

## Contents

### Volume 1

#### Preface *xxiii*

|          |                                                                                  |           |
|----------|----------------------------------------------------------------------------------|-----------|
| <b>1</b> | <b>Introduction: The Future of Carbon Materials – The Industrial Perspective</b> | <b>1</b>  |
|          | <i>Hubert Jäger, Wilhelm Frohs, and Tilo Hauke</i>                               |           |
| 1.1      | Overview                                                                         | 1         |
| 1.2      | Traditional Carbon and Graphite Materials                                        | 2         |
| 1.3      | Modern Application of Carbon Materials                                           | 12        |
| 1.4      | Future Application of Carbon Materials                                           | 18        |
| 1.5      | Conclusion                                                                       | 20        |
| <b>2</b> | <b>The Element Carbon</b>                                                        | <b>21</b> |
|          | <i>Wilhelm Frohs and Hubert Jäger</i>                                            |           |
| 2.1      | Introduction                                                                     | 21        |
| 2.2      | Diamond                                                                          | 28        |
| 2.3      | Graphite                                                                         | 28        |
| 2.4      | Non-graphitic Carbon                                                             | 29        |
| 2.5      | Carbyne and Chaoite                                                              | 29        |
| 2.6      | Nanoforms of Carbon                                                              | 30        |
|          | References                                                                       | 30        |
|          | Further Reading                                                                  | 31        |
| <b>3</b> | <b>History of Carbon Materials</b>                                               | <b>33</b> |
|          | <i>Gerd Collin</i>                                                               |           |
| 3.1      | Origin of Elemental Carbon                                                       | 33        |
| 3.2      | Formation and Economic Development of Natural Diamonds                           | 34        |
| 3.3      | Formation and Use of Natural Graphite                                            | 34        |
| 3.4      | History of Charcoal from Wood and Coke from Coal                                 | 35        |
| 3.5      | History of Carbon Black                                                          | 35        |
| 3.6      | History of Activated Carbon                                                      | 38        |
| 3.7      | Development of Synthetic Graphite                                                | 38        |
| 3.8      | Development of Synthetic Diamonds                                                | 39        |
| 3.9      | Development of Carbon Fibers                                                     | 39        |

|      |                                                                                        |    |
|------|----------------------------------------------------------------------------------------|----|
| 3.10 | Discovery and Inventions of Nanocarbons: Fullerenes, Nanotubes, and Graphene           | 40 |
|      | References                                                                             | 42 |
| 4    | <b>Recommended Terminology for the Description of Carbon as a Solid (© 1995 IUPAC)</b> | 45 |
|      | <i>E. Fitzer, K.-H. Köchling, H.P. Böhm, and H. Marsh</i>                              |    |
|      | List of Terms                                                                          | 45 |
|      | Description of the Terms                                                               | 48 |
|      | Acetylene Black                                                                        | 48 |
|      | Description                                                                            | 48 |
|      | Notes                                                                                  | 48 |
|      | Acheson Graphite                                                                       | 48 |
|      | Description                                                                            | 48 |
|      | Notes                                                                                  | 48 |
|      | Activated Carbon                                                                       | 49 |
|      | Description                                                                            | 49 |
|      | Notes                                                                                  | 49 |
|      | Activated Charcoal                                                                     | 49 |
|      | Description                                                                            | 49 |
|      | Agranular Carbon                                                                       | 49 |
|      | Description                                                                            | 49 |
|      | Notes                                                                                  | 49 |
|      | Amorphous Carbon                                                                       | 49 |
|      | Description                                                                            | 49 |
|      | Notes                                                                                  | 50 |
|      | Artificial Graphite                                                                    | 50 |
|      | Description                                                                            | 50 |
|      | Notes                                                                                  | 50 |
|      | Baking                                                                                 | 50 |
|      | Description                                                                            | 50 |
|      | Binder                                                                                 | 50 |
|      | Description                                                                            | 50 |
|      | Binder Coke                                                                            | 51 |
|      | Description                                                                            | 51 |
|      | Notes                                                                                  | 51 |
|      | Brooks and Taylor Structure in the Carbonaceous Mesophase                              | 51 |
|      | Description                                                                            | 51 |
|      | Notes                                                                                  | 51 |
|      | Bulk Mesophase                                                                         | 51 |
|      | Description                                                                            | 51 |
|      | Notes                                                                                  | 52 |
|      | Calcined Coke                                                                          | 52 |
|      | Description                                                                            | 52 |
|      | Notes                                                                                  | 52 |
|      | Carbon                                                                                 | 52 |
|      | Description                                                                            | 52 |

