Local Fields	69
3.4.4	Transformation Yielding and Twinning of TTC	73
3.4.5	Transformation Yielding under Uniaxial Loading	76
4	Elastic Solutions for Isolated Transformable Spots	81
4.1	Centres of Transformation	81
4.1.1	Centre of Dilatation	84
4.1.2	Centre of Shear	85
4.1.3	Planar Transformation Strains	87
4.1.4	Complex Representation	89
4.2	Transformation Spots	93
4.2.1	Transformation Spots in an Infinite Plane	93
4.2.2	Transformation Spots in a Half-Plane	96
4.3	Homogeneous Dilatant Inclusions	97
4.3.1	Weight Functions for a Single Inclusion in an Infinite Plane	101
4.3.2	Weight Functions for a Subsurface Inclusion	102
4.3.3	Weight Functions for a Row of Inclusions	103
4.3.4	Weight Functions for a Stack of Inclusions	105
4.3.5	Weight Functions for a Row of Subsurface Inclusions	106
5	Interaction between Cracks and Isolated Transformable Particles	109
5.1	Interaction of a Spot with a Crack	109
5.1.1	Finite crack	109
5.1.2	Semi-Infinite Crack	114
5.2	Stress Intensity Factors	117
5.3	Mode-I Spot Distributions	118
6	Modelling of Cracks by Dislocations	129
6.1	Dislocation Formalism	129
6.1.1	Complex Representation of Dislocations	131
6.2	Representation of Cracks by Dislocations	132
6.2.1	Weight Functions for an Edge Dislocations in an Infinite Plane	136

6.2.2	Weight Functions for a Subsurface Dislocation . . .	137
6.2.3	Weight Functions for a Row of Dislocations	140
6.2.4	Weight Functions for a Stack of Dislocations . . .	143
6.2.5	Weight Functions for a Row of Subsurface Dislocations	146

II Transformation Toughening 151

7	Steady-State Toughening due to Dilatation	153
7.1	Introduction	153
7.2	Toughness Increment for a Semi-Infinite Stationary Crack	155
7.3	Toughening due to Steady-State Crack Growth	157
7.3.1	Steady-State Crack Growth in Super-Critically Transforming Materials	160
7.3.2	Steady-State Crack Growth in Sub-Critically Transforming Materials	166
7.3.3	Influence of Shear on Super-Critical Steady-State Toughening	182
8	R-Curve Analysis	187
8.1	Semi-Infinite Cracks	187
8.1.1	Stationary and Growing Semi-Infinite Crack	191
8.2	Single Internal Cracks	196
8.2.1	Stationary and Growing Internal Crack	199
8.2.2	Relation Between Toughening and Strengthening .	205
8.2.3	Biaxially Loaded Internal Crack	208
8.3	Array of Internal Cracks	214
8.3.1	Mathematical Formulation	214
8.3.2	Onset of crack growth	217
8.3.3	Growing cracks	226
8.4	Surface Cracks	231
8.4.1	Model Description and Theory	232
8.4.2	Single Surface Cracks	236
8.5	Array of Surface Cracks	242
8.6	Steady-State Analysis of an Array of Semi-Infinite Cracks	247
8.6.1	Results and Discussion	253
8.7	Solution Strategies for Interacting Cracks and Inclusions .	261

9	Three-Dimensional Transformation Toughening	271
9.1	Introduction	271
9.2	Three-Dimensional Weight Functions	272
9.3	Dilatational Transformation Strains	285
9.4	Shear Transformation Strains	286
9.4.1	Simple Transformation Domains	289
10	Transformation Zones from Discrete Particles	303
10.1	Introduction	303
10.2	Semi-Infinite Stationary Crack	305
10.3	Semi-Infinite Quasi-Statically Growing Crack	324
10.4	Self-Propagating Transformation (Autocatalysis)	331
10.4.1	A Strip of Transformable Material	331
10.4.2	A Row of Transformable Particles	337
III	Related Topics	341
11	Toughening in DZC	343
11.1	Introduction	343
11.2	Contribution of Phase Transformation to the Toughening of DZC	344
11.2.1	Experimental Evidence	345
11.2.2	Dilatational Contribution to the Toughening of ZTA	347
11.3	Contribution of Microcracking to the Toughening of DZC	351
11.3.1	Introduction	351
11.3.2	Reduction in Moduli and Release of Residual Stress	353
11.3.3	K^{tip}/K^{appl} for Arbitrarily Shaped Regions Con- taining a Dilute Distribution of Randomly Ori- ented Microcracks	358
11.3.4	K^{tip}/K^{appl} for two Nucleation Criteria for Sta- tionary and Steadily-Growing Cracks	359
11.4	Contribution of Small Moduli Differences to the Toughening of TTC	367
11.4.1	Introduction	367
11.4.2	Mathematical Formulation	368
11.4.3	Calculation of Displacement Field	375
11.4.4	Evaluation of Some Integrals	378
11.4.5	Correction for Moduli Differences	384

11.4.6	Results and Discussion	389
11.5	Effective Transformation Strain in Binary Composites . .	390
11.5.1	Introduction	390
11.5.2	Effective Transformation Strains	391
11.5.3	General Bounds and Dilute Estimates	393
12	Toughening in DZC by Crack Trapping	395
12.1	Introduction	395
12.2	Small-Scale Crack Bridging	396
12.3	Crack Trapping by Second-Phase Dispersion	402
12.3.1	Two-Dimensional Crack Trapping Model	402
12.3.2	Three-Dimensional Small-Scale Crack Trapping . .	408
12.4	Crack Trapping by Transformable Second-Phase Dispersion	412
13	Toughening in DZC by Crack Deflection	425
13.1	Stress Intensity Factors at a Kinked Crack Tip	426
13.2	Interaction Between Crack Deflection and Phase Transformation Mechanisms	429
13.3	Crack Deflection in a Zone of Non-homogeneous Transformable Particles	434
13.3.1	Computational Procedure	437
14	Fatigue Crack Growth in Transformation Toughening Ceramics	443
14.1	Introduction	443
14.2	Fatigue Crack Growth From Small Surface Cracks in Transformation Toughening Ceramics	444
14.2.1	Examples of Fatigue Crack Growth	446
14.3	Arrest of Fatigue Cracks in Transformation Toughened Ceramics	453
14.4	Improved Endurance Limit of Zirconia Ceramics by Overloading	459
15	Wear in ZTC	465
15.1	Experimental Observations of Wear in Zirconia Ceramics	465
15.1.1	Partially Stabilized Zirconia, PSZ	465
15.1.2	Tetragonal Zirconia Polycrystal, TZP	468
15.1.3	Zirconia Toughened Alumina, ZTA	469
15.2	Subsurface and Surface Cracks under Contact Loading in Transformation Toughened Ceramics	470

15.3 Mathematical Formulation	472
15.4 Subsurface Crack under Contact Loading	478
15.5 Surface Crack under Contact Loading	485
15.6 Concluding Remarks	497
Bibliography	501
Author Index	517
Subject Index	521