

Contents

Preface *xi*

List of Contributors *xiii*

1 Self-healing Materials: Fundamentals, Design Strategies, and Applications 1

Swapan Kumar Ghosh

- 1.1 Introduction 1
- 1.2 Definition of Self-healing 1
- 1.3 Design Strategies 2
 - 1.3.1 Release of Healing Agents 2
 - 1.3.1.1 Microcapsule Embedment 3
 - 1.3.1.2 Hollow Fiber Embedment 4
 - 1.3.1.3 Microvascular System 8
 - 1.3.2 Reversible Cross-links 9
 - 1.3.2.1 Diels–Alder (DA) and Retro-DA Reactions 10
 - 1.3.2.2 Ionomers 12
 - 1.3.2.3 Supramolecular Polymers 13
 - 1.3.3 Miscellaneous Technologies 17
 - 1.3.3.1 Electrohydrodynamics 17
 - 1.3.3.2 Conductivity 20
 - 1.3.3.3 Shape Memory Effect 21
 - 1.3.3.4 Nanoparticle Migrations 22
 - 1.3.3.5 Co-deposition 22
- 1.4 Applications 23
- 1.5 Concluding Remarks 25

2 Self-healing Polymers and Polymer Composites 29

Ming Qiu Zhang, Min Zhi Rong and Tao Yin

- 2.1 Introduction and the State of the Art 29
- 2.2 Preparation and Characterization of the Self-healing Agent Consisting of Microencapsulated Epoxy and Latent Curing Agent 35
 - 2.2.1 Preparation of Epoxy-loaded Microcapsules and the Latent Curing Agent $\text{CuBr}_2(2\text{-MeIm})_4$ 35

VI Contents

- 2.2.2 Characterization of the Microencapsulated Epoxy 36
- 2.2.3 Curing Kinetics of Epoxy Catalyzed by $\text{CuBr}_2(2\text{-MeIm})_4$ 38
- 2.3 Mechanical Performance and Fracture Toughness of Self-healing Epoxy 43
 - 2.3.1 Tensile Performance of Self-healing Epoxy 43
 - 2.3.2 Fracture Toughness of Self-healing Epoxy 43
 - 2.3.3 Fracture Toughness of Repaired Epoxy 45
- 2.4 Evaluation of the Self-healing Woven Glass Fabric/Epoxy Laminates 49
 - 2.4.1 Tensile Performance of the Laminates 49
 - 2.4.2 Interlaminar Fracture Toughness Properties of the Laminates 51
 - 2.4.3 Self-healing of Impact Damage in the Laminates 57
- 2.5 Conclusions 68

- 3 Self-Healing Ionomers 73**
Stephen J. Kalista, Jr.
 - 3.1 Introduction 73
 - 3.2 Ionomer Background 74
 - 3.2.1 Morphology 75
 - 3.2.2 Ionomers Studied for Self-healing 78
 - 3.3 Self-healing of Ionomers 79
 - 3.3.1 Healing versus Self-healing 80
 - 3.3.2 Damage Modes 81
 - 3.3.3 Ballistic Self-healing Mechanism 83
 - 3.3.4 Is Self-healing an Ionic Phenomenon? (Part I) 84
 - 3.3.5 Is Self-healing an Ionic Phenomenon? (Part II) 86
 - 3.3.6 Self-healing Stimulus 88
 - 3.4 Other Ionomer Studies 89
 - 3.5 Self-healing Ionomer Composites 95
 - 3.6 Conclusions 97

- 4 Self-healing Anticorrosion Coatings 101**
Mikhail Zheludkevich
 - 4.1 Introduction 101
 - 4.2 Reflow-based and Self-sealing Coatings 103
 - 4.2.1 Self-healing Bulk Composites 103
 - 4.2.2 Coatings with Self-healing Ability based on the Reflow Effect 105
 - 4.2.3 Self-sealing Protective Coatings 108
 - 4.3 Self-healing Coating-based Active Corrosion Protection 109
 - 4.3.1 Conductive Polymer Coatings 110
 - 4.3.2 Active Anticorrosion Conversion Coatings 113
 - 4.3.3 Protective Coatings with Inhibitor-doped Matrix 119
 - 4.3.4 Self-healing Anticorrosion Coatings based on Nano-/Microcontainers of Corrosion Inhibitors 122
 - 4.3.4.1 Coatings with Micro-/Nanocarriers of Corrosion Inhibitors 123

4.3.4.2	Coatings with Micro-/Nanocontainers of Corrosion Inhibitors	128
4.4	Conclusive Remarks and Outlook	133
5	Self-healing Processes in Concrete	141
	<i>Erk Schlangen and Christopher Joseph</i>	
5.1	Introduction	141
5.2	State of the Art	144
5.2.1	Definition of Terms	144
5.2.1.1	Intelligent Materials	144
5.2.1.2	Smart Materials	145
5.2.1.3	Smart Structures	145
5.2.1.4	Sensory Structures	146
5.2.2	Autogenic Healing of Concrete	146
5.2.3	Autonomic Healing of Concrete	147
5.2.3.1	Healing Agents	148
5.2.3.2	Encapsulation Techniques	149
5.3	Self-healing Research at Delft	152
5.3.1	Introduction	152
5.3.2	Description of Test Setup for Healing of Early Age Cracks	152
5.3.3	Description of Tested Variables	154
5.3.4	Experimental Findings	155
5.3.4.1	Influence of Compressive Stress	155
5.3.4.2	Influence of Cement Type	156
5.3.4.3	Influence of Age When the First Crack is Produced	158
5.3.4.4	Influence of Crack Width	159
5.3.4.5	Influence of Relative Humidity	159
5.3.5	Simulation of Crack Healing	159
5.3.6	Discussion on Early Age Crack Healing	163
5.3.7	Measuring Permeability	164
5.3.8	Self-healing of Cracked Concrete: A Bacterial Approach	165
5.4	Self-healing Research at Cardiff	168
5.4.1	Introduction	168
5.4.2	Experimental Work	169
5.4.2.1	Preliminary Investigations	169
5.4.2.2	Experimental Procedure	172
5.4.3	Results and Discussion	173
5.4.4	Modeling the Self-healing Process	175
5.4.5	Conclusions and Future Work	177
5.5	A View to the Future	178
5.6	Acknowledgments	179
6	Self-healing of Surface Cracks in Structural Ceramics	183
	<i>Wataru Nakao, Koji Takahashi and Kotoji Ando</i>	
6.1	Introduction	183
6.2	Fracture Manner of Ceramics	183