|                                     |    |
|-------------------------------------|----|
| Notes                               | 52 |
| Carbon Artifact                     | 52 |
| Description                         | 52 |
| Notes                               | 52 |
| Carbon Black                        | 53 |
| Description                         | 53 |
| Notes                               | 53 |
| Carbon–Carbon Composite             | 53 |
| Description                         | 53 |
| Carbon Cenospheres                  | 53 |
| Description                         | 53 |
| Carbon Cloth                        | 53 |
| Description                         | 53 |
| Notes                               | 54 |
| Carbon Electrode                    | 54 |
| Description                         | 54 |
| Notes                               | 54 |
| Carbon Felt                         | 54 |
| Description                         | 54 |
| Notes                               | 54 |
| Carbon Fiber                        | 54 |
| Description                         | 54 |
| Notes                               | 55 |
| Carbon Fiber Fabrics                | 55 |
| Description                         | 55 |
| Carbon Fibers Type HM               | 55 |
| Description                         | 55 |
| Notes                               | 55 |
| Carbon Fibers Type HT               | 55 |
| Description                         | 55 |
| Notes                               | 56 |
| Carbon Fibers Type IM               | 56 |
| Description                         | 56 |
| Notes                               | 56 |
| Carbon Fibers Type LM (Low Modulus) | 56 |
| Description                         | 56 |
| Notes                               | 56 |
| Carbon Fibers Type UHM              | 57 |
| Description                         | 57 |
| Carbon Material                     | 57 |
| Description                         | 57 |
| Notes                               | 57 |
| Carbon Mix                          | 57 |
| Description                         | 57 |
| Carbon Whiskers                     | 57 |
| Description                         | 57 |
| Carbonaceous Mesophase              | 57 |

|                           |    |
|---------------------------|----|
| Description               | 57 |
| Notes                     | 58 |
| Carbonization             | 58 |
| Description               | 58 |
| Notes                     | 58 |
| Catalytic Graphitization  | 58 |
| Description               | 58 |
| Notes                     | 58 |
| Char                      | 59 |
| Description               | 59 |
| Notes                     | 59 |
| Charcoal                  | 59 |
| Description               | 59 |
| Notes                     | 59 |
| Coal-Derived Pitch Coke   | 59 |
| Description               | 59 |
| Notes                     | 59 |
| Coal-Tar Pitch            | 60 |
| Description               | 60 |
| Notes                     | 60 |
| Coalification             | 60 |
| Description               | 60 |
| Notes                     | 60 |
| Coke                      | 60 |
| Description               | 60 |
| Notes                     | 60 |
| Coke Breeze               | 61 |
| Description               | 61 |
| Colloidal Carbon          | 61 |
| Description               | 61 |
| Notes                     | 61 |
| Delayed Coke              | 61 |
| Description               | 61 |
| Notes                     | 61 |
| Delayed Coking Process    | 61 |
| Description               | 61 |
| Notes                     | 62 |
| Diamond                   | 62 |
| Description               | 62 |
| Notes                     | 62 |
| Diamond by CVD            | 62 |
| Description               | 62 |
| Notes                     | 62 |
| Diamond-Like Carbon Films | 63 |
| Description               | 63 |
| Notes                     | 63 |
| Electrographite           | 63 |

|                               |    |
|-------------------------------|----|
| Description                   | 63 |
| Exfoliated Graphite           | 63 |
| Description                   | 63 |
| Notes                         | 64 |
| Fibrous Activated Carbon      | 64 |
| Description                   | 64 |
| Notes                         | 64 |
| Fibrous Carbon                | 64 |
| Description                   | 64 |
| Filamentous Carbon            | 64 |
| Description                   | 64 |
| Notes                         | 64 |
| Filler                        | 65 |
| Description                   | 65 |
| Filler Coke                   | 65 |
| Description                   | 65 |
| Notes                         | 65 |
| Fluid Coke                    | 65 |
| Description                   | 65 |
| Notes                         | 65 |
| Fullerenes                    | 66 |
| Description                   | 66 |
| Notes                         | 66 |
| Furnace Black                 | 66 |
| Description                   | 66 |
| Notes                         | 66 |
| Gas-Phase-Grown Carbon Fibers | 66 |
| Description                   | 66 |
| Notes                         | 66 |
| Glass-Like Carbon             | 67 |
| Description                   | 67 |
| Notes                         | 67 |
| Granular Carbon               | 67 |
| Description                   | 67 |
| Notes                         | 67 |
| Graphene Layer                | 67 |
| Description                   | 67 |
| Notes                         | 68 |
| Graphite                      | 68 |
| Description                   | 68 |
| Notes                         | 68 |
| Graphite Electrode            | 68 |
| Description                   | 68 |
| Graphite Fibers               | 68 |
| Description                   | 68 |
| Notes                         | 69 |
| Graphite Material             | 69 |

|                                     |    |
|-------------------------------------|----|
| Description                         | 69 |
| Notes                               | 69 |
| Graphite Whiskers                   | 69 |
| Description                         | 69 |
| Notes                               | 69 |
| GRAPHITIC CARBON                    | 70 |
| Description                         | 70 |
| Notes                               | 70 |
| Graphitizable Carbon                | 70 |
| Description                         | 70 |
| Notes                               | 70 |
| Graphitization                      | 70 |
| Description                         | 70 |
| Notes                               | 70 |
| Graphitization Heat Treatment       | 71 |
| Description                         | 71 |
| Notes                               | 71 |
| Graphitized Carbon                  | 71 |
| Description                         | 71 |
| Notes                               | 71 |
| Green Coke                          | 71 |
| Description                         | 71 |
| Notes                               | 72 |
| Hard Amorphous Carbon Films         | 72 |
| Description                         | 72 |
| Hexagonal Graphite                  | 72 |
| Description                         | 72 |
| Notes                               | 72 |
| High-Pressure Graphitization        | 72 |
| Description                         | 72 |
| Highly Oriented Pyrolytic Graphite  | 73 |
| Description                         | 73 |
| Notes                               | 73 |
| Isotropic Carbon                    | 73 |
| Description                         | 73 |
| Notes                               | 73 |
| Isotropic Pitch-Based Carbon Fibers | 73 |
| Description                         | 73 |
| Notes                               | 73 |
| Lamp Black                          | 74 |
| Description                         | 74 |
| Mesogenic Pitch                     | 74 |
| Description                         | 74 |
| Mesophase Pitch                     | 74 |
| Description                         | 74 |
| Notes                               | 74 |
| Mesophase Pitch-Based Carbon Fibers | 74 |

|                           |    |
|---------------------------|----|
| Description               | 74 |
| Metallurgical Coke        | 75 |
| Description               | 75 |
| Notes                     | 75 |
| Microporous Carbon        | 75 |
| Description               | 75 |
| Notes                     | 75 |
| MPP-Based Carbon Fibers   | 75 |
| Description               | 75 |
| Natural Graphite          | 75 |
| Description               | 75 |
| Notes                     | 76 |
| Needle Coke               | 76 |
| Description               | 76 |
| Notes                     | 76 |
| Non-graphitic Carbon      | 76 |
| Description               | 76 |
| Notes                     | 76 |
| Non-graphitizable Carbon  | 77 |
| Description               | 77 |
| Notes                     | 77 |
| Nuclear Graphite          | 77 |
| Description               | 77 |
| Notes                     | 77 |
| Pan-Based Carbon Fibers   | 77 |
| Description               | 77 |
| Particulate Carbon        | 78 |
| Description               | 78 |
| Notes                     | 78 |
| Petroleum Coke            | 78 |
| Description               | 78 |
| Notes                     | 78 |
| Petroleum Pitch           | 78 |
| Description               | 78 |
| Notes                     | 78 |
| Pitch                     | 79 |
| Description               | 79 |
| Notes                     | 79 |
| Pitch-Based Carbon Fibers | 79 |
| Description               | 79 |
| Notes                     | 79 |
| Polycrystalline Graphite  | 79 |
| Description               | 79 |
| Notes                     | 80 |
| Polygranular Carbon       | 80 |
| Description               | 80 |
| Notes                     | 80 |

|                                                                             |    |
|-----------------------------------------------------------------------------|----|
| Polygranular Graphite                                                       | 80 |
| Description                                                                 | 80 |
| Notes                                                                       | 80 |
| Premium Coke                                                                | 81 |
| Description                                                                 | 81 |
| Notes                                                                       | 81 |
| Puffing                                                                     | 81 |
| Description                                                                 | 81 |
| Notes                                                                       | 81 |
| Puffing Inhibitor                                                           | 81 |
| Description                                                                 | 81 |
| Notes                                                                       | 81 |
| Pyrolytic Carbon                                                            | 82 |
| Description                                                                 | 82 |
| Notes                                                                       | 82 |
| Pyrolytic Graphite                                                          | 82 |
| Description                                                                 | 82 |
| Notes                                                                       | 82 |
| Raw Coke                                                                    | 82 |
| Description                                                                 | 82 |
| Notes                                                                       | 83 |
| Rayon-Based Carbon Fibers                                                   | 83 |
| Description                                                                 | 83 |
| Notes                                                                       | 83 |
| Regular Coke                                                                | 83 |
| Description                                                                 | 83 |
| Notes                                                                       | 83 |
| Rhombohedral Graphite                                                       | 84 |
| Description                                                                 | 84 |
| Notes                                                                       | 84 |
| Semicoke                                                                    | 84 |
| Description                                                                 | 84 |
| Notes                                                                       | 84 |
| Soot                                                                        | 84 |
| Description                                                                 | 84 |
| Notes                                                                       | 85 |
| Spherical Carbonaceous Mesophase                                            | 85 |
| Description                                                                 | 85 |
| Stabilization Treatment of Thermoplastic Precursor Fibers for Carbon Fibers | 85 |
| Description                                                                 | 85 |
| Notes                                                                       | 85 |
| Stress Graphitization                                                       | 85 |
| Description                                                                 | 85 |
| Notes                                                                       | 86 |
| Synthetic Graphite                                                          | 86 |
| Description                                                                 | 86 |

|               |    |
|---------------|----|
| Notes         | 86 |
| Thermal Black | 86 |
| Description   | 86 |
| References    | 86 |

## 5      **Graphite** 89

*Otto Vohler, Ferdinand von Sturm, Erhard Wege, and Wilhelm Frohs*

|       |                           |     |
|-------|---------------------------|-----|
| 5.1   | Graphite Single Crystal   | 89  |
| 5.2   | Natural Graphite          | 94  |
| 5.2.1 | Occurrence and Properties | 94  |
| 5.3   | Synthetic Graphite        | 95  |
|       | References                | 101 |
|       | Further Reading           | 103 |

## 6      **Industrial Carbons** 105

### 6.1      **Introduction to Polygranular Carbon and Graphite**

|                   |     |
|-------------------|-----|
| <b>Materials</b>  | 106 |
| <b>References</b> | 106 |

#### 6.1.1      **Polygranular Carbon and Graphite Materials** 107

*Hubert Jäger, Wilhelm Frohs, Ferdinand von Sturm, Otto Vohler, and Erhard Wege*

|             |                                |     |
|-------------|--------------------------------|-----|
| 6.1.1.1     | The Relevance of Raw Materials | 107 |
| 6.1.1.1.1   | Petroleum Coke                 | 109 |
| 6.1.1.1.2   | Coal-Tar Pitch Coke            | 113 |
| 6.1.1.1.3   | Anthracite                     | 114 |
| 6.1.1.1.4   | Binder Materials               | 115 |
| 6.1.1.1.4.1 | Coal-Tar Pitch                 | 115 |
| 6.1.1.1.4.2 | Petroleum Pitch                | 117 |
| 6.1.1.1.4.3 | Thermosetting Resins           | 119 |
|             | References                     | 120 |
|             | Further Reading                | 121 |

#### 6.1.2      **Petroleum Coke** 122

*Heinrich Predel and Srini Srivatsan*

|             |                                     |     |
|-------------|-------------------------------------|-----|
| 6.1.2.1     | Introduction                        | 122 |
| 6.1.2.2     | Physical and Chemical Properties    | 122 |
| 6.1.2.2.1   | Physical Properties                 | 122 |
| 6.1.2.2.2   | Chemical Properties and Composition | 124 |
| 6.1.2.3     | Production                          | 125 |
| 6.1.2.3.1   | Production Processes                | 125 |
| 6.1.2.3.1.1 | Delayed Coking                      | 125 |
| 6.1.2.3.1.2 | Fluid Coking                        | 132 |
| 6.1.2.3.1.3 | Flexicoking                         | 134 |
| 6.1.2.3.2   | Calcination                         | 135 |

|              |                                                                       |            |
|--------------|-----------------------------------------------------------------------|------------|
| 6.1.2.3.2.1  | Rotary Kiln Calciner                                                  | 137        |
| 6.1.2.3.2.2  | Rotary Hearth Calciner                                                | 138        |
| 6.1.2.3.2.3  | Shaft Kiln Calciner                                                   | 138        |
| 6.1.2.4      | Uses and Economic Aspects                                             | 138        |
| 6.1.2.4.1    | Green Petroleum Coke                                                  | 140        |
| 6.1.2.4.2    | Calcined Petroleum Coke                                               | 141        |
| 6.1.2.4.2.1  | Anode-Grade Coke (Regular Calcinate)                                  | 141        |
| 6.1.2.4.2.2  | Needle Coke                                                           | 141        |
| 6.1.2.5      | Quality Aspects                                                       | 142        |
| 6.1.2.5.1    | Green Coke                                                            | 142        |
| 6.1.2.5.2    | Regular Calcinate                                                     | 143        |
| 6.1.2.5.3    | Needle Coke                                                           | 144        |
| 6.1.2.6      | Environmental and Safety Aspects                                      | 145        |
| 6.1.2.6.1    | Green Coke                                                            | 145        |
| 6.1.2.6.2    | Calcined Petroleum Coke                                               | 146        |
|              | References                                                            | 147        |
|              | Further Reading                                                       | 149        |
| <b>6.1.3</b> | <b>Coal-Tar Pitch Coke</b>                                            | <b>150</b> |
|              | <i>Tetsusei Fukuda</i>                                                |            |
| 6.1.3.1      | Introduction                                                          | 150        |
| 6.1.3.2      | Physical and Chemical Properties                                      | 151        |
| 6.1.3.2.1    | Physical Properties                                                   | 151        |
| 6.1.3.2.2    | Chemical Properties                                                   | 151        |
| 6.1.3.3      | Production of Pitch Coke                                              | 152        |
| 6.1.3.3.1    | Production Process                                                    | 152        |
| 6.1.3.3.1.1  | Chamber Coking Process                                                | 153        |
| 6.1.3.3.1.2  | Delayed Coker and Calciner                                            | 155        |
| 6.1.3.4      | Uses                                                                  | 161        |
| 6.1.3.4.1    | Aggregate of Graphite Electrode for Aluminum Smelting                 | 161        |
| 6.1.3.4.2    | Aggregate for Graphite Electrode in Electric Arc Furnace Steelmaking  | 161        |
| 6.1.3.5      | Environmental and Safety Aspects                                      | 162        |
|              | References                                                            | 164        |
| <b>6.1.4</b> | <b>Natural Graphite</b>                                               | <b>165</b> |
|              | <i>Werner Handl</i>                                                   |            |
| 6.1.4.1      | Occurrence and Classification                                         | 165        |
| 6.1.4.2      | Mining and Cleaning                                                   | 165        |
| 6.1.4.3      | Applications of Natural Graphite                                      | 169        |
| 6.1.4.4      | Economic Aspects                                                      | 170        |
|              | References                                                            | 171        |
| <b>6.1.5</b> | <b>Tar and Pitch</b>                                                  | <b>172</b> |
|              | <i>Gerd-Peter Blümer, Gerd Collin, and Hartmut Höke</i>               |            |
| 6.1.5.1      | Origin, Classification, and Industrial Importance of Tars and Pitches | 172        |

|              |                                                    |            |
|--------------|----------------------------------------------------|------------|
| 6.1.5.1.1    | Origin and Classification                          | 172        |
| 6.1.5.1.2    | History                                            | 173        |
| 6.1.5.1.3    | Industrial Importance                              | 174        |
| 6.1.5.2      | Properties                                         | 174        |
| 6.1.5.3      | Processing of Coke-Oven Coal Tar                   | 184        |
| 6.1.5.3.1    | Survey                                             | 184        |
| 6.1.5.3.2    | Primary Distillation                               | 185        |
| 6.1.5.3.3    | Processing of Coal-Tar Pitch                       | 189        |
| 6.1.5.3.3.1  | Cooling                                            | 189        |
| 6.1.5.3.3.2  | Production of Electrode Pitch                      | 190        |
| 6.1.5.3.3.3  | Production of Special Pitches                      | 194        |
| 6.1.5.3.4    | Processing of Tar Distillates                      | 196        |
| 6.1.5.3.4.1  | Carbon Black Oils                                  | 196        |
| 6.1.5.3.4.2  | Impregnating Oils                                  | 196        |
| 6.1.5.3.4.3  | Fuel oils                                          | 199        |
| 6.1.5.3.4.4  | Diesel Fuels                                       | 199        |
| 6.1.5.3.4.5  | Fluxing Oils                                       | 199        |
| 6.1.5.4      | Processing of Low-Temperature Coal Tars            | 199        |
| 6.1.5.5      | Processing of Other Tars and Tarlike Raw Materials | 201        |
| 6.1.5.5.1    | Lignite Tars                                       | 201        |
| 6.1.5.5.2    | Peat Tars                                          | 201        |
| 6.1.5.5.3    | Wood Tars                                          | 202        |
| 6.1.5.5.4    | Oil-Shale Tars                                     | 202        |
| 6.1.5.5.5    | Pyrolysis Residual Oils                            | 202        |
| 6.1.5.6      | Uses of Tar Products and Their Economic Importance | 203        |
| 6.1.5.7      | Toxicology and Ecotoxicology                       | 204        |
| 6.1.5.7.1    | Toxicology                                         | 204        |
| 6.1.5.7.2    | Ecotoxicology                                      | 206        |
| 6.1.5.7.3    | Classification and Legislation                     | 206        |
|              | References                                         | 207        |
| <b>6.1.6</b> | <b>Thermosetting Resins</b>                        | <b>211</b> |
|              | <i>Josef Suren</i>                                 |            |
|              | References                                         | 213        |
| <b>6.2</b>   | <b>Manufacturing</b>                               | <b>214</b> |
|              | <i>Johann Daimer</i>                               |            |
| 6.2.1        | Grinding and Sizing                                | 214        |
| 6.2.2        | Mixing                                             | 214        |
| 6.2.3        | Forming                                            | 215        |
| 6.2.3.1      | Molding                                            | 216        |
| 6.2.3.2      | Isostatic Molding                                  | 216        |
| 6.2.3.3      | Vibration Molding                                  | 217        |
| 6.2.3.4      | Other Forming Methods                              | 217        |
| 6.2.4        | Baking                                             | 217        |
| 6.2.4.1      | Ring Furnace                                       | 219        |
| 6.2.4.2      | Car-Bottom Furnace/Single-Chamber Furnace          | 221        |

|              |                                                                                          |            |
|--------------|------------------------------------------------------------------------------------------|------------|
| 6.2.4.3      | Tunnel Kiln                                                                              | 221        |
| 6.2.4.4      | Other Furnaces                                                                           | 222        |
| 6.2.5        | Graphitization                                                                           | 222        |
| 6.2.5.1      | Acheson Furnace                                                                          | 224        |
| 6.2.5.2      | Castner Furnace                                                                          | 224        |
| 6.2.5.3      | Induction Furnace                                                                        | 225        |
| 6.2.5.4      | Radiation Heating                                                                        | 225        |
| 6.2.6        | Purification                                                                             | 225        |
| 6.2.7        | Machining                                                                                | 226        |
| 6.2.8        | Impregnation and Surface Coating                                                         | 226        |
|              | References                                                                               | 227        |
| <b>6.3</b>   | <b>Environmental, Health and Safety Aspects of the Production of Carbon and Graphite</b> | <b>230</b> |
|              | <i>Ruediger Meyer zu Reckendorf</i>                                                      |            |
| 6.3.1        | Environmental Aspects                                                                    | 230        |
| 6.3.1.1      | Raw Materials                                                                            | 230        |
| 6.3.1.2      | Processes and Energy                                                                     | 231        |
| 6.3.2        | Occupational Safety and Health Aspects                                                   | 232        |
| 6.3.2.1      | Coal Tar Pitch                                                                           | 232        |
| 6.3.2.2      | Risk Strategy for Benzopyrene                                                            | 232        |
| 6.3.2.3      | Gases                                                                                    | 233        |
| 6.3.2.4      | Electric Current                                                                         | 234        |
| 6.3.2.5      | Dust                                                                                     | 234        |
| 6.3.3        | Process Safety                                                                           | 234        |
|              | References                                                                               | 235        |
| <b>6.4</b>   | <b>Properties of Polygranular Carbon and Graphite Materials</b>                          | <b>237</b> |
|              | <i>Marcus Franz, Franz Fendt, and Karl Wimmer</i>                                        |            |
| 6.4.1        | Physical Properties                                                                      | 237        |
| 6.4.2        | Chemical Properties                                                                      | 241        |
|              | References                                                                               | 242        |
|              | Further Reading                                                                          | 242        |
| <b>6.5</b>   | <b>Applications</b>                                                                      | <b>243</b> |
| <b>6.5.1</b> | <b>Prebaked Anodes for Aluminum Electrolysis</b>                                         | <b>244</b> |
|              | <i>Jean-Claude Fischer and Raymond Cecil Perruchoud</i>                                  |            |
| 6.5.1.1      | Introduction                                                                             | 244        |
| 6.5.1.2      | The Electrolysis Cell                                                                    | 244        |
| 6.5.1.3      | The Role of Anodes in the Pots                                                           | 245        |
| 6.5.1.3.1    | Current Conductor Aspects                                                                | 245        |
| 6.5.1.3.2    | Thermal Aspects                                                                          | 248        |
| 6.5.1.3.3    | Anode Failure and Consumption Mechanisms                                                 | 249        |
| 6.5.1.3.4    | Carbon Consumption Figures                                                               | 252        |

