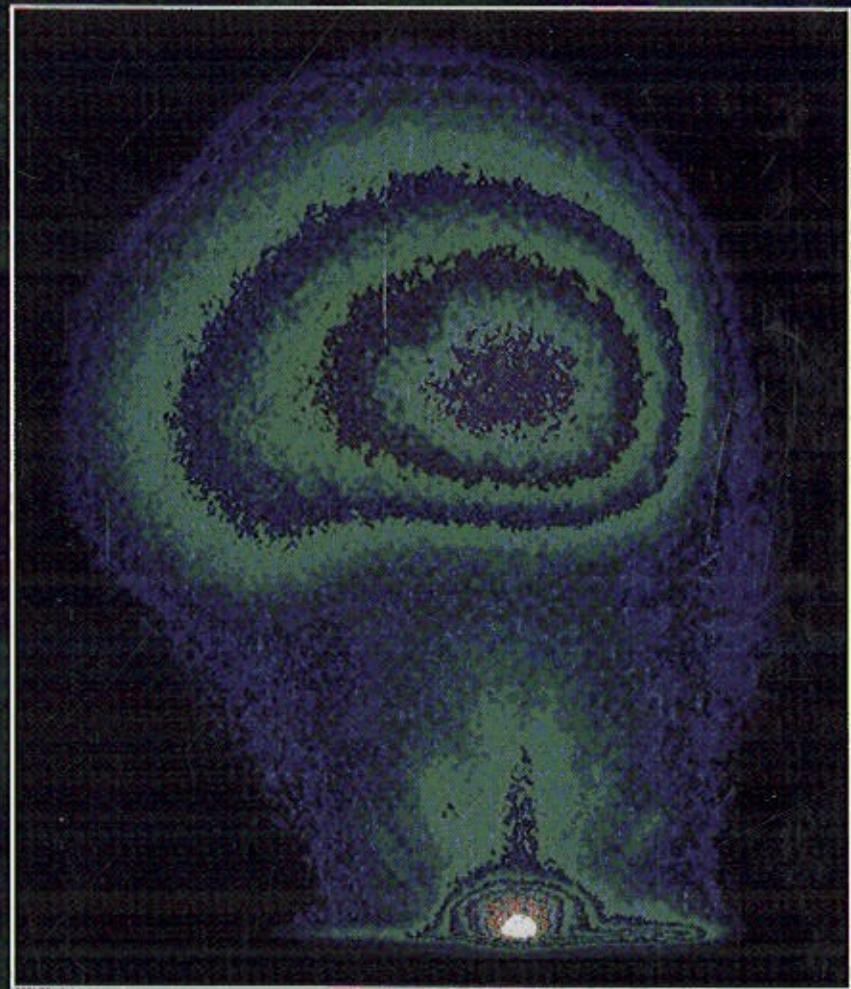


# CARBON FIBERS *and their* COMPOSITES



PETER MORGAN



Taylor & Francis  
Taylor & Francis Group

# Contents

<b>Chapter 1</b>	Structure of the Carbon Atom .....	1
1.1.	Introduction to the Element Carbon, its Isotopes and Allotropes .....	1
1.2.	Structure of Carbon.....	2
1.2.1.	Structure of the Atom .....	2
1.2.2.	Atomic Spectra and Quantum Theory .....	2
1.2.3.	Directional Characteristics of Atomic Orbitals .....	6
1.2.4.	Hybridization of Atomic Orbitals .....	7
1.2.5.	Covalence and Molecular Orbitals .....	9
References .....		13
<b>Chapter 2</b>	The Forms of Carbon.....	15
2.1.	The Allotropes of Carbon .....	15
2.2.	The Carbon Phase Diagram .....	16
2.3.	Diamond .....	17
2.3.1.	Occurrence, Production and Uses of Diamond .....	17
2.3.1.1.	Natural diamonds.....	17
2.3.1.2.	High pressure synthetic diamonds.....	17
2.3.1.3.	Polycrystalline diamond (PCD).....	18
2.3.1.4.	Chemical Vapor Deposition (CVD) diamond .....	18
2.3.1.5.	Diamond-like carbon (DLC).....	18
2.3.2.	Classification of Diamonds .....	19
2.3.3.	Identification of Diamond .....	19
2.3.4.	The Crystal Structure of Diamond .....	19
2.3.5.	The Properties of Diamond.....	20
2.3.5.1.	Density.....	20
2.3.5.2.	Mechanical properties .....	22
2.3.5.2.1.	Hardness .....	22
2.3.5.2.2.	Friction .....	22
2.3.5.2.3.	Elastic properties .....	22
2.3.5.2.4.	Strength .....	23
2.3.5.3.	Thermal properties .....	23
2.3.5.4.	Optical properties .....	23
2.3.5.5.	Electrical properties .....	23
2.3.5.6.	Graphitization .....	23
2.3.5.7.	Chemical resistance .....	23
2.4.	Graphite.....	24
2.4.1.	Introduction.....	24
2.4.2.	Occurrence, Production and Uses of Graphite .....	24
2.4.2.1.	Natural graphite .....	24
2.4.2.2.	Kish graphite .....	24
2.4.2.3.	Synthetic graphite .....	25
2.4.3.	Structure of Graphite .....	27
2.4.4.	The Properties of Graphite.....	31
2.4.4.1.	Density.....	31
2.4.4.2.	Mechanical properties .....	32
2.4.4.2.1.	Elastic properties .....	33

2.4.4.3. Thermal properties .....	35
2.4.4.4. Electrical properties .....	35
2.4.4.5. Chemical resistance.....	36
2.5. Pyrolytic Carbon and Pyrolytic Graphite.....	38
2.6. Glass-like Carbon .....	41
2.7. Carbon Fibers .....	42
2.8. Graphite Whiskers .....	42
2.9. Vapor-Grown Carbon Fibers (VGCF) and Catalytic Chemical Vapor-Deposited (CCVD) Filaments .....	43
2.10. Other Forms of Carbon.....	44
2.10.1. Carbon Black.....	44
2.10.2. Charcoal .....	45
2.10.3. Coal .....	45
2.10.4. Coke .....	46
2.10.5. Soot .....	46
2.11. New Forms of Carbon.....	46
2.11.1. Fullerenes.....	46
2.11.1.1. Discovery and production of fullerenes .....	46
2.11.1.2. Properties and uses of fullerenes .....	53
2.11.2. Carbon Nanotubes .....	56
2.11.2.1. Discovery and production of carbon nanotubes .....	56
2.11.3. Hyperfullerenes.....	59
2.12. Summary of Allotropic Forms of Carbon.....	60
References .....	60

<b>Chapter 3 History and Early Development of Carbon Fibers .....</b>	65
3.1. The Early Inventors.....	65
3.2. Work in the USA .....	66
3.2.1. Black ‘Orlon’ .....	66
3.2.2. Some Early US Carbon Fibers.....	67
3.2.3. More Recent US Carbon Fibers.....	71
3.3. Work in Japan .....	71
3.3.1. Early Work in Japan with PAN Precursor .....	71
3.3.2. Work in Japan with Pitch Precursors .....	72
3.4. Work in the UK with PAN Precursors .....	72
3.4.1. Work at RAE, Farnborough.....	72
3.4.1.1. The RAE work with carbon fiber and cross-licensing of their patent.....	72
3.4.1.2. Surface treatment .....	78
3.4.1.3. Testing and properties of single filaments and composites.....	78
3.4.1.4. Composite fabrication .....	79
3.4.1.5. Friction and wear .....	79
3.4.2. Work at the Atomic Energy Research Establishment, Harwell.....	79
3.4.2.1. Fiber production .....	79
3.4.2.2. Surface treatment .....	84
3.4.2.3. Testing and properties of single filaments and composites .....	84
3.4.2.4. Carbon fiber reinforced ceramics, glass and cement.....	86

