

# Contents

<b>Aims and scope</b>	<b>xv</b>
<b>Acknowledgments</b>	<b>xviii</b>
<b>Errata</b>	<b>xviii</b>
<b>Contributors</b>	<b>xix</b>
<b>1 Electromagnetic effects, Ernest K. Condon III and Paul J. Jonas</b>	<b>1</b>
1.1 Major design areas for electromagnetic effects . . . . .	1
1.1.1 Electromagnetic compatibility . . . . .	2
1.1.2 Electromagnetic interference . . . . .	2
1.1.3 Electrical bonding and grounding . . . . .	3
1.1.4 Direct effects of lightning . . . . .	3
1.1.5 Indirect effects of lightning . . . . .	4
1.1.6 Precipitation static . . . . .	4
1.1.7 High intensity radiated field . . . . .	5
1.1.8 Power distribution . . . . .	5
1.1.9 Electrostatic discharge . . . . .	5
1.1.10 Nuclear electromagnetic pulse . . . . .	5
1.1.11 Atmospheric radiation . . . . .	6
1.1.12 Antenna performance . . . . .	6
1.2 Primary physical characteristics affecting EME . . . . .	6
1.2.1 Conductivity/resistivity . . . . .	6
1.2.2 Shielding effectiveness . . . . .	7
1.2.3 Contact resistance . . . . .	7
1.3 Test/analysis methods . . . . .	7
1.3.1 Conductivity/resistivity . . . . .	7
1.3.2 Shielding effectiveness . . . . .	8
1.4 Specific impacts to EME and mitigation approaches . . . . .	9
1.4.1 Electromagnetic compatibility . . . . .	9
1.4.2 Electromagnetic interference (EMI) . . . . .	9
1.4.3 Electrical bonding and grounding . . . . .	11
1.4.4 Direct effects of lightning . . . . .	12
1.4.5 Indirect effects of lightning . . . . .	13

1.4.6	Precipitation static . . . . .	18
1.4.7	High intensity radiated field . . . . .	19
1.4.8	Power distribution . . . . .	20
1.4.9	Electrostatic discharge . . . . .	20
1.4.10	Nuclear electromagnetic pulse . . . . .	21
1.4.11	Atmospheric radiation . . . . .	21
1.4.12	Antenna performance . . . . .	21
1.5	Conclusions . . . . .	22
	Bibliography . . . . .	22
<b>2</b>	<b>Lightning strike protection systems, Gasser F. Abdelal</b>	<b>25</b>
2.1	Introduction . . . . .	25
2.2	Experimental verification . . . . .	31
2.3	Virtual verification . . . . .	33
2.4	Free electric arc model . . . . .	46
2.4.1	Formulation . . . . .	48
2.4.2	Electric module (ec) and Magnetic module (mf) . . . . .	48
2.5	Similitude modeling . . . . .	50
2.6	Numerical simulation . . . . .	53
2.7	Conclusions . . . . .	54
	Bibliography . . . . .	57
<b>3</b>	<b>Toughening for impact damage, Timothy L. Norman and C. T. Sun</b>	<b>61</b>
3.1	Low velocity impact . . . . .	61
3.2	Low velocity impact testing . . . . .	65
3.3	Impact damage characterization . . . . .	66
3.3.1	Impact surface inspection . . . . .	66
3.3.2	X-ray analysis . . . . .	66
3.3.3	Ultrasonic c-scan . . . . .	66
3.3.4	Cross sectional analysis using photomicrographs . . . . .	68
3.4	Modes of failure in low velocity impact . . . . .	68
3.4.1	Matrix cracking and transverse shear cracking . . . . .	68
3.4.2	Delamination . . . . .	69
3.4.3	Fiber breakage . . . . .	70
3.5	Post-impact residual properties . . . . .	70
3.5.1	Residual compressive strength . . . . .	72
3.5.2	Residual tensile strength . . . . .	72
3.6	Approaches to reduce low velocity impact damage . . . . .	72
3.6.1	Enhancements to fiber, matrix, and interphase . . . . .	73
3.6.2	Nanoparticles/Nanotubes . . . . .	76
3.6.3	Self-healing fiber reinforced composites . . . . .	79
3.6.4	Hybridization . . . . .	80
3.6.5	Textile composites . . . . .	81
3.6.6	Stitching . . . . .	83
3.7	Conclusions . . . . .	89