|              |                                                          |            |
|--------------|----------------------------------------------------------|------------|
| 6.5.1.4      | The Cost of Al Production Related to the Anodes          | 252        |
| 6.5.1.5      | The Anode Manufacture for Large Modern Smelters          | 253        |
| 6.5.1.6      | The Raw Materials                                        | 254        |
| 6.5.1.7      | The Green Mill                                           | 255        |
| 6.5.1.7.1    | Dry Aggregate Preparation                                | 255        |
| 6.5.1.7.2    | Paste and Green Block Production                         | 260        |
| 6.5.1.7.3    | The Baking Furnace                                       | 264        |
| 6.5.1.7.4    | Anode Slotting                                           | 268        |
| 6.5.1.7.5    | Anode Rodding                                            | 269        |
| 6.5.1.7.6    | Anode Quality Control                                    | 271        |
| 6.5.1.8      | Outlook                                                  | 271        |
|              | References                                               | 273        |
| <b>6.5.2</b> | <b>Cathodes for Aluminum Electrolysis</b>                | <b>275</b> |
|              | <i>Frank Hiltmann</i>                                    |            |
| 6.5.2.1      | Cathodes in the Aluminum Smelting Process                | 275        |
| 6.5.2.2      | Cathode Classification                                   | 275        |
| 6.5.2.3      | Cathode Lifetime                                         | 277        |
| 6.5.2.4      | Wettable Cathodes                                        | 278        |
| 6.5.2.5      | Surface-Profiled Cathodes                                | 279        |
| 6.5.2.6      | Spent Potlining                                          | 280        |
|              | References                                               | 280        |
|              | Further Reading                                          | 280        |
| <b>6.5.3</b> | <b>Graphite Electrodes for Electric Arc Furnaces</b>     | <b>281</b> |
|              | <i>Daniel Steppich</i>                                   |            |
| 6.5.3.1      | Graphite Electrodes for Electric Arc Furnaces            | 281        |
| 6.5.3.1.1    | Steel Production                                         | 281        |
| 6.5.3.1.1.1  | The Era of Iron and Steel                                | 282        |
| 6.5.3.1.1.2  | Steel Recycling in an Electric Arc Furnace               | 287        |
| 6.5.3.1.1.3  | Steel Market Outlook                                     | 296        |
| 6.5.3.1.2    | Graphite Electrodes in the Steel Recycling Process       | 298        |
| 6.5.3.1.2.1  | Application Requirements                                 | 299        |
| 6.5.3.1.2.2  | Wear Mechanisms                                          | 303        |
| 6.5.3.1.2.3  | Future Developments                                      | 308        |
| 6.5.3.1.2.4  | Graphite Electrode Market Outlook                        | 312        |
|              | References                                               | 314        |
| <b>6.5.4</b> | <b>Linings and Casting</b>                               | <b>320</b> |
|              | <i>Otto Vohler, Ferdinand von Sturm, and Erhard Wege</i> |            |
|              | References                                               | 321        |
|              | Further Reading                                          | 321        |
| <b>6.5.5</b> | <b>Carbon Electrodes</b>                                 | <b>322</b> |
|              | <i>Eckhard Escher</i>                                    |            |
| 6.5.5.1      | Introduction                                             | 322        |