3.4.2.5.	Carbon fiber reinforced metal composites .....	87
3.4.2.6.	Composite fabrication and design.....	89
3.4.3.	Work at Rolls Royce, Derby.....	89
3.4.3.1.	Fiber production .....	89
3.4.3.2.	Factors affecting tensile strength of carbon fibers.....	91
3.4.3.3.	Resin formulation and composite fabrication.....	92
3.4.3.4.	Carbon fiber reinforced metal composites .....	97
3.4.4.	Work at Morganite Modmor, London .....	97
3.4.5.	Work at Courtaulds, Coventry.....	98
3.4.5.1.	Carbon fiber production .....	98
3.4.5.2.	Early work with X-ray diffraction to establish structure.....	100
3.4.5.3.	Precursor technology .....	101
3.4.5.4.	Oxidation stage.....	103
3.4.5.5.	Surface treatment .....	111
3.4.5.6.	Testing and properties of virgin carbon fiber and composites .....	112
3.4.5.7.	Production procedures using carbon fiber .....	112
3.4.5.8.	Use and design of carbon fiber in composite materials.....	113
3.5.	Early UK Prepreggers.....	114
3.5.1.	Ciba (ARL) Ltd., Duxford.....	114
3.5.2.	Courtaulds Ltd., Coventry .....	114
3.5.3.	Fothergill and Harvey Ltd. (F&H), Littleborough.....	115
3.5.4.	Rotorway Components Ltd., Clevedon.....	115
References .....		115

<b>Chapter 4</b>	<b>Precursors for Carbon Fiber Manufacture.....</b>	<b>121</b>
4.1.	Introduction .....	121
4.2.	PAN Precursors .....	121
4.2.1.	History .....	122
4.2.1.1.	Commercially available PAN fiber .....	122
4.2.2.	Requirements for a PAN Precursor .....	123
4.2.3.	Homopolymer PAN .....	125
4.2.4.	Comonomers.....	125
4.2.5.	Methods of Polymerization .....	130
4.2.5.1.	Solution polymerization .....	130
4.2.5.2.	Aqueous dispersion polymerization .....	134
4.2.6.	Methods of Spinning .....	136
4.2.6.1.	Wet spinning.....	136
4.2.6.2.	Dry spinning.....	136
4.2.6.3.	Air gap spinning.....	136
4.2.6.4.	Melt spinning.....	139
4.2.7.	Processing Stages .....	141
4.2.8.	Modification of Spun Fiber.....	145
4.2.8.1.	Stretching.....	145
4.2.8.2.	Chemical treatment .....	145
4.2.9.	Structure of PAN Fibers .....	146
4.3.	Cellulosic Precursors .....	148
4.3.1.	Historical Introduction.....	148
4.3.2.	Viscose Rayon Process .....	150

4.3.2.1.	Introduction.....	150
4.3.2.2.	Steeping stage .....	150
4.3.2.3.	Shredding and ageing stages .....	151
4.3.2.4.	Xanthation stage .....	152
4.3.2.5.	Mixing and ripening stages .....	152
4.3.2.6.	Spinning stage.....	152
4.3.2.7.	Final treatment stage.....	153
4.3.3.	Structure of Rayon Fibers.....	154
4.4.	Pitch Precursors .....	156
4.4.1.	Introduction.....	156
4.4.1.1.	Petroleum pitch .....	157
4.4.1.2.	Coal tar pitch .....	158
4.4.2.	Characterization of the Pitch .....	158
4.4.3.	Isotropic Pitches .....	160
4.4.4.	Preparation of Mesophase Pitches .....	161
4.4.4.1.	Introduction.....	161
4.4.4.2.	'Production of mesophase by pyrolysis.....	162
4.4.4.3.	Production of mesophase by solvent extraction.....	164
4.4.4.4.	Production of mesophase by hydrogenation.....	164
4.4.4.5.	Production of mesophase by catalytic modification.....	165
4.4.5.	Melt Spinning Mesophase Precursor Fibers.....	166
4.4.6.	Structure of Pitch Precursor .....	171
4.5.	Other Precursors .....	171
	References .....	175

<b>Chapter 5</b>	<b>Carbon Fiber Production using a PAN Precursor .....</b>	185
5.1.	Introduction .....	185
5.2.	Carbon Fiber Manufacturers.....	185
5.3.	World Supply of PAN based Carbon Fiber.....	186
5.4.	Manufacturing Costs of PAN based Carbon Fiber .....	187
5.5.	Choice of Precursor .....	191
5.6.	Desirable Attributes of a PAN based Precursor Polymer and its Subsequent Production .....	192
5.7.	Types of PAN based Carbon Fiber.....	194
5.8.	A Carbon Fiber Production Line .....	194
5.8.1.	Precursor Station.....	194
5.8.2.	Oxidation.....	195
5.8.3.	Oxidation Plant .....	196
5.8.4.	Removal of Effluent Gases Evolved in the Oxidation Process.....	200
5.8.5.	Oxidized PAN Fiber.....	200
5.8.6.	Low Temperature Carbonization.....	200
5.8.7.	High Temperature Carbonization .....	200
5.8.8.	High Modulus Fiber Production.....	202
5.8.9.	Shrinkage during the Carbon Fiber Process .....	203
5.8.10.	Surface Treatment .....	203
5.8.11.	Sizing .....	203
5.8.12.	Collection .....	203
5.9.	Fine Structure and Texture of PAN based Carbon Fibers .....	203

5.10.	Aspects of Stabilization .....	215
5.10.1.	Structure of PAN Fibers Thermally Stabilized at 350°C.....	218
5.11.	Aspects of Carbonization.....	221
5.11.1.	Methods of Increasing Fiber Modulus and Effect on Strength.....	225
5.11.1.1.	Hot stretching .....	225
5.11.1.2.	Effects of neutron irradiation .....	228
5.11.1.3.	Annealing in the presence of boron .....	229
5.11.2.	Carbon Fiber Yield .....	230
5.12.	Relation of Carbon Fiber Tensile Properties to Process Conditions .....	230
5.13.	Developments.....	232
5.13.1.	Improvements in Carbon Fiber Properties .....	232
5.13.2.	Alternative Polymer Formulations.....	232
5.13.3.	A Family of Controlled Resistance Carbon Fibers .....	233
5.14.	A Review of the Stabilization of PAN Precursors .....	234
5.14.1.	Stabilization Schemes of PAN and Associated Observations.....	235
5.15.	Mechanisms for the Carbonization Stages of PAN Carbon Fibers .....	254
	References .....	259

<b>Chapter 6</b>	<b>Carbon Fiber Production using a Cellulosic based Precursor.....</b>	<b>269</b>
6.1.	Introduction .....	269
6.2.	Current Production.....	272
6.2.1.	Choice of a Suitable Precursor.....	272
6.2.2.	Pyrolysis.....	274
6.2.3.	Carbonization .....	279
6.2.4.	Hot Stretching during Processing of Carbon Fiber .....	279
6.2.5.	Sizing .....	280
6.3.	Mechanisms for the Pyrolysis and Carbonization Stages of Cellulosic based Precursors.....	280
	References .....	292

<b>Chapter 7</b>	<b>Carbon Fiber Production using a Pitch based Precursor .....</b>	<b>295</b>
7.1.	Introduction .....	295
7.2.	Choice of Melt Spun Precursor .....	295
7.3.	The Manufacturing Process .....	296
7.3.1.	Stabilization (thermosetting) of Spun Fiber.....	296
7.3.2.	Carbonization .....	301
7.3.3.	Graphitization.....	303
7.3.4.	Surface Treatment of Pitch based Carbon Fibers .....	304
7.4.	The Structural Ordering and Morphology of Mesophase Pitch Fibers .....	305
7.4.1.	Mechanisms Associated with the Preparation of Pitch Precursors .....	309
7.4.2.	Mechanisms Associated with the Stabilization of Pitch Fiber Precursors.....	320
7.4.3.	Mechanisms Associated with the Carbonization of Pitch Fibers.....	321
	References .....	322

