

CONTENTS

| | |
|--|-------------|
| Contributors | xi |
| Preface | xiii |
| Acronyms | xvii |
| 1 Introduction to Flame Retardancy and Polymer Flammability | 1 |
| <i>Sergei V. Levchik</i> | |
| 1.1 Introduction, 1 | |
| 1.2 Polymer Combustion and Testing, 3 | |
| 1.2.1 Laboratory Flammability Tests, 3 | |
| 1.2.2 Polymer Combustion, 5 | |
| 1.3 Flame Retardancy, 7 | |
| 1.3.1 General Flame Retardant Mechanisms, 7 | |
| 1.3.2 Specific Flame Retardant Mechanisms, 7 | |
| 1.3.3 Criteria for Selection of Flame Retardants, 20 | |
| 1.3.4 Highly Dispersed Flame Retardants, 20 | |
| 1.4 Conclusions and Future Outlook, 22 | |
| References, 23 | |
| 2 Fundamentals of Polymer Nanocomposite Technology | 31 |
| <i>E. Manias, G. Polizos, H. Nakajima, and M. J. Heidecker</i> | |
| 2.1 Introduction, 31 | |
| 2.2 Fundamentals of Polymer Nanocomposites, 33 | |
| 2.2.1 Thermodynamics of Nanoscale Filler Dispersion, 33 | |

| | | |
|----------|--|------------|
| 2.2.2 | Synthetic Routes for Nanocomposite Formation, 36 | |
| 2.2.3 | Dispersion Characterization: Common Techniques and Limitations, 42 | |
| 2.3 | Effects of Nanofillers on Material Properties, 45 | |
| 2.3.1 | Effects on Polymer Crystallization, 45 | |
| 2.3.2 | Effects on Mechanical Properties, 51 | |
| 2.3.3 | Effects on Barrier Properties, 56 | |
| 2.4 | Future Outlook, 60 | |
| | References, 61 | |
| 3 | Flame Retardant Mechanism of Polymer–Clay Nanocomposites | 67 |
| | <i>Jeffrey W. Gilman</i> | |
| 3.1 | Introduction, 67 | |
| 3.1.1 | Initial Discoveries, 68 | |
| 3.2 | Flame Retardant Mechanism, 69 | |
| 3.2.1 | Polystyrene Nanocomposites, 69 | |
| 3.2.2 | Polypropylene–Clay Nanocomposites, 75 | |
| 3.2.3 | Thermal Analysis of Polymer–Clay Nanocomposites, 81 | |
| 3.3 | Conclusions and Future Outlook, 82 | |
| | References, 83 | |
| 4 | Molecular Mechanics Calculations of the Thermodynamic Stabilities of Polymer–Carbon Nanotube Composites | 89 |
| | <i>Stanislav I. Stoliarov and Marc R. Nyden</i> | |
| 4.1 | Introduction, 89 | |
| 4.2 | Background and Context, 90 | |
| 4.3 | Description of the Method, 93 | |
| 4.4 | Application to PS–CNT Composites, 96 | |
| 4.5 | Uncertainties and Limitations, 100 | |
| 4.6 | Summary and Conclusions, 104 | |
| | References, 105 | |
| 5 | Considerations Regarding Specific Impacts of the Principal Fire Retardancy Mechanisms in Nanocomposites | 107 |
| | <i>Bernhard Schartel</i> | |
| 5.1 | Introduction, 107 | |
| 5.2 | Influence of Nanostructured Morphology, 108 | |
| 5.2.1 | Intercalation, Delamination, Distribution, and Exfoliation, 108 | |
| 5.2.2 | Orientation, 111 | |

| | | |
|----------|--|------------|
| 5.2.3 | Morphology During Combustion or Barrier Formation, 112 | |
| 5.3 | Fire Retardancy Effects and Their Impact on the Fire Behavior of Nanocomposites, 113 | |
| 5.3.1 | Inert Filler and Char Formation, 113 | |
| 5.3.2 | Decomposition and Permeability, 115 | |
| 5.3.3 | Viscosity and Mechanical Reinforcement, 117 | |
| 5.3.4 | Barrier for Heat and Mass Transport, 118 | |
| 5.4 | Assessment of Fire Retardancy, 121 | |
| 5.4.1 | Differentiated Analysis with Regard to Different Fire Properties, 121 | |
| 5.4.2 | Different Fire Scenarios Highlight Different Effects of Nanocomposites, 123 | |
| 5.5 | Summary and Conclusions, 124 | |
| | References, 125 | |
| 6 | Intumescence and Nanocomposites: a Novel Route for Flame-Retarding Polymeric Materials | 131 |
| | <i>Serge Bourbigot and Sophie Duquesne</i> | |
| 6.1 | Introduction, 131 | |
| 6.2 | Basics of Intumescence, 133 | |
| 6.3 | Zeolites as Synergistic Agents in Intumescent Systems, 138 | |
| 6.4 | Intumescent in Polymer Nanocomposites, 143 | |
| 6.5 | Nanofillers as Synergists in Intumescent Systems, 147 | |
| 6.6 | Critical Overview of Recent Advances, 153 | |
| 6.7 | Summary and Conclusion, 157 | |
| | References, 157 | |
| 7 | Flame Retardant Properties of Organoclays and Carbon Nanotubes and Their Combinations with Alumina Trihydrate | 163 |
| | <i>Günter Beyer</i> | |
| 7.1 | Introduction, 163 | |
| 7.2 | Experimental Process, 168 | |
| 7.2.1 | Materials, 168 | |
| 7.2.2 | Compounding, 169 | |
| 7.2.3 | Analyses, 169 | |
| 7.3 | Organoclay Nanocomposites, 169 | |
| 7.3.1 | Processing and Structure of EVA/Organoclay-Based Nanocomposites, 169 | |
| 7.3.2 | Thermal Stability of EVA/Organoclay-Based Nanocomposