

Contents

| | | |
|------------------|---|-----------|
| Chapter 1 | 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 |
| Chapter 2 | 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 |

| | |
|---|----|
| Chapter 3 History and Early Development of Carbon Fibers | 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 |

| | | |
|------------------|--|------------|
| Chapter 4 | Precursors for Carbon Fiber Manufacture | 121 |
| 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 |

| | | |
|------------------|---|------------|
| Chapter 5 | Carbon Fiber Production using a PAN Precursor | 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 |

| | |
|---|-----|
| Chapter 6 Carbon Fiber Production using a Cellulosic based Precursor..... | 269 |
| 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 |

| | |
|---|-----|
| Chapter 7 Carbon Fiber Production using a Pitch based Precursor | 295 |
| 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 |

| | |
|---|-----|
| Chapter 8 Production of Vapor Grown Carbon Fibers (VGCF) | 325 |
| 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 |

| | |
|--|-----|
| Chapter 9 Surface Treatment and Sizing of Carbon Fibers..... | 347 |
| 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 |

| | |
|--|-----|
| Chapter 10 Guidelines for the Design of Equipment for Carbon Fiber Plant..... | 377 |
| 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 |
| 10.14. Surface Treatment | 403 |
| 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 |
| References | 420 |
| | |
| Chapter 11 Operation of Carbon Fiber Plant and Safety Aspects..... | 421 |
| 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 |
| References | 451 |

| | | |
|-------------------|---|-----|
| Chapter 12 | 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 |

| | | |
|-------------------|---|-----|
| Chapter 13 | 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 |

| | | |
|-------------------|---|------------|
| Chapter 14 | 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 |

| | | |
|-------------------|--|------------|
| Chapter 15 | 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 (Al_2O_3) | 603 |
| 2. Mullite ($3\text{Al}_2\text{O}_3 \cdot 2\text{SiO}_2$)..... | 603 |
| 3. Zirconia (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 (B_4C) | 604 |
| 4. Titanium boride (TiB_2) | 604 |
| 5. Boron nitride (BN)..... | 604 |
| 6. Aluminium nitride (AlN) | 604 |
| 7. Silicon nitride (Si_3N_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 |

| | |
|---|-----|
| Chapter 16 Carbon Fibers in Metal Matrices | 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 |

| | | |
|-------------------|---|------------|
| Chapter 17 | Testing of PAN Precursor, Virgin Carbon Fibers, Carbon Fiber Composites and Related Products | 657 |
| 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 |

| | | |
|-------------------|---|-----|
| Chapter 18 | 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 σ) 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 |

| | | |
|-------------------|---|-----|
| Chapter 19 | 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 | 776 |
| 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 Feigenbaum..... | 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 |

| | | |
|-------------------|--|-----|
| Chapter 20 | Properties of Carbon Fibers | 791 |
| 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 | 861 |
| 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 |
| 1. Chopped strand mat (csm)..... | 863 |
| 2. Carbon fiber tissue..... | 864 |
| 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 |
| 1. Warp UD fabric..... | 866 |
| 2. Weft UD fabric | 866 |
| 21.1.4. Woven Fabrics (2-D Planar or Biaxial Reinforcement)..... | 866 |
| 1. Plain or square weave..... | 868 |
| 2. Basket (Hopsack) weave..... | 868 |
| 3. Leno weave..... | 869 |
| 4. Mock Leno weave | 870 |
| 5. Twill weave..... | 871 |
| 6. Satin weave..... | 871 |
| 7. High modulus (non-crimp) weave | 872 |
| 21.1.5. Woven Spread Tow | 872 |
| 21.1.6. Knitted Fabrics..... | 872 |
| 21.1.6.1. Weft knitting | 874 |
| 1. Plain knitting..... | 874 |
| 21.1.6.2. Warp knitting..... | 876 |
| 1. Plain tricot..... | 877 |
| 2. Raschel | 877 |
| 21.1.7. Inlaid Fabrics | 877 |
| 21.1.8. Braiding | 877 |
| 21.1.8.1. Forms of braiding | 879 |
| 1. Flat braids | 879 |
| 2. Sleevings | 879 |
| 3. Wide braided fabric..... | 879 |
| 4. Overbraids | 880 |
| 21.1.8.2. Braid architecture..... | 880 |
| 1. Biaxial 2-D braid..... | 880 |
| 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 TM | 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 TM | 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 (SCRIMPT TM) | 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 TM) | 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 TM 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 |
| Chapter 22 | Design | 935 |
| 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 |

| | | |
|-------------------|---|------------|
| Chapter 23 | 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 cfrp | 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 |
| Chapter 24 | Looking to the Future | 1043 |
| 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 |
| Index..... | 1133 |