<b>Chapter 8</b>	<b>Production of Vapor Grown Carbon Fibers (VGCF) .....</b>	<b>325</b>
8.1.	Introduction .....	325

8.2. Preparation of VGCF.....	325
8.3. Growth Process.....	334
8.4. Mode of Tensile Failure .....	339
8.5. Mechanical Properties.....	339
References .....	343
<b>Chapter 9 Surface Treatment and Sizing of Carbon Fibers.....</b>	<b>347</b>
9.1. Introduction .....	347
9.2. Oxidative Processes.....	347
9.2.1. Gas Phase Oxidation .....	348
9.2.2. Liquid Phase Oxidation.....	350
9.2.3. Anodic Oxidation .....	352
9.3. Plasma.....	355
9.4. Non-oxidative Surface Treatment—Whiskerization.....	356
9.5. Effect of Surface Treatment on Fiber Properties .....	357
9.5.1. Introduction.....	357
9.5.2. The Effects of Surface Treatment .....	358
9.5.3. Summary.....	362
9.6. Coupling Agents .....	363
9.7. Sizing Carbon Fiber.....	363
9.7.1. Deposition from Solution of a Polymer onto the Fiber Surface .....	363
9.7.2. Deposition of a Polymer onto the Fiber Surface by Electrodeposition .....	367
9.7.3. Deposition of a Polymer onto the Fiber Surface by Electropolymerization.....	369
References .....	370
<b>Chapter 10 Guidelines for the Design of Equipment for Carbon Fiber Plant.....</b>	<b>377</b>
10.1. Introduction .....	377
10.2. Precursor Handling .....	377
10.3. Drive Systems.....	379
10.4. Ovens for Oxidation.....	380
10.5. Removal of Effluent Gases Evolved in the Oxidation Process .....	383
10.6. Application of an Antistatic Finish .....	384
10.7. Plaiter Table.....	384
10.8. LT Carbonization Furnace .....	384
10.8.1. LT Furnace Gas Seals .....	386
10.8.2. LT Furnace Insulation.....	387
10.8.3. Element Materials for LT Furnaces .....	388
10.9. LT Furnace Exhaust Removal .....	392
10.10. HT Carbonization Furnace.....	395
10.10.1. HT Furnace Gas Seals .....	396
10.10.2. HT Furnace Insulation .....	396
10.10.3. Element Materials for HT Furnaces .....	397
10.11. Typical Calculations for the Design of an HT Furnace.....	398
10.12. Sodium Removal.....	400
10.13. HM Heat Treatment Furnace.....	401
10.13.1. HM Furnace Gas Seals.....	401

10.13.2. HM Furnace Insulation .....	402
10.13.3. HM Furnace Element Design .....	402
<b>10.14. Surface Treatment .....</b>	<b>403</b>
10.15. Sizing .....	404
10.16. Drying .....	405
10.17. Online Collection .....	409
10.18. Offline Winding .....	411
10.19. Packaging .....	415
10.20. Exhaust Systems .....	415
10.21. Dust Extraction .....	418
10.22. Application of Closed Circuit Television (CCTV) .....	420
<b>References .....</b>	<b>420</b>
<b>Chapter 11 Operation of Carbon Fiber Plant and Safety Aspects.....</b>	<b>421</b>
11.1. Introduction .....	421
11.2. Serendipity .....	421
11.3. Maintenance .....	423
11.4. Protecting Electrical Equipment .....	423
11.5. Air Flow Measurement .....	424
11.5.1. Measurement of Pressure .....	424
11.5.2. Determination of Velocity .....	424
11.5.3. Determination of Volume Flow .....	429
11.6. Collimation and Spreading of Oxidized and Carbonized Fiber .....	433
11.6.1. Lateral Movement .....	433
11.6.2. Lateral Expansion or Contraction .....	434
11.7. Splicing Small Tows .....	435
11.8. Drive Systems and Rotating Rollers .....	436
11.9. Precursor Creel .....	438
11.10. Oxidation Plant .....	439
11.11. Pyrolysis Plant .....	440
11.12. Low Temperature Carbonization Furnace .....	440
11.13. High Temperature Carbonization Furnace .....	441
11.13.1. Calibration of Pyrometer .....	441
11.14. High Modulus Furnace .....	442
11.15. Surface Treatment .....	442
11.16. Sizing .....	443
11.17. Winding .....	443
11.18. Dealing with Emissions .....	444
11.19. Treatment of Cyanide Effluent .....	444
11.20. Protecting the Environment .....	446
11.21. Safety Committee .....	448
11.22. COSH-H Requirements .....	448
11.23. Toxicology of Carbon Fibers .....	449
11.23.1. Definitions of Exposure Limits .....	449
11.23.2. Data for UK Exposure Limits for Gaseous Emissions .....	449
11.23.3. Possible Hazards with Carbon and Graphite Fibers .....	449
11.24. The Risks of Carbon Fiber Composites in a Fire .....	450
<b>References .....</b>	<b>451</b>

<b>Chapter 12</b>	Techniques for Determining the Structure of Carbon Fibers.....	453
12.1.	Introduction .....	453
12.2.	Optical Microscope .....	453
12.3.	Scanning Electron Microscope (SEM).....	456
12.4.	Transmission Electron Microscope (TEM).....	460
12.5.	X-ray Diffraction .....	464
12.5.1.	Convention for Axes in Graphite and Carbon Fibers and Dimensional Notation.....	464
12.5.2.	Wide Angle X-ray Diffraction.....	466
12.5.3.	Single Crystal X-ray Diffraction .....	470
12.5.4.	X-ray Powder Diffraction .....	470
12.5.5.	Low Angle X-ray Diffraction.....	473
12.6.	Auger Electron Spectroscopy (AES).....	473
12.7.	X-ray Photoelectron Spectroscopy (XPS or ESCA).....	475
12.8.	Ultraviolet Photoemission Spectroscopy (UPS).....	477
12.9.	Infrared Spectroscopy .....	479
12.9.1.	Introduction.....	479
12.9.2.	Fourier Transform Infrared Spectroscopy (FTIR) .....	481
12.9.3.	Fourier Transform Infrared/Attenuated Total Reflectance Spectroscopy (FTIR/ATR).....	483
12.10.	Electron Energy Loss Spectroscopy (EELS).....	483
12.11.	Raman Spectroscopy.....	485
12.11.1.	Surface Enhanced Raman Scattering (SERS) .....	485
12.12.	Secondary Ion Mass Spectrometry (SIMS) .....	485
12.12.1.	Static SIMS.....	486
12.12.2.	Dynamic SIMS .....	489
12.12.3.	Imaging or Microscope SIMS.....	489
12.13.	Scanning Tunnelling Microscopy (STM) .....	490
12.14.	Atomic Force Microscopy (AFM) or Scanning Force Microscopy (SFM) .....	493
	References .....	494

<b>Chapter 13</b>	Polymer Matrices for Carbon Fiber Composites.....	501
13.1.	Selected Thermoset Resins.....	501
13.1.1.	Introduction .....	501
13.1.2.	Phenolic Resins .....	502
13.1.3.	Polyester Resins .....	503
13.1.4.	Epoxy Vinyl Ester Resins .....	507
13.1.5.	Epoxide Resins.....	508
13.1.5.1.	Bisphenol resins .....	508
13.1.5.2.	Novalac resins.....	509
13.1.5.3.	Trifunctional resins.....	511
13.1.5.4.	Tetrafunctional resins .....	511
13.1.5.5.	Cycloaliphatic resins .....	512
13.1.5.6.	New developments.....	512
13.1.5.7.	Epoxy diluents .....	513
13.1.5.8.	Characterization of epoxy resins .....	513
13.1.5.9.	Curing epoxide resins .....	513
13.1.5.10.	Calculating stoichiometric ratios for epoxy resins and curing agents .....	519

