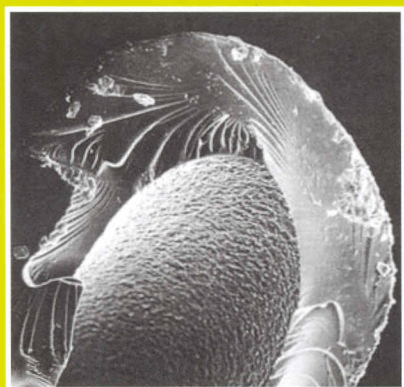


WOODHEAD PUBLISHING IN MATERIALS



Forensic polymer engineering

Why polymer products
fail in service

Peter Rhys Lewis and Colin Gagg



WP

Contents

	<i>Preface</i>	xv
	<i>Acknowledgements</i>	xxi
1	Introduction	1
1.1	Product failure	1
1.1.1	Non-metallic elements	2
1.1.2	Bonding	2
	<i>Covalent bonds</i>	3
	<i>Electrostatic bonds</i>	6
	<i>Hydrogen bonds</i>	7
	<i>van der Waals bonds</i>	9
1.2	Properties of polymers	11
1.2.1	Polymers	11
	<i>High performance polymer fibres</i>	15
	<i>Other uses</i>	15
1.2.2	Natural materials	17
1.2.3	Properties of elastomers	18
1.3	Failure modes	19
1.3.1	Mechanical failure	20
	<i>Loading patterns</i>	21
	<i>Load path</i>	22
	<i>Stress concentrations</i>	23
1.3.2	Chemical attack	26
	<i>Oxidation</i>	27
	<i>Hydrolysis</i>	27
	<i>Ultraviolet radiation</i>	28
1.3.3	Stress corrosion cracking	29
1.3.4	Environmental stress cracking (ESC)	30
1.4	Methods of investigating product failure	32
1.4.1	Sifting the evidence	32

	<i>Witness evidence</i>	33
	<i>Records</i>	33
	<i>Surviving remains</i>	34
1.5	Public information sources	35
1.5.1	Textbooks	36
1.5.2	Event reporting	36
1.5.3	Public domain	37
1.5.4	Materials and product standards	37
1.5.5	Disasters	38
1.6	References	40
2	Examination and analysis of failed components	42
2.1	Introduction	42
2.2	Processing methods and defects	42
2.2.1	Injection moulding	43
2.2.2	Extrusion	47
2.2.3	Other moulding methods	48
2.2.4	Other shaping routes	48
2.3	Mechanical testing	50
2.3.1	Tensile testing	50
2.3.2	Creep and stress relaxation	51
2.3.3	Composite materials	52
2.3.4	Photoelastic strain analysis	53
2.4	Techniques for recording product failures	55
2.4.1	Visual observation	55
2.4.2	Forensic macroscopy	56
2.4.3	Radiography	56
2.5	Forensic microscopy	58
2.5.1	Optical microscopy	59
2.5.2	Scanning electron microscopy	61
2.5.3	ESEM	62
2.6	Types of product defect	63
2.6.1	Mechanical defects	64
2.6.2	Fatigue	66
2.6.3	Friction and wear	67
2.6.4	Environmental failure	68
2.7	Molecular analysis of polymer properties	69
2.7.1	Sampling	69
2.7.2	Chromatography	70
2.7.3	Infra-red spectroscopy	72
2.7.4	Fingerprint spectroscopy	76
2.7.5	Beer-Lambert law	76
2.7.6	UV spectroscopy	77

2.7.7	NMR spectroscopy	79
2.7.8	Other methods	80
2.7.9	Thermal analysis	81
2.8	Integrity of results	85
2.9	Conclusions	86
2.10	References	88
3	Polymeric medical devices	89
3.1	Introduction	89
3.2	Failed catheter	90
3.2.1	Thermoplastic elastomers	91
3.2.2	Accident at childbirth	92
3.2.3	ESEM of the failed end	94
3.2.4	Material and mechanical testing	96
3.2.5	Degradation theory	99
3.2.6	Conclusions	101
3.3	Failure of connectors	102
3.3.1	Connector failures	102
3.3.2	Premature cracking of connectors	103
3.3.3	Disclosure	106
3.3.4	Literature	106
3.3.5	Joint expert examination	107
3.3.6	Injection moulding	110
3.3.7	ESC/SCC hypothesis	110
3.3.8	Discussion	111
3.3.9	Balloon catheters and angioplasty	112
3.4	Failure of a breast tissue expander	114
3.4.1	Failure of tissue expander	114
3.4.2	Loading pattern	118
3.4.3	Conclusion	119
3.4.4	Other cases	120
3.5	Failure of sutures	121
3.5.1	Wound opening	121
3.5.2	Analysis of new suture	122
3.5.3	Possible causes of failure	123
3.5.4	Outcome	124
3.6	Failure of breathing tubes	124
3.6.1	Development of sight tube	124
3.6.2	Faulty tubes	126
3.6.3	Trial	129
3.6.4	Lessons	130
3.7	Conclusions	130
3.8	References	132