|              |                                                              |            |
|--------------|--------------------------------------------------------------|------------|
| 6.5.5.1.1    | Raw Materials                                                | 322        |
| 6.5.5.1.2    | Manufacturing                                                | 323        |
| 6.5.5.1.3    | Typical Properties                                           | 323        |
| 6.5.5.1.4    | Dimensions                                                   | 324        |
| 6.5.5.1.5    | Joint Systems                                                | 324        |
| 6.5.5.1.6    | Carbon Electrode Market                                      | 325        |
|              | Reference                                                    | 325        |
| <b>6.5.6</b> | <b>Self-Baking Electrodes</b>                                | <b>326</b> |
|              | <i>Johann-Christian Leye and Robert Becker</i>               |            |
| 6.5.6.1      | Raw Materials                                                | 327        |
| 6.5.6.2      | Manufacturing                                                | 327        |
| 6.5.6.3      | Properties                                                   | 328        |
| 6.5.6.4      | Operation Mode                                               | 328        |
| 6.5.6.4.1    | The Process of Self-Baking Electrodes                        | 328        |
|              | References                                                   | 329        |
| <b>6.5.7</b> | <b>Graphite Process Equipment</b>                            | <b>331</b> |
|              | <i>Marcus Franz</i>                                          |            |
| 6.5.7.1      | Heat Exchangers                                              | 332        |
| 6.5.7.2      | Absorbers, Desorbers, and Distillation Columns               | 335        |
| 6.5.7.3      | Hydrochloric Acid and Gas Synthesis Units                    | 335        |
| 6.5.7.4      | Reactors                                                     | 336        |
| 6.5.7.5      | Pumps                                                        | 336        |
| <b>6.5.8</b> | <b>Fine-Grained Graphite</b>                                 | <b>338</b> |
|              | <i>Werner Richard Hoffmann</i>                               |            |
| 6.5.8.1      | Markets and Applications                                     | 338        |
| 6.5.8.2      | Applications in the Electronic Industry                      | 338        |
| 6.5.8.3      | Applications in the Metallurgy                               | 341        |
| 6.5.8.4      | Applications in the Ceramics                                 | 344        |
| 6.5.8.5      | Applications in the Glass and Quartz-Glass Production        | 345        |
| 6.5.8.6      | Applications for Current Transmission                        | 345        |
| 6.5.8.6.1    | Carbon Brushes                                               | 345        |
| 6.5.8.6.2    | Current Collectors                                           | 346        |
| 6.5.8.7      | Applications in the Analytical Technology                    | 347        |
| <b>6.5.9</b> | <b>Synthetic Graphite in Nuclear Applications</b>            | <b>349</b> |
|              | <i>Rainer Schmitt</i>                                        |            |
| 6.5.9.1      | Early Graphites in Nuclear Reactor Technology                | 349        |
| 6.5.9.2      | Requirements for Nuclear Graphite                            | 350        |
| 6.5.9.3      | Radiation Damage in Nuclear Graphite                         | 351        |
| 6.5.9.3.1    | Structure of Polycrystalline Graphite                        | 351        |
| 6.5.9.3.2    | Basic Effects of Radiation on the Graphite Lattice Structure | 353        |
| 6.5.9.3.3    | Graphite Property Changes Due to Fast Neutron Irradiation    | 355        |
| 6.5.9.3.3.1  | Dimensional Changes                                          | 355        |

|               |                                                              |            |
|---------------|--------------------------------------------------------------|------------|
| 6.5.9.3.3.2   | Thermal Expansion Coefficient (CTE)                          | 355        |
| 6.5.9.3.3.3   | Thermal Conductivity and Resistivity                         | 358        |
| 6.5.9.3.3.4   | Young's Modulus                                              | 358        |
| 6.5.9.3.3.5   | Tensile Strength                                             | 359        |
| 6.5.9.3.3.6   | Irradiation-Induced Creep                                    | 359        |
| 6.5.9.4       | Decommissioning                                              | 361        |
| 6.5.9.5       | Outlook                                                      | 362        |
|               | References                                                   | 363        |
| <b>6.5.10</b> | <b>Expanded Graphite and Graphite Foils</b>                  | <b>364</b> |
|               | <i>Martin Christ</i>                                         |            |
| 6.5.10.1      | Production                                                   | 364        |
| 6.5.10.2      | Properties                                                   | 365        |
| 6.5.10.3      | Applications                                                 | 367        |
| 6.5.10.3.1    | Sealing Applications                                         | 367        |
| 6.5.10.3.2    | Conductive Fillers                                           | 368        |
| 6.5.10.3.3    | Latent Heat Storage                                          | 369        |
| 6.5.10.3.4    | Other Applications                                           | 370        |
| 6.5.10.4      | Economic Aspects                                             | 370        |
|               | References                                                   | 370        |
|               | Further Reading                                              | 371        |
| <b>6.5.11</b> | <b>Other Classes of Carbon</b>                               | <b>372</b> |
|               | <i>Otto Vohler, Ferdinand von Sturm, and Erhard Wege</i>     |            |
| 6.5.11.1      | Glass-Like Carbon                                            | 372        |
| 6.5.11.2      | Pyrocarbon and Pyrographite                                  | 373        |
| 6.5.11.3      | Graphite Compounds                                           | 374        |
| 6.5.11.3.1    | Surface Complexes                                            | 374        |
| 6.5.11.3.2    | Graphite Intercalation Compounds                             | 375        |
|               | References                                                   | 376        |
|               | Further Reading                                              | 377        |
| <b>7</b>      | <b>Carbon and Graphite for Electrochemical Power Sources</b> | <b>379</b> |
|               | <i>Mario Wachtler, Oswin Öttinger, and Rüdiger Schweiss</i>  |            |
| 7.1           | Introduction                                                 | 379        |
| 7.2           | Primary Batteries                                            | 380        |
| 7.3           | Lead Acid Batteries                                          | 381        |
| 7.4           | Li-Ion Batteries                                             | 387        |
| 7.4.1         | Introduction                                                 | 387        |
| 7.4.2         | Active Materials: General Concepts                           | 390        |
| 7.4.2.1       | Types of Carbon and Graphite Materials                       | 391        |
| 7.4.2.2       | Mechanism of Charge Storage in Graphitic Materials           | 392        |
| 7.4.2.3       | Graphitization Degree and Reversible Capacity                | 395        |
| 7.4.2.4       | The Solid Electrolyte Interphase                             | 397        |
| 7.4.2.5       | Solvent Co-intercalation and Graphite Exfoliation            | 398        |