13.1.6. Cyanate Resins .....	520
13.1.7. Polyimide Resins.....	521
13.1.7.1. Condensation type polyimides.....	523
13.1.7.2. Addition type polyimides.....	525
13.1.7.2.1. The earliest bismaleimides.....	525
13.1.7.2.2. Bismaleimides .....	527
13.1.7.2.3. Acetylene (ethynyl) terminated polyimides .....	529
13.1.8. Special Resin Systems.....	530
13.1.9. Introducing Toughness to Thermoset Resin Systems.....	530
13.1.9.1. Introduction .....	530
13.1.9.2. Toughening versus flexibilizing.....	531
13.1.9.3. Types of elastomeric modifiers .....	531
13.1.9.4. Duplex materials .....	532
13.1.9.5. Thermoplastic modifiers.....	532
13.1.9.6. Effect of carbon fiber reinforcement.....	533
13.2. Selected Thermoplastic Resins.....	533
13.2.1. Introduction .....	533
13.2.2. Morphology Property Relationships in Semi-crystalline Thermoplastics .....	535
13.2.3. Polyamide (PA) Resins.....	538
13.2.4. Polycarbonate (PC) Resin .....	540
13.2.5. Polyetheretherketone (PEEK) Resin .....	540
13.2.6. Polyetherimide (PEI) Resin.....	542
13.2.7. Polyethersulfone (PES) Resin.....	542
13.2.8. Polyphenylene Sulfide (PPS) Resin .....	543
13.3. Improving the Bond with Carbon Fiber/Thermoplastics .....	543
References .....	544
 <b>Chapter 14</b> Carbon Fiber Carbon Matrix Composites .....	551
14.1. Introduction .....	551
14.2. Selection of Materials for Carbon-Carbon Processing.....	552
14.2.1. Types of Reinforcement.....	552
14.2.1.1. Oxidized PAN fiber (opf).....	552
14.2.1.2. PAN based carbon fibers .....	552
14.2.1.3. Pitch based carbon fibers (pbcf) .....	554
14.2.1.4. Cellulose based carbon fibers....	555
14.2.2. Type of Matrix.....	555
14.2.2.1. Thermosetting resin.....	556
1. Furan resin .....	556
2. Phenolic resins .....	557
3. Polyimide resins .....	557
14.2.2.2. Thermoplastic matrix precursors .....	558
1. Pitch.....	558
2. Other thermoplastic matrices.....	559
14.3. Methods of Processing Carbon-Carbon Matrix Materials.....	560
14.3.1. Introduction .....	560
14.3.2. Use of Gas Phase Impregnation and Densification.....	560
14.3.2.1. Introduction .....	560

14.3.2.2.	CVI processes .....	565	
1.	Isothermal CVI process.....	565	
2.	Thermal gradient CVI process (TG-CVI).....	566	
3.	Pressure gradient process .....	566	
4.	Pulse CVD process.....	566	
5.	Possible new routes .....	566	
14.3.3.	Processing with Thermosetting Resin Matrices .....	567	
14.3.3.1.	Low pressure impregnation (LPI).....	567	
14.3.3.2.	Pressure impregnation and carbonization (PIC).....	568	
14.3.3.3.	Hot isostatic pressure impregnation carbonization (HIPIC) .....	568	
14.4.	Some Thoughts on Carbon-Carbon Processing .....	569	
14.4.1.	Chemical Vapor Deposition.....	569	
14.4.2.	Liquid Infiltration .....	572	
14.5.	Provision for Providing Oxidation Protection.....	573	
14.5.1.	Introduction .....	573	
14.5.2.	The Use of Inhibitors to Provide Oxidation Protection .....	574	
1.	Boron.....	574	
2.	Phosphorus .....	575	
14.5.3.	The Use of a Barrier Coating .....	575	
1.	Noble metals.....	575	
2.	Silicon coatings .....	575	
14.5.4.	Other Coating Systems.....	578	
	References .....	578	
 <b>Chapter 15</b> Carbon Fiber Reinforced Ceramic Matrices .....			583
15.1.	Introduction .....	583	
15.2.	Cement, Concrete and Gypsum Matrices.....	583	
15.2.1.	Cement .....	583	
15.2.2.	Concrete .....	584	
15.2.3.	Concrete Additives .....	584	
15.2.3.1.	Silica fume .....	584	
15.2.3.2.	Dispersant .....	584	
15.2.3.3.	Water reducing agent .....	585	
15.2.3.4.	Accelerator .....	585	
15.2.4.	Work Undertaken with Mortar and Concrete.....	585	
15.2.5.	Theory .....	591	
15.2.6.	Fabrication Processes for cfrc .....	591	
15.3.	Glass Matrices.....	592	
15.3.1.	The Glass Matrix .....	592	
15.3.2.	Methods of Preparation of Carbon Fiber Reinforced Glasses .....	594	
15.3.2.1.	Mode of reinforcement.....	594	
15.3.2.2.	Slurry with hot pressing .....	594	
15.3.2.3.	Hot filament winding under tension with hot pressing above the annealing temperature.....	597	
15.3.2.4.	Melt infiltration.....	597	
15.3.2.5.	Sol gel .....	598	
15.3.3.	Work Undertaken with Carbon Fiber Filled Glass Matrices.....	599	
15.3.4.	Coating Carbon Fiber to Improve the Bond to a Glass .....	601	

15.4. Ceramic Matrices .....	602
15.4.1. Processing Ceramic Matrix Composites.....	602
15.4.2. Types of Ceramic Matrices .....	602
15.4.2.1. Oxide matrix materials .....	603
1. Alumina ( $\text{Al}_2\text{O}_3$ ) .....	603
2. Mullite ( $3\text{Al}_2\text{O}_3 \cdot 2\text{SiO}_2$ ).....	603
3. Zirconia ( $\text{ZrO}_2$ ) .....	603
15.4.2.2. Non-oxide matrix materials .....	603
1. Silicon carbide (SiC) .....	603
2. Titanium carbide (TiC) .....	604
3. Boron carbide ( $\text{B}_4\text{C}$ ) .....	604
4. Titanium boride ( $\text{TiB}_2$ ) .....	604
5. Boron nitride (BN).....	604
6. Aluminium nitride (AlN) .....	604
7. Silicon nitride ( $\text{Si}_3\text{N}_4$ ).....	604
15.4.3. Fiber Reinforcement .....	605
15.4.4. Processing Techniques.....	605
15.4.4.1. Slurry infiltration.....	605
15.4.4.2. Slip casting.....	605
15.4.4.3. Filament winding.....	605
15.4.4.4. Chemical synthesis.....	606
1. Sol gel.....	606
2. Polymer precursor .....	607
15.4.4.5. Melt infiltration .....	609
15.4.4.6. In situ chemical reactions .....	611
1. CVI (or CVD).....	611
2. Slurry pulse/CVI .....	612
3. Hot Isotactic Pressing (HIPing) .....	613
4. Reaction bonding.....	614
15.4.4.7. Consolidation and densification .....	615
1. Sintering .....	615
2. Pressureless sintering .....	615
3. Hot pressing .....	615
15.5.5. Protective Coatings .....	615
15.6.6. Fracture Mechanics.....	617
References .....	617