4	Polymer storage tanks	134
4.1	Introduction	134
4.2	The Boston molasses disaster	134
4.2.1	Causes of failure	136
4.3	Failure of polypropylene storage tanks	137
4.3.1	Catastrophic failure	138
4.3.2	Investigation	138
4.3.3	Stress concentration	140
4.3.4	Cause of failure	141
4.3.5	Other problems	143
4.3.6	Paint accident	143
4.3.7	Rotational moulded tanks	144
4.3.8	UV degradation	148
4.3.9	Failed battery cases	152
4.4	Failure of fibreglass storage tanks	153
4.4.1	Chopped strand mat	154
4.4.2	Catastrophic failure on Teesside	154
4.4.3	Plant damage	155
4.4.4	Wall and base sections	157
4.4.5	Reassembly of failed parts	160
4.4.6	Fracture locus	162
4.4.7	History of usage	163
4.4.8	Thermal properties of composite	164
4.5	Reconstructing the events leading to failure	166
4.5.1	Thermal expansion	166
4.5.2	Hoop stress	167
4.5.3	Strength of material	167
4.5.4	Reactions in tank	168
4.5.5	Failure sequence	168
4.5.6	The bund	169
4.6	Dealing with the aftermath	170
4.6.1	Standards	170
4.6.2	Acid storage tanks	171
4.6.3	Other failures	172
4.6.4	Glass fibre attack	173
4.7	Setting new standards	173
4.8	References	175
5	Small polymeric containers	176
5.1	Introduction	176
5.2	Failure of battery containers	177
5.2.1	Military batteries	177
5.2.2	Failures	178

5.2.3	Investigation	179
5.2.4	Material analysis	180
5.2.5	Conclusions	181
5.2.6	Aircraft batteries	182
5.2.7	Patent action	182
5.3	Failure of buckets	184
5.3.1	Weld line formation	186
5.4	Exploding batteries	187
5.4.1	Fire brigade incident	188
5.4.2	Material quality	190
5.4.3	Hydrogen explosions	190
5.4.4	Personal injury	191
5.4.5	<i>Hindenburg</i> disaster, 1937	193
5.5	Failed truck battery cases	195
5.5.1	First failures	196
5.6	Failures in miner lamp battery casings	198
5.6.1	New design in polycarbonate	200
5.6.2	First failures	200
5.6.3	Solvent cracking	201
5.6.4	Strain birefringence	203
5.6.5	Property checks	206
5.6.6	Polishing	207
5.6.7	Moulding conditions	211
5.6.8	Stress concentrations	213
5.6.9	Practical applications	215
5.6.10	Colliery experience	217
5.7	Improving design to prevent failure	219
5.7.1	Alleged hydrogen explosion	220
5.7.2	South African lamps	221
5.7.3	Further developments	223
5.8	Conclusions	224
5.9	References	225
6	Polymeric pipes and fittings	226
6.1	Introduction	226
6.2	Fracture of PVC water piping	227
6.2.1	Factory crisis	227
6.2.2	Analysis of broken pipe	228
6.2.3	Reconstruction	232
6.2.4	Stresses on pipe	233
6.2.5	Cause of failure	235
6.3	Failure of PVC water pumps	235
6.3.1	Rising mains	236

6.3.2	Fatigue tests	238
6.3.3	Machined PVC problem	240
6.3.4	Mediation	242
6.4	Failures in gas pipelines	243
6.4.1	Fracture surface	248
6.5	Failures in ABS pipes and fittings	250
6.5.1	Immingham docks	250
6.5.2	Conclusions	253
6.6	Compressed gas explosion	253
6.6.1	Cracked pipe	254
6.6.2	Mechanics	257
6.6.3	Controversy	258
6.7	Failures in polybutylene pipes and acetal resin fittings	259
6.7.1	Acetal fitting fracture	259
6.7.2	Literature review	260
6.7.3	Acetal albatross	263
6.7.4	Degradation mechanism	264
6.7.5	Pipe failures	266
6.7.6	Recent developments	267
6.8	Conclusions	268
6.9	References	270
7	Polymeric seals	272
7.1	Introduction	272
7.2	Failure of elastomeric seals in brakes	273
7.2.1	Scanning electron microscope (SEM) of fracture surface	274
7.2.2	Elastomer analysis	276
7.2.3	Explanation of accident	277
7.3	The Challenger disaster	278
7.4	Failed elastomeric seals in a semi-conductor factory	281
7.4.1	Failed diaphragm seal	282
7.4.2	More failed seals	283
7.4.3	Ozonolysis	287
7.4.4	Independent analyses	287
7.4.5	Sources of ozone	289
7.4.6	Chasing the problem	290
7.4.7	Conclusions	292
7.5	Failures in TPE radiator washers	293
7.5.1	New washers	294
7.5.2	Leaks in CHS systems	294
7.5.3	Simulation experiments	296