|         |                                                  |     |
|---------|--------------------------------------------------|-----|
| 7.4.2.6 | Further Material Design Aspects                  | 401 |
| 7.4.2.7 | Mechanism of Charge Storage in Amorphous Carbons | 403 |
| 7.4.3   | Commercialized Active Materials                  | 404 |
| 7.4.3.1 | Amorphous Carbons (Hard and Soft Carbons)        | 406 |
| 7.4.3.2 | Graphitized Mesophase Carbon Materials           | 409 |
| 7.4.3.3 | Natural Graphite                                 | 409 |
| 7.4.3.4 | Synthetic Graphite                               | 411 |
| 7.4.3.5 | Carbon/Graphite-Silicon and Composites           | 412 |
| 7.4.3.6 | Other Anode Materials                            | 413 |
| 7.4.4   | Conductive Additives                             | 415 |
| 7.4.5   | Carbon Coatings                                  | 417 |
| 7.5     | “Beyond Li-Ion” Battery Chemistries              | 418 |
| 7.5.1   | Na-Ion Battery                                   | 418 |
| 7.5.2   | Li-Sulfur Battery                                | 419 |
| 7.5.3   | Li-Oxygen/Air Battery                            | 420 |
| 7.6     | Electrochemical Double-Layer Capacitors          | 420 |
| 7.6.1   | Introduction                                     | 420 |
| 7.6.2   | Effect of Porosity on Capacitance                | 423 |
| 7.6.3   | Carbon-Based Electrode Materials                 | 425 |
| 7.6.3.1 | Activated Carbons                                | 426 |
| 7.6.3.2 | Other Carbon Materials                           | 427 |
| 7.7     | Redox Flow Batteries                             | 427 |
| 7.7.1   | Introduction                                     | 427 |
| 7.7.2   | Bipolar Plates                                   | 428 |
| 7.7.3   | Electrode Materials                              | 431 |
| 7.7.3.1 | Carbon Felts                                     | 431 |
| 7.7.3.2 | Reticulated Vitreous Carbon                      | 433 |
| 7.7.3.3 | Other Electrode Concepts                         | 434 |
| 7.7.3.4 | Relevance of Carbon Materials                    | 436 |
| 7.8     | Fuel Cells                                       | 438 |
| 7.8.1   | Introduction                                     | 438 |
| 7.8.2   | Bipolar Plates                                   | 439 |
| 7.8.2.1 | Manufacturing                                    | 440 |
| 7.8.2.2 | Properties                                       | 440 |
| 7.8.3   | Gas Diffusion Layers and Electrodes              | 440 |
| 7.8.3.1 | Gas Diffusion Layer Substrates                   | 442 |
| 7.8.3.2 | Microporous Layers                               | 444 |
| 7.8.3.3 | Gas Diffusion Electrodes and Catalyst Layers     | 446 |
|         | References                                       | 448 |
|         | Further Reading                                  | 455 |

## Volume 2

### Preface xv

|   |                                               |     |
|---|-----------------------------------------------|-----|
| 8 | Carbon and Graphite for Catalysis             | 457 |
|   | <i>Dang Sheng Su, Wei Qi, and Guodong Wen</i> |     |

|      |                                                                                                                                                                       |
|------|-----------------------------------------------------------------------------------------------------------------------------------------------------------------------|
| 9    | <b>Activated Carbon</b> 491                                                                                                                                           |
|      | <i>Klaus-Dirk Henning and Hartmut von Kienle</i>                                                                                                                      |
| 10   | <b>Carbon Black</b> 533                                                                                                                                               |
|      | <i>Conny Oswald Vogler and Manfred Voll</i>                                                                                                                           |
| 11   | <b>Carbon Fibers</b> 603                                                                                                                                              |
|      | <i>Michael Heine</i>                                                                                                                                                  |
| 12   | <b>Carbon Fiber Composites</b> 697                                                                                                                                    |
| 12.1 | <b>Carbon Fiber Reinforced Polymers</b> 698                                                                                                                           |
|      | <i>Klaus Drechsler, Michael Heine, and Peter Mitschang</i>                                                                                                            |
| 12.2 | <b>Carbon Fiber Reinforced Carbon</b> 740                                                                                                                             |
|      | <i>Udo Gruber, Oswin Öttinger, Walter Baur, and Ludger Fischer</i>                                                                                                    |
| 12.3 | <b>Carbon Fiber Reinforced Ceramic Composites</b> 825                                                                                                                 |
|      | <i>Bernhard Heidenreich and Andreas Kienzle</i>                                                                                                                       |
| 13   | <b>Nanocarbons</b> 885                                                                                                                                                |
|      | <i>Kazunori Fujisawa, Yoong Ahm Kim, Takuya Hayashi, Kenji Takeuchi, Hiroyuki Muramatsu, Shuji Tsuruoka, Takashi Yanagisawa, Mauricio Terrones, and Morinobu Endo</i> |
|      | <b>Index</b> 945                                                                                                                                                      |