<b>Chapter 16 Carbon Fibers in Metal Matrices .....</b>	629
16.1. Introduction .....	629
16.2. Metal Matrix Composites .....	629
16.3. Carbon Fiber for Reinforcement of Metal Matrices.....	629
16.4. Coating Processes to Improve Wettability.....	631
16.4.1. CVD Process.....	631
16.4.2. Liquid Metal Transfer Agent (LMTA) Technique.....	632
16.4.3. Cementation.....	632
16.4.4. Electroless Plating .....	632
16.4.5. Electroplating.....	633
16.4.6. Solution Coating .....	633
16.4.7. Flux .....	634

16.4.8.	INCO Ni Coated Carbon Fiber .....	634
16.4.9.	Other Coating Processes .....	635
16.5.	Metal Matrices .....	635
16.5.1.	Aluminium.....	635
16.5.2.	Magnesium .....	639
16.5.3.	Copper.....	639
16.5.4.	Nickel .....	640
16.5.5.	Lead.....	640
16.5.6.	Tin .....	640
16.6.	Techniques for Fabricating Carbon Fiber Reinforced Metal Matrix Composites .....	641
16.6.1.	Factors Influencing Processing of Metal Matrix Composites.....	641
16.6.1.1.	Capillary effects .....	641
16.6.1.2.	Fluid flow into the preform.....	641
16.6.1.3.	Fiber matrix interactions .....	641
16.6.1.4.	The solidification process .....	642
16.6.2.	Processing Methods for Fabricating Metal Matrix Composites.....	642
16.6.2.1.	Solid state processing methods.....	643
1.	Powder metallurgy .....	643
2.	Diffusion bonding.....	643
16.6.2.2.	Liquid state processing .....	644
1.	Melt stirring .....	644
2.	Compocasting or rheocasting.....	644
3.	Slurry casting .....	644
4.	Gravity or vacuum casting.....	644
5.	Pressure casting .....	644
6.	Squeeze casting.....	644
7.	Fiber tow (liquid) infiltration.....	645
8.	Lanxide process.....	646
9.	Liquid phase hot pressing, liquid phase diffusion bonding or liquid phase sintering .....	646
16.6.2.3..	Deposition processes.....	647
1.	Ion plating.....	647
2.	Plasma spraying .....	647
16.6.3.	Fundamental Considerations .....	647
16.6.3.1.	Capillarity .....	647
16.6.3.2.	Fluid flow into the preform.....	648
16.6.3.3.	Fiber matrix interactions .....	648
16.6.3.4.	The solidification process and matrix microstructure .....	648
References .....		649

<b>Chapter 17</b>	<b>Testing of PAN Precursor, Virgin Carbon Fibers, Carbon Fiber Composites and Related Products .....</b>	<b>657</b>
17.1.	Introduction .....	657
17.2.	Testing of PAN Precursor .....	657
17.2.1.	Filament Diameter Distribution in PAN Tow .....	657
17.2.2.	Measurement of Precursor d'tex using the Vibroskop (ASTM D1577).....	660

17.2.3.	Determination of Fiber Moisture Content and Fiber Moisture Regain .....	660
17.2.4.	Determination of Residual Solvent (NaSCN) in Courtelle Precursor.....	661
17.2.5.	Determination of Sodium Content in the Precursor .....	661
	1. Atomic absorption spectrophotometer.....	661
	2. Ion chromatograph.....	661
17.2.6.	Determination of the Soft Finish Content in Courtelle Precursor.....	662
17.2.7.	Silver Sulphide Staining Test for Checking Structure of a PAN Precursor.....	662
17.2.8.	An Experimental Rig for Determination of Precursor Burn-up Temperature.....	662
17.3.	Testing of Oxidized PAN Fiber (OPF) and Virgin Carbon Fiber .....	662
17.3.1.	Mass per Unit Length .....	662
17.3.2.	Determination of Density .....	663
17.3.3.	Determination of Diameter .....	666
	1. Mounting a single filament .....	666
	2. Determining filament diameter using a Watson image shearing eyepiece .....	667
	3. Determination of filament diameter using a He/Ne laser .....	668
	4. Calibration of a Stereoscan with a traceable reference standard .....	669
	5. Preparation of a mini composite (impregnated tow) .....	670
17.3.4.	Tensile Testing of Filament .....	670
	17.3.4.1. Determination of compliance of the tensile test machine system .....	670
	17.3.4.2. Measurment of filament tensile modulus.....	671
	17.3.4.3. Measurment of filament tensile strength .....	674
17.3.5.	Determination of Oxidized PAN Fiber Finish Content.....	674
17.3.6.	Determination of Carbon Fiber Size Content.....	676
17.3.7.	Conductivity of a Water Extract .....	677
17.3.8.	Skin Core.....	677
17.3.9.	Measurement of Electrical Properties.....	678
17.4.	Carbon Fiber Tow Testing .....	678
17.4.1.	Dry Tow Test.....	678
17.4.2.	Testing of the Impregnated Tow .....	679
17.5.	Testing of Carbon Fiber Yarn and Fabric .....	682
17.5.1.	Determination of Twist .....	683
17.5.2.	Determination of Ends and Picks .....	683
17.6.	Testing of Matrix .....	684
17.6.1.	Fineness of Grind .....	684
17.6.2.	Selection of a Suitable Grade of Paper for Resin Coating .....	684
17.6.3.	Determination of Gel Time .....	685
	1. Using the Kofler hotbench.....	685
	2. Determination of gel time at ambient temperature .....	686
17.6.4.	Determination of the Viscosity of a Resin Mix .....	686
17.6.5.	Determination of the Epoxy Molar Mass (EMM) of Epoxy Resins .....	687

1.	Cetyl trimethylammonium bromide-perchloric acid titration method .....	687
2.	Determination of EMM by potentiometric titration .....	688
17.7.	Testing of Carbon Fiber Prepreg .....	688
17.7.1.	Mass per unit Area .....	688
17.7.2.	Volatiles Content.....	688
17.7.3.	Fiber Content.....	688
17.7.4.	Resin Gel Time .....	689
17.8.	Testing of Carbon Fiber Composite .....	689
17.8.1.	Introduction .....	689
17.8.2.	Preparation of Composite Specimen from Wet Resins.....	690
17.8.3.	Preparation of Composite Specimen from Prepreg Systems.....	692
17.8.4.	Determination of Carbon Fiber Content .....	693
17.8.5.	Measurement of Tensile Modulus.....	693
17.8.6.	Measurement Tensile Strength .....	695
17.8.7.	Measurement of Strain using Resistance Strain Gages .....	697
17.8.8.	Measurment of Shear Strength .....	699
17.8.8.1.	Interlaminar shear strength .....	699
17.8.8.2.	In-plane shear tests .....	700
1.	The torsion test.....	700
2.	Two-rail or three-rail shear test.....	701
3.	The double V-notch shear (Iosipescu test) .....	702
4.	Tension coupon test.....	702
5.	The 10° off-axis test.....	704
17.8.9.	Measurement of Flexural Strength and Modulus.....	706
17.8.10.	Measurement of Uniaxial Compressive Strength and Modulus .....	708
17.8.11.	Testing of Fatigue.....	710
17.8.12.	Measurement of Creep.....	712
17.8.13.	Testing of Impact Behavior .....	714
17.8.14.	Measurement of Interlaminar Fracture Toughness .....	714
17.9.	Testing of Carbon Fiber Filled Thermoplastics.....	714
17.9.1.	Measurement of Moisture Content .....	714
17.9.2.	Molding .....	715
17.9.3.	Determination of Melt Flow Index (MFI) .....	717
17.9.4.	Impact Testing of Thermoplastics.....	718
17.10.	Instrumental Analysis .....	718
17.10.1.	Optical Microscope .....	718
17.10.2.	Laboratory Furnace .....	720
17.10.3.	Thermal Analysis .....	721
17.10.3.1.	Differential scanning calorimeter (DSC) .....	721
1.	Classical DTA.....	721
2.	Boersma DTA.....	722
3.	DSC .....	722
17.10.3.2.	Thermogravimetric analysis (TGA) .....	725
17.10.3.3.	Dynamic mechanical analysis (DMA) .....	726
17.10.3.4.	Thermomechanical analysis (TMA).....	729
17.10.4.	Chromatography .....	729
17.10.5.	Infrared Analysis (IR) .....	732
17.10.6.	Elemental Analysis .....	735