Bibliography . . . . .	89
<b>4 Erosion resistance, Edmond Tobin, Aidan Cloonan, and Trevor Young</b>	<b>99</b>
4.1 Liquid droplet erosion . . . . .	99
4.1.1 Erosion mechanism . . . . .	100
4.1.2 Test methods . . . . .	104
4.1.3 Theoretical models . . . . .	109
4.2 Solid particle erosion . . . . .	113
4.2.1 SPE performance of neat polymers . . . . .	113
4.2.2 Effects of particulate and fibrous components . . . . .	114
4.2.3 Solid particle erosion mechanisms . . . . .	115
4.2.4 Design considerations for composites subjected to SPE . . . . .	117
4.2.5 SPE test methods . . . . .	118
4.3 Other degradation mechanisms . . . . .	121
4.4 Application examples . . . . .	122
4.4.1 Surface protection for wind turbine blades . . . . .	122
4.4.2 Surface protection for propellers and helicopter rotor blades . . . . .	123
4.5 Conclusions . . . . .	124
Bibliography . . . . .	125
<b>5 Acoustic and vibration damping, Edith R. Fotsing, Annie Ross, and Edu Ruiz</b>	<b>133</b>
5.1 Introduction and definitions . . . . .	133
5.2 Aircraft engine acoustic damping . . . . .	138
5.2.1 Porous materials . . . . .	141
5.2.2 Impedance tube . . . . .	142
5.3 Damping of composites in aerospace . . . . .	145
5.3.1 Structural passive damping . . . . .	145
5.3.2 Active vibration damping . . . . .	148
5.4 Viscoelasticity principles . . . . .	148
5.4.1 Damping materials . . . . .	151
5.4.2 Recent developments in damping materials . . . . .	151
5.5 Viscoelastic material characterization . . . . .	153
5.5.1 Dynamic mechanical analysis . . . . .	153
5.6 New trends in passive damping . . . . .	155
5.6.1 Viscoelastic layers embedded into composite laminates . . . . .	155
5.6.2 Analytical modeling of structural damping . . . . .	158
5.6.3 Embedded damping elements into composites . . . . .	160
5.7 Conclusions . . . . .	162
Bibliography . . . . .	164
<b>6 Viscoelastic damping treatments, R.A.S. Moreira</b>	<b>169</b>
6.1 Introduction . . . . .	169
6.2 Viscoelastic damping treatments . . . . .	170
6.2.1 Unconstrained layer damping treatments . . . . .	171

6.2.2	Constrained layer damping treatments . . . . .	172
6.2.3	Integrated layer damping treatments . . . . .	172
6.3	Viscoelastic materials . . . . .	172
6.3.1	Experimental characterization of VEMs . . . . .	173
6.3.2	Experimental data analysis and constitutive model . . . . .	177
6.3.3	Experimental characterization of VEMs – case study . . . . .	178
6.4	Numerical simulation of viscoelastic damping treatments . . . . .	180
6.4.1	Spatial model of layered structures . . . . .	181
6.4.2	Viscoelastic constitutive models . . . . .	184
6.4.3	Analysis method . . . . .	185
6.5	Multilayer and multi material damping treatments . . . . .	188
6.6	Optimization of viscoelastic damping treatments . . . . .	189
6.6.1	Partial damping treatments . . . . .	189
6.6.2	Optimized multilayer damping treatments . . . . .	190
6.6.3	Special spatial configurations . . . . .	191
6.6.4	Hybrid damping treatments . . . . .	192
6.7	Design of viscoelastic damping treatments: fundamental rules . . . . .	193
6.8	Conclusions . . . . .	198
	Bibliography . . . . .	199
<b>7</b>	<b>Self-healing in polymers and structural composites, Kathryn Mireles and Micheal R. Kessler</b>	<b>205</b>
7.1	Introduction to self-healing polymers . . . . .	205
7.2	Self-healing systems: background and design . . . . .	207
7.2.1	Transport assisted self-healing . . . . .	207
7.2.2	Homogeneous self-healing . . . . .	212
7.2.3	Chemistry . . . . .	214
7.3	Self-healing structural polymer composites . . . . .	217
7.3.1	Background and applications of fiber reinforced composites . . . . .	217
7.3.2	Self-healing ‘smart’ composite systems . . . . .	221
7.4	Evaluation of self-healing effects . . . . .	221
7.4.1	Effect on structural properties . . . . .	221
7.4.2	Self-healing efficiency and mechanical properties . . . . .	222
7.4.3	Theoretical considerations . . . . .	226
7.5	Conclusions . . . . .	227
7.5.1	Summary of challenges . . . . .	227
7.5.2	Current state and future directions . . . . .	229
	Bibliography . . . . .	230
<b>8</b>	<b>Microvascular transport, Christopher J. Hansen</b>	<b>237</b>
8.1	Introduction . . . . .	237
8.2	Biological inspiration . . . . .	238
8.2.1	System approach to microvascular transport . . . . .	238
8.2.2	Structural biocomposites with embedded microvasculature . . . . .	239
8.3	Engineering design of microvascular transport . . . . .	240