VIII | Contents

- 6.3 History 185
- 6.4 Mechanism 187
- 6.5 Composition and Structure 190
 - 6.5.1 Composition 190
 - 6.5.2 SiC Figuration 192
 - 6.5.3 Matrix 193
- 6.6 Valid Conditions 194
 - 6.6.1 Atmosphere 194
 - 6.6.2 Temperature 195
 - 6.6.3 Stress 198
- 6.7 Crack-healing Effect 200
 - 6.7.1 Crack-healing Effects on Fracture Probability 200
 - 6.7.2 Fatigue Strength 202
 - 6.7.3 Crack-healing Effects on Machining Efficiency 204
- 6.8 New Structural Integrity Method 207
 - 6.8.1 Outline 207
 - 6.8.2 Theory 207
 - 6.8.3 Temperature Dependence of the Minimum Fracture Stress Guaranteed 209
- 6.9 Advanced Self-crack Healing Ceramics 212
 - 6.9.1 Multicomposite 212
 - 6.9.2 SiC Nanoparticle Composites 213
- 7 Self-healing of Metallic Materials: Self-healing of Creep Cavity and Fatigue Cavity/crack 219**
Norio Shinya
 - 7.1 Introduction 219
 - 7.2 Self-healing of Creep Cavity in Heat Resisting Steels 220
 - 7.2.1 Creep Fracture Mechanism and Creep Cavity 221
 - 7.2.2 Sintering of Creep Cavity at Service Temperature 223
 - 7.2.3 Self-healing Mechanism of Creep Cavity 225
 - 7.2.3.1 Creep Cavity Growth Mechanism 225
 - 7.2.3.2 Self-healing Layer on Creep Cavity Surface 226
 - 7.2.4 Self-healing of Creep Cavity by B Segregation 227
 - 7.2.4.1 Segregation of Trace Elements 227
 - 7.2.4.2 Self-healing of Creep Cavity by B Segregation onto Creep Cavity Surface 229
 - 7.2.4.3 Effect of B Segregation on Creep Rupture Properties 234
 - 7.2.5 Self-healing of Creep Cavity by BN Precipitation on to Creep Cavity Surface 234
 - 7.2.5.1 Precipitation of BN on Outer Free Surface by Heating in Vacuum 234
 - 7.2.5.2 Self-healing of Creep Cavity by BN Precipitation 234
 - 7.2.5.3 Effect of BN Precipitation on Creep Rupture Properties 238
 - 7.3 Self-healing of Fatigue Damage 241
 - 7.3.1 Fatigue Damage Leading to Fracture 241

7.3.2	Delivery of Solute Atom to Damage Site	242
7.3.2.1	Pipe Diffusion	242
7.3.2.2	Solute-vacancy Complexes	243
7.3.3	Self-healing Mechanism for Fatigue Cavity/Crack	243
7.3.3.1	Closure of Fatigue Cavity/Crack by Deposition of Precipitate	244
7.3.3.2	Closure of Fatigue Cavity/Crack by Volume Expansion with Precipitation	244
7.3.3.3	Replenishment of Strengthening Phase by Dynamic Precipitation on Dislocation	244
7.3.4	Effect of Self-healing on Fatigue Properties of Al Alloy	246
7.4	Summary and Remarks	247
8	Principles of Self-healing in Metals and Alloys: An Introduction	251
	<i>Michele V. Manuel</i>	
8.1	Introduction	251
8.2	Liquid-based Healing Mechanism	252
8.2.1	Modeling of a Liquid-assisted Self-healing Metal	256
8.3	Healing in the Solid State: Precipitation-assisted Self-healing Metals	257
8.3.1	Basic Phenomena: Age (Precipitation) Hardening	257
8.3.2	Self-healing in Aluminum Alloys	258
8.3.3	Self-healing in Steels	261
8.3.4	Modeling of Solid-state Healing	262
8.4	Conclusions	263
9	Modeling Self-healing of Fiber-reinforced Polymer–matrix Composites with Distributed Damage	267
	<i>Ever J. Barbero, Kevin J. Ford, Joan A. Mayugo</i>	
9.1	Introduction	267
9.2	Damage Model	268
9.2.1	Damage Variable	268
9.2.2	Free-energy Potential	269
9.2.3	Damage Evolution Equations	270
9.3	Healing Model	272
9.4	Damage and Plasticity Identification	274
9.5	Healing Identification	277
9.6	Damage and Healing Hardening	279
9.7	Verification	280
	Index	285