17.11.	Non-destructive Testing (NDT) .....	735
17.11.1.	Ultrasonic Testing .....	736
17.11.2.	Radiography .....	738
17.11.3.	Acoustic Emission .....	738
17.12.	Supplement 1 .....	738
17.12.1.	Sinclair's Loop Test for Filament Testing .....	738
	1. Tension testing .....	739
	2. Compression testing .....	739
	References .....	739

<b>Chapter 18</b>	Statistics and Statistical Process Control (SPC) .....	747
18.1.	Frequency Distribution .....	747
18.2.	Location of Data .....	748
18.3.	Measures of Dispersion .....	750
18.4.	Standard Error .....	751
18.5.	Sample Correlation Coefficient .....	751
18.6.	Linear Regression .....	752
18.7.	Normal Distribution .....	753
18.8.	Weibull Distribution .....	756
18.9.	Variation .....	756
18.10.	Control Chart Method .....	758
18.11.	Statistical Process Control Charts .....	758
18.11.1.	Average and Range ( $\bar{x}$ and $R$ ) Chart .....	760
18.11.2.	Mean and Standard Deviation ( $\bar{x}$ and $\sigma$ ) Chart .....	764
18.11.3.	Median Control Chart .....	766
18.11.4.	Rules for Detecting Out-of-control Conditions on Control Charts .....	766
18.11.5.	Cumulative Sum Chart (Cusum) .....	769
18.12.	Capability Index .....	770
18.13.	Failure Mode Effect Analysis (FMEA) .....	771
	References .....	771

<b>Chapter 19</b>	Quality Control .....	773
19.1.	Inhouse Testing .....	773
19.2.	Quality Management and Quality Assurance Standards .....	773
19.3.	The ISO 9000 Family of Standards and Quality Systems .....	774
Para 4.1	Management Responsibility .....	774
Para 4.2	Quality System .....	774
Para 4.3	Contract Review .....	774
Para 4.4	Design Control .....	774
Para 4.5	Document Control and Data .....	774
Para 4.6	Purchasing .....	774
Para 4.7	Control of Customer Supplied Product .....	774
Para 4.8	Product Identification and Traceability .....	774
Para 4.9	Process Control .....	774
Para 4.10	Inspection and Testing .....	774
Para 4.11	Control of Inspection, Measuring and Test Equipment .....	775
Para 4.12	Inspection and Test Status .....	775

Para 4.13	Control of Non-Conforming Product .....	775
Para 4.14	Corrective and Preventive Action .....	775
Para 4.15	Handling, Storage, Packaging, Preservation and Delivery.....	775
Para 4.16	Control of Quality Records.....	775
Para 4.17	Internal Quality Audits.....	775
Para 4.18	Training .....	775
Para 4.19	Servicing.....	775
Para 4.20	Statistical Techniques.....	775
19.4.	Quality Gurus .....	775
19.4.1.	The Early Americans.....	776
19.4.1.1.	W Edwards Deeming .....	776
19.4.1.2.	Joseph M Juran.....	778
19.4.1.3.	Armand V Fiegenbaum.....	779
19.4.2.	The Japanese Gurus .....	779
19.4.2.1.	Dr Kaoru Ishikawa.....	779
19.4.2.2.	Dr Genichi Taguchi .....	780
19.4.2.3.	Shigeo Shindo .....	781
19.4.3.	The New Western Group of Gurus .....	782
19.4.3.1.	Philip B Crosby .....	782
19.4.3.2.	Tom Peters .....	783
19.4.3.3.	Claus Møller.....	784
19.5.	Quality Circles.....	785
19.6.	Total Quality Management.....	786
19.7.	Quality Costing .....	788
	References .....	789

<b>Chapter 20</b>	<b>Properties of Carbon Fibers .....</b>	<b>791</b>
20.1.	The Role of Carbon Fibers.....	791
20.2.	Types of Carbon Fibers Available in the World Market .....	792
20.3.	Tensile Properties .....	800
20.4.	Factors Effecting Composite Strength .....	808
20.5.	The Importance of Critical Aspect Ratio .....	810
20.6.	Elastic Constants.....	811
20.7.	Flexural Properties .....	814
20.8.	Effect of Surface Treatment and Sizing on Composite Properties .....	815
20.9.	Compression Properties .....	817
20.10.	Thermal Properties .....	823
20.11.	Thermal Expansion of Carbon Fibers .....	829
20.12.	Thermal Conductivity of Carbon Fibers .....	831
20.13.	Creep Properties .....	831
20.14.	Impact Strength and Fracture Toughness .....	833
20.15.	Fatigue Properties .....	834
20.16.	Electrical Properties .....	834
20.17.	Chemical Resistance .....	836
20.17.1.	Intercalation .....	837
20.18.	Friction and Wear .....	837
20.19.	Hybrid Composites .....	838
20.20.	Some Selected Properties of Composites .....	839
20.20.1.	Thermoplastic Polymer Matrices.....	839

20.20.2.	Cement Matrices.....	839
20.20.3.	Glass and Ceramic Matrices.....	841
20.20.4.	Carbon-Carbon .....	844
20.21.	Metal Matrices .....	845
	References .....	849

## **Chapter 21 Manufacturing Techniques for Carbon Fiber Reinforced Composites in Thermoset and Thermoplastic Matrices .....**

21.1.	Carbon Fiber Reinforcement and Architecture.....	861
21.1.1.	Virgin Carbon Fiber.....	861
21.1.2.	Non-woven Discontinuous Reinforcement (Staple Fiber) .....	863
21.1.2.1.	Adhesive bonded reinforcements .....	863
21.1.2.1.1.	1. Chopped strand mat (csm).....	863
21.1.2.1.2.	2. Carbon fiber tissue .....	864
21.1.2.1.3.	3. Carbon fiber paper reinforcement.....	864
21.1.2.2.	Needled mat .....	864
21.1.2.3.	Milled fiber.....	864
21.1.2.4.	Chopped carbon fiber .....	865
21.1.3.	Unidirectional Fabrics .....	865
21.1.3.1.	Non-woven UD fabrics.....	865
21.1.3.2.	Woven UD fabrics .....	866
21.1.3.2.1.	1. Warp UD fabric .....	866
21.1.3.2.2.	2. Weft UD fabric .....	866
21.1.4.	Woven Fabrics (2-D Planar or Biaxial Reinforcement).....	866
21.1.4.1.	1. Plain or square weave.....	868
21.1.4.2.	2. Basket (Hopsack) weave.....	868
21.1.4.3.	3. Leno weave .....	869
21.1.4.4.	4. Mock Leno weave .....	870
21.1.4.5.	5. Twill weave .....	871
21.1.4.6.	6. Satin weave .....	871
21.1.4.7.	7. High modulus (non-crimp) weave .....	872
21.1.5.	Woven Spread Tow .....	872
21.1.6.	Knitted Fabrics.....	872
21.1.6.1.	21.1.6.1. Weft knitting .....	874
21.1.6.1.1.	1. Plain knitting.....	874
21.1.6.2.	21.1.6.2. Warp knitting.....	876
21.1.6.2.1.	1. Plain tricot.....	877
21.1.6.2.2.	2. Raschel .....	877
21.1.7.	Inlaid Fabrics .....	877
21.1.8.	Braiding .....	877
21.1.8.1.	21.1.8.1. Forms of braiding .....	879
21.1.8.1.1.	1. Flat braids .....	879
21.1.8.1.2.	2. Sleevings .....	879
21.1.8.1.3.	3. Wide braided fabric.....	879
21.1.8.1.4.	4. Overbraids .....	880
21.1.8.2.	21.1.8.2. Braid architecture.....	880
21.1.8.2.1.	1. Biaxial 2-D braid.....	880
21.1.8.2.2.	2. Triaxial 3-D braid .....	881
21.1.9.	3-D Reinforcements.....	882