8.3.1	Physics of microfluidic transport . . . . .	241
8.3.2	Mechanics of embedded vasculature . . . . .	242
8.3.3	Network design . . . . .	245
8.3.4	Pump considerations . . . . .	246
8.3.5	Tools for optimized design . . . . .	247
8.4	Composites processing . . . . .	248
8.4.1	Discrete fluid reservoirs . . . . .	248
8.4.2	Subtractive manufacturing processes . . . . .	248
8.4.3	Additive manufacturing processes . . . . .	249
8.4.4	Non-woven fiber-based processes . . . . .	250
8.4.5	Woven textile-based processes . . . . .	252
8.5	Measurement of microvascular-based functionality . . . . .	252
8.5.1	Fluid transport . . . . .	253
8.5.2	Mechanical effects . . . . .	253
8.5.3	Thermal profile . . . . .	253
8.6	Embodiments of microvascular composites . . . . .	254
8.6.1	Self-healing . . . . .	254
8.6.2	Thermal regulation . . . . .	258
8.6.3	Structural health monitoring . . . . .	260
8.6.4	Structural fluid storage . . . . .	260
8.6.5	Recovery of macroscale mass loss . . . . .	261
8.7	Conclusions . . . . .	261
	Bibliography . . . . .	263
<b>9</b>	<b>Permeation, Shaokai Wang and Ayou Hao</b>	<b>271</b>
9.1	Introduction to gas permeation . . . . .	271
9.2	Gas permeation through polymeric materials . . . . .	273
9.3	Structure and properties of barrier nanoparticles . . . . .	274
9.3.1	Silicate clay . . . . .	274
9.3.2	Graphene . . . . .	274
9.3.3	Other fillers . . . . .	276
9.4	Theoretical analysis of gas permeation . . . . .	277
9.5	Fabrication process of polymer nanocomposites . . . . .	280
9.5.1	Conventional approaches for uniformly dispersed nanocomposites	281
9.5.2	Preparation for nanolaminate structure . . . . .	282
9.6	Influence factors and enhancement of barrier properties . . . . .	283
9.6.1	Geometric factors of barrier nanoplatelets . . . . .	283
9.6.2	Influence of swelling in humid environments . . . . .	284
9.6.3	Alignment of nanofillers . . . . .	286
9.6.4	Influence of hydrophilic or hydrophobic nature . . . . .	287
9.6.5	Enhancement of tortuosity . . . . .	288
9.6.6	Barrier properties of typical polymer nanocomposites . . . . .	292
9.7	Multifunctional characteristics of barrier materials . . . . .	292
9.8	Application of barrier materials . . . . .	294
9.8.1	Fiber-reinforced composites . . . . .	294