7.5.4	Direct examination	298
7.5.5	Hydrolysis	299
7.6	Failures in silicone mastics	301
7.6.1	Fire station training building	301
7.6.2	Sealant analysis	302
7.6.3	Calorimetry	303
7.6.4	Conclusions	304
7.7	Conclusions	306
7.8	References	308
8	Tools and ladders	310
8.1	Introduction	310
8.2	Failure of polypropylene hobby knives	311
8.2.1	Accident reconstruction	311
8.3	Failure of polystyrene components in hobby knives	313
8.3.1	Knife inspection	314
8.4	Failure of handles in angle grinders	316
8.4.1	Fracture surface	317
8.4.2	British Standard for tools	320
8.4.3	Another handle failure	320
8.4.4	The fracture	320
8.4.5	Conclusions	323
8.5	Failure of security caps for gas cylinders	324
8.5.1	Storage failures	325
8.5.2	Development of torque test	327
8.6	Failure of an ABS handle	328
8.6.1	Scanning microscopy	331
8.7	Failure of chairs manufactured from polypropylene	331
8.7.1	Material analysis	333
8.7.2	Another failure	334
8.7.3	Litigation	335
8.8	Failure of swimming pool steps	336
8.8.1	Fatigue crack	336
8.9	Failed polyamide fittings in ladders	338
8.9.1	Failed stepladders	339
8.9.2	Scanning microscopy	342
8.9.3	Another accident	343
8.9.4	Scanning microscopy	344
8.9.5	Product design, quality and testing	345
8.10	Conclusions	346
8.11	References	348

9	Components in transport applications	349
9.1	Introduction	349
9.2	Failure of tailpack in a motorbike accident	350
9.2.1	Seized wheel	350
9.2.2	Deeper analysis	352
9.2.3	Bungee cords	354
9.2.4	Alternative theory	355
9.2.5	Critical speed	357
9.2.6	Skid mark analysis	358
9.2.7	Tailpack design	358
9.3	Failure of drive belts	359
9.3.1	Belt remains	360
9.3.2	Brittle fracture surface	362
9.3.3	Sequence of events	363
9.3.4	Other composite belts	365
9.4	Failure of tyres	365
9.4.1	Truck tyre failure	366
9.4.2	Oxygen and ozone cracking	369
9.4.3	Sequence of events	370
9.4.4	Modern tyre technology	371
9.5	Failed Rilsan nylon fuel pipes	374
9.5.1	First encounters	374
9.5.2	Spider lines	376
9.5.3	Sir John Gielgud	377
9.5.4	Fiat fuel lines	379
9.5.5	A car fire in Ireland	383
9.5.6	Murphy infants-v-Fiat spa	385
9.5.7	Other Mirafiori fires	387
9.5.8	Global markets	388
9.5.9	Fires in tunnels	389
9.6	Stress corrosion cracking of nylon connectors	390
9.7	Conclusions	393
9.8	References	394
10	Consumer products	396
10.1	Introduction	396
10.2	Failure of Noryl plugs	397
10.2.1	Microscopy	398
10.2.2	Material analysis	402
10.2.3	Injection moulding conditions	405
10.2.4	Conclusions	407
10.3	Failure of Noryl busbar plugs	408
10.3.1	Quality control	410

10.4	Residual current devices (RCDs)	411
10.4.1	Patent action	413
10.5	Failure of kettle switches	414
10.6	Failure of fittings on luggage carriers	416
10.6.1	First accident	417
10.6.2	Fracture and other surfaces	417
10.6.3	Failure sequence	419
10.6.4	Conclusion	420
10.6.5	Second accident	420
10.6.6	Fracture surface	421
10.6.7	Contamination	424
10.7	Failure of ABS joints on bike carriers	425
10.7.1	Damaged shells	427
10.7.2	Stress analysis	429
10.7.3	Conclusions	429
10.8	Failure of HDPE baby cot latches	430
10.8.1	Broken latch	431
10.8.2	Analysis	433
10.9	Conclusions	434
10.10	References	437
11	Conclusions	438
11.1	Introduction: causes of product failure	438
11.2	Poor manufacturing methods	438
11.2.1	Faulty moulding	439
11.2.2	Assembly problem	439
11.2.3	Medical devices	440
11.3	Poor design	441
11.3.1	Stress concentrations	442
11.4	Poor choice of materials	443
11.5	Environmental stresses	444
11.5.1	Stress corrosion cracking	445
11.5.2	Oxidation and ozonolysis	446
11.5.3	Environmental stress cracking	448
11.5.4	Data compilations	449
11.6	Access to information	449
11.6.1	Published literature	450
11.6.2	Old problems	451
11.6.3	The internet	452
11.6.4	Wikipedia	453
11.7	References	454
	<i>Index</i>	455