21.1.9.1.	Multiaxial non-crimp reinforcements .....	882
1.	Producing a stitched fabric by the simultaneous stitch process .....	883
2.	Producing a stitched fabric by the weave and stitch process .....	885
3.	Double bias fabrics.....	885
4.	Triaxial weave .....	885
5.	Quadraxial .....	889
21.1.9.2.	Woven 3-D fabrics .....	889
21.1.9.3.	Proprietary 3-D weaving processes .....	889
21.1.9.4.	Knitted 3-D fabrics .....	890
21.1.9.5.	Braided 3-D multiaxial.....	890
21.1.9.6.	n-D orthogonal blocks .....	891
21.1.9.7.	Aztex Inc Z-Fiber <sup>TM</sup> .....	893
21.2.	Core Materials .....	893
21.3.	Manufacturing Processes for Carbon Fibers in Thermoset Matrices.....	894
21.3.1.	Contact Molding Wet Lay-up .....	894
21.3.1.1.	Hand lay-up (contact molding) .....	895
21.3.1.2.	Spray lay-up.....	895
21.3.2.	Hot Press Matched Metal Molding.....	896
21.3.2.1.	Thermoset dough molding compound (DMC).....	896
21.3.2.2.	Thermoset bulk molding compound (BMC) .....	896
21.3.2.3.	Thermoset sheet molding compound (SMC).....	896
21.3.3.	Resin Transfer Molding (RTM) .....	897
21.3.3.1.	Dow AdvRTM <sup>TM</sup> .....	898
21.3.3.2.	Vacuum assisted resin transfer molding (VARTM) .....	900
21.3.3.3.	Vacuum infusion processing (VIP) .....	901
21.3.3.4.	Seemann Composite Resin Infusion Molding Process (SCRIMP <sup>TM</sup> ) .....	901
21.3.3.5.	Resin infusion under flexible tooling (RIFT) .....	901
21.3.3.6.	Vacuum infusion molding process (VIMP) .....	901
21.3.3.7.	SP Resin Infusion Technology (SPRINT <sup>TM</sup> ) .....	901
21.3.3.8.	Resin film infusion (RFI) .....	902
21.3.4.	Sequential Multiport Resin Injection System (SMRIM).....	904
21.3.5.	Reaction Injection Molding (RIM) .....	904
21.3.6.	Centrifugal Molding .....	904
21.3.7.	Preparation of Fiber Preforms.....	904
21.3.8.	Flow and Cure Monitoring of Resin Infusion Processes .....	904
21.3.9.	Filament Winding .....	905
1.	Hoop winding.....	906
2.	Helical winding.....	906
3.	Polar winding .....	906
4.	Multiaxial winding .....	907
5.	Variants of multiaxial winding .....	907
21.3.10.	Pultrusion.....	909
1.	Reinforcement handling .....	910
2.	Resin impregnation .....	911
3.	Pre-die forming.....	911
4.	Heated die to shape and cure the resin .....	911
5.	Pulling unit to provide traction.....	912

6.	Cut off saw .....	912
7.	Post cure oven.....	912
21.3.11.	Prepreg Molding .....	913
21.3.11.1.	Prepreg manufacture .....	913
21.3.11.2.	Manufacture of composites from prepreg.....	916
1.	Ply cutting and stacking prepreg .....	916
2.	Compression molding of prepreg .....	916
3.	Vacuum bag molding.....	916
4.	Press-clave molding .....	917
5.	Autoclave molding.....	918
6.	Quickstep <sup>TM</sup> Molding.....	920
7.	Tube rolling .....	921
8.	Automatic tape lay-up.....	921
21.3.12.	Fiber Placement Systems .....	921
21.3.13.	Mold Release .....	922
1.	Polyvinyl alcohol (PVA) .....	923
2.	Waxes.....	923
3.	Internal mold release agents .....	923
4.	Silicones .....	923
5.	Fluorocarbons.....	923
6.	New products.....	923
21.4.	Carbon Fibers in Thermoplastic Matrices.....	923
21.4.1.	The Importance of Critical Aspect Ratio.....	923
21.4.2.	Preparation of Thermoplastic Molding Compounds .....	924
21.4.2.1.	Sizing carbon fiber with compatible thermoplastic polymer size.....	924
21.4.2.2.	Manufacture of thermoplastic molding compound .....	924
1.	Short fiber process .....	924
2.	Long fiber process.....	924
21.4.3.	Injection Molding .....	925
21.4.4.	Film Stacking Process .....	927
21.4.5.	Thermoplastic Prepreg .....	927
1.	Molding carbon fiber/PEI laminate .....	928
2.	Platen pressing of carbon fiber/PEEK laminate .....	928
21.4.6.	Thermoplastic Filament Winding.....	928
21.4.7.	Thermoplastic Pultrusion .....	929
21.4.8.	Continuous Fiber Reinforced Plastic Materials .....	929
21.5.	Hybrid Composites .....	929
	References .....	930
<b>Chapter 22</b>	<b>Design .....</b>	<b>935</b>
22.1.	Design Considerations .....	935
22.2.	Micromechanics .....	935
22.3.	Selection of Materials .....	940
22.4.	Elastic Behavior of Multidirectional Laminates .....	940
22.5.	Choice of Composite Manufacturing Method.....	943
22.6.	Bonding and Joining.....	943
22.7.	Fabrication.....	944

22.8.	Testing and Inspection .....	944
22.9.	Smart Devices .....	944
22.10.	Design Cases .....	945
22.10.1.	Expanding Core Technique .....	945
22.10.2.	A Yacht Mast.....	946
	References .....	946
	Supplementary Bibliography.....	947
 <b>Chapter 23</b> The Uses of Carbon Fibers..... 951		
23.1.	Uses of Oxidized PAN Fiber (OPF).....	951
23.1.1.	Flameproof Applications.....	951
23.1.1.1.	Aviation and aerospace .....	953
23.1.1.2.	Industrial workwear .....	954
23.1.1.3.	Defence and law enforcement .....	954
23.1.1.4.	Transportation and furnishings.....	955
23.1.1.5.	Cable insulation.....	955
23.1.2.	Friction Materials .....	955
23.1.3.	Gland Packings .....	955
23.1.4.	Precursor for PAN based Carbon Fiber and Activated Carbon Fibers .....	955
23.2.	Uses of Virgin Carbon Fiber .....	955
23.2.1.	Activated Carbon Fibers (ACF).....	955
23.2.2.	Molecular Sieves .....	958
23.2.3.	Catalysts.....	958
23.2.4.	Biomedical Applications .....	958
23.3.	Electrical Applications .....	960
23.3.1.	Electrical Conduction .....	960
23.3.2.	Tailored Resistance Carbon Fiber .....	960
23.3.3.	Cathodic Protection .....	960
23.3.4.	Elimination of Static .....	960
23.3.5.	Electrodes.....	961
23.3.6.	Batteries .....	962
23.3.6.1.	Lithium Ion Batteries .....	962
23.3.7.	Fuel Cells .....	964
23.3.7.1.	Alkaline Fuel Cell (AFC).....	965
23.3.7.2.	Proton Exchange Membrane Fuel Cell (PEMFC).....	966
23.3.7.3.	Phosphoric Acid Fuel Cell (PAFC) .....	967
23.3.7.4.	Molten Carbonate Fuel Cell (MCFC) .....	968
23.3.7.5.	Solid Oxide Fuel Cell (SOFC) .....	969
23.3.7.6.	Carbon fiber in fuel cells.....	969
23.4.	Thermal Insulation.....	970
23.5.	Packing Materials and Gaskets .....	973
23.6.	Carbon Fibers in Thermoset Matrices.....	973
23.6.1.	Aerospace.....	973
23.6.1.1.	Defence aircraft .....	973
23.6.1.2.	Civil aircraft .....	973
23.6.1.3.	Helicopters.....	977
23.6.1.4.	Aero engines .....	977
23.6.1.5.	Propeller blades .....	977