9.8.2	Electronics industry . . . . .	296
9.8.3	Food packaging . . . . .	297
9.8.4	Anti-corrosion coatings . . . . .	297
9.9	Conclusions . . . . .	298
	Bibliography . . . . .	298
<b>10</b>	<b>Fire safety, Ning Tian and Aixi Zhou</b>	<b>305</b>
10.1	Introduction . . . . .	305
10.2	Mechanisms of ignition and fire growth . . . . .	307
10.3	Fire safety objectives and strategies . . . . .	308
10.4	Fire properties of PMC materials . . . . .	310
10.4.1	Fire reaction properties . . . . .	311
10.4.2	Fire resistant properties . . . . .	315
10.5	Mechanisms for improving the fire performance of PMCs . . . . .	316
10.5.1	Halogen-based fire retardants (HFRs) . . . . .	317
10.5.2	Phosphorus-based flame retardants (PFRs) . . . . .	318
10.5.3	Intumescent flame retardants (IFRs) . . . . .	319
10.5.4	Mineral filler flame retardants (MFRs) . . . . .	321
10.6	New developments . . . . .	322
10.6.1	Nanofiller fire retardants . . . . .	322
10.6.2	Synergy with traditional FRs . . . . .	323
10.7	Conclusions . . . . .	327
	Bibliography . . . . .	327
<b>11</b>	<b>Thermal protection systems, Maurizio Natali, Luigi Torre, and José Maria Kenny</b>	<b>337</b>
11.1	The hyperthermal environment . . . . .	337
11.2	Non-ablative TPS materials . . . . .	339
11.2.1	NA-TPS on the Space Shuttle . . . . .	339
11.2.2	SSO reusable surface insulation . . . . .	341
11.2.3	Conclusion remarks on non-ablative TPS materials . . . . .	342
11.3	High temperature composites as polymeric ablatives . . . . .	342
11.4	Testing facilities . . . . .	348
11.4.1	The oxy-acetylene torch testbed - OATT . . . . .	349
11.4.2	The simulated solid rocket motor - SSRM . . . . .	349
11.4.3	Plasma jet torches . . . . .	351
11.4.4	Recession rate sensing techniques for TPSs . . . . .	352
11.5	PAs as thermal insulating materials . . . . .	356
11.5.1	Rigid HSMs . . . . .	356
11.5.2	Flexible HSMs for TPSs . . . . .	356
11.5.3	Elastomeric HSMs for SRMs . . . . .	357
11.6	Phenolic impregnated carbon ablators . . . . .	359
11.7	Differences between FRPAs and LCAs . . . . .	360
11.8	Nanostructured ablative materials . . . . .	360
11.8.1	Nanosilica as filler for traditional and nanostructured ablatives	363

11.8.2 Carbon nanofilaments based NRAMs . . . . .	366
11.9 Conclusions . . . . .	368
Bibliography . . . . .	369
<b>12 Magnetoelectric composites, Tomas I. Muchenik and Ever J. Barbero</b>	<b>377</b>
12.1 Introduction . . . . .	377
12.1.1 Electrostatics . . . . .	377
12.1.2 Magnetostatics . . . . .	379
12.1.3 Elasticity . . . . .	379
12.1.4 Direct magnetoelectric effect . . . . .	380
12.1.5 Historical review . . . . .	380
12.1.6 ME effect in composite materials . . . . .	381
12.1.7 Particulate ME composites . . . . .	385
12.1.8 Laminated composites . . . . .	389
12.1.9 Resonance frequency . . . . .	392
12.2 ME thin films . . . . .	393
12.2.1 ME thin films characterization . . . . .	394
12.3 Applications . . . . .	395
12.3.1 Magnetic sensors . . . . .	395
12.3.2 ME harvesters . . . . .	396
12.4 Constitutive equations . . . . .	398
12.5 Geometric configurations . . . . .	402
12.6 Intrinsic properties . . . . .	403
12.6.1 Summary of intrinsic properties . . . . .	406
12.7 Extrinsic ME properties . . . . .	407
12.7.1 Extrinsic ME voltage coefficient . . . . .	409
12.7.2 Extrinsic ME charge coefficient . . . . .	412
12.7.3 Extrinsic ME coupling factor . . . . .	415
12.8 Conclusions . . . . .	417
Bibliography . . . . .	418
<b>Index</b>	<b>425</b>