23.6.1.6.	Antenna, lightening conductors .....	979
23.6.1.7.	Gliders and sailplanes .....	982
23.6.1.8.	Unmanned Aerial Vehicles (UAVs) .....	982
23.6.1.9.	Stealth aerial vehicles .....	982
23.6.2.	Space .....	982
23.6.3.	Rocket Motor Cases .....	983
23.6.4.	Flywheels.....	983
23.6.5.	Marine Applications .....	987
23.6.5.1.	Yachts.....	987
23.6.5.2.	Submarines .....	989
23.6.5.3.	Air cushion vehicle.....	989
23.6.6.	Oil Exploration .....	989
23.6.7.	Automobile and Racing Car Applications .....	991
23.6.7.1.	Chassis, body and interior .....	991
23.6.7.2.	Brakes and clutches.....	992
23.6.7.3.	Suspension systems.....	992
23.6.7.4.	Push rods.....	993
23.6.7.5.	Air bags.....	993
23.6.8.	Heavy Goods Vehicles and Buses.....	993
23.6.8.1.	Drive shafts .....	993
23.6.8.2.	Buses.....	994
23.6.9.	CNG Storage Cylinders .....	994
23.6.10.	Motor Bikes .....	994
23.6.11.	Railways.....	995
23.6.12.	Engineering and Textile Applications.....	995
23.6.12.1.	Structural work .....	995
23.6.12.2.	Robot arms.....	995
23.6.12.3.	Rollers .....	995
23.6.13.	Turbine Blades .....	995
23.6.13.1.	Wind turbine blades .....	995
23.6.13.2.	Tidal turbine blades.....	997
23.6.14.	Textile Applications .....	998
23.6.15.	Chemical and Nuclear Applications .....	998
23.6.16.	Medical and Prosthetic Applications .....	998
23.6.16.1.	Hospital equipment .....	1000
23.6.17.	Dental .....	1000
23.6.18.	Sports and Leisure Goods .....	1001
23.6.18.1.	Bicycles, tandem .....	1001
23.6.18.2.	Bows and arrows .....	1002
23.6.18.3.	Rifles.....	1002
23.6.18.4.	Skis and ski sticks.....	1002
23.6.18.5.	Snowboards .....	1002
23.6.18.6.	Baseball bats.....	1002
23.6.18.7.	Cricket bats.....	1003
23.6.18.8.	Hockey sticks.....	1003
23.6.18.9.	Golf shafts and heads .....	1003
23.6.18.10.	Tennis, racquetball, badminton and squash racquets.....	1004
23.6.18.11.	Snooker and pool cues .....	1004
23.6.18.12.	Fishing rods and reels .....	1005

23.6.18.13.	Hang glider.....	1005
23.6.18.14.	Canoe paddles .....	1005
23.6.18.15.	Wind surfing.....	1005
23.6.19.	Musical Instruments and Hi-Fi.....	1005
23.6.19.1.	Loudspeaker cones .....	1006
23.6.19.2.	Carbon fiber cable .....	1006
23.6.19.3.	Satellite reflectors .....	1006
23.6.19.4.	Stringed instruments .....	1006
23.6.19.5.	Bows for cello and violin .....	1007
23.6.20.	Other End Uses in Thermoset Matrices.....	1007
23.6.20.1.	Model aeroplanes.....	1007
23.6.20.2.	Knives, fountain pens, watches.....	1007
23.6.20.3.	Precision instruments .....	1008
23.6.20.4.	Tripods .....	1008
23.6.20.5.	Optical instruments .....	1008
	23.6.20.5.1. Telescopes .....	1008
	23.6.20.5.2. Binoculars .....	1009
23.6.21.	Furniture.....	1009
23.6.22.	Carbon Fiber and Wood .....	1009
23.7.	Carbon Fibers in Thermoplastic Matrices .....	1009
23.7.1.	Thermoplastic Molding Compounds.....	1010
23.8.	Carbon Fibers for Carbon-Carbon Applications.....	1010
23.8.1.	Carbon-Carbon Braking Systems.....	1011
23.8.2.	Carbon-Carbon Clutches and Limited Slip Differentials.....	1018
23.8.3.	Carbon-Carbon in Space.....	1020
23.8.4.	Carbon-Carbon for Aircraft.....	1021
23.8.5.	Rocket Motor Nozzles and Expansion Tubes .....	1021
23.8.6.	Carbon-Carbon in Engines.....	1022
23.8.7.	Carbon-Carbon for Biomedical End Uses .....	1022
23.8.8.	Carbon-Carbon in Industry .....	1022
23.8.9.	Carbon-Carbon as a Dielectric Heat Sink .....	1023
23.9.	Carbon Fibers in Cement and Concrete .....	1023
23.9.1.	Carbon Fibers in Cement and Concrete .....	1024
23.9.2.	Carbon Fiber Cement as a Replacement for Asbestos Cement.....	1024
23.9.3.	Strengthening of Reinforced Concrete Chimneys, Columns, Beams and Retrofits .....	1024
23.9.4.	New Structures with cfsp .....	1030
23.10.	Carbon Fibers in Glass Matrices .....	1031
23.11.	Carbon Fibers in Ceramic Matrices .....	1031
23.12.	Carbon Fibers in Metal Matrices .....	1031
23.12.1.	Electromagnetic Interference (EMI) and Heat Dissipation .....	1031
23.13.	Other End Uses for Carbon Fibers .....	1032
	References .....	1032
<b>Chapter 24</b>	<b>Looking to the Future .....</b>	<b>1043</b>
24.1.	The Future .....	1043
24.2.	The Production Process .....	1043
24.2.1.	Precursor Developments .....	1043
24.2.2.	Plant Developments .....	1044

24.3. Carbon Fiber .....	1044
24.4. Composite Manufacturing Techniques .....	1045
24.5. Quality Management Standards .....	1045
24.6. Recycling .....	1046
24.7. Innovative Developments.....	1046
24.8. Conclusion .....	1047
References .....	1047

## **Appendix**

Appendix 1 Glossary .....	1049
Appendix 2 The Elements .....	1061
Appendix 3 The Greek Alphabet .....	1063
Appendix 4 Some Definitions and Handy Conversion Factors.....	1065
Appendix 5 ISO Standard Prefixes for SI Units.....	1067
Appendix 6 Interconversion of Common English and SI Units.....	1069
Appendix 7 Textile Terminology.....	1073
Appendix 8 Temperature Estimation from Color.....	1075
Appendix 9 Humidities over Saturated Salt Solutions.....	1077
Appendix 10 Wet and Dry Bulb Humidity Table.....	1079
Appendix 11 Detection of Cyanide [1] .....	1081
Appendix 12 British Standards on Quality .....	1083
Appendix 13 Abbreviations used in Spectroscopy and Microscopy .....	1087
Appendix 14 Typical Properties of Unreinforced Plastic Polymers .....	1089
Appendix 15 Acronyms for Thermoplastic Polymers .....	1117
Appendix 16 Companies Involved with Carbon Fibers and their Composites Throughout the World .....	1119

<b>Index.....</b>	<b>1133</b>
-------------------	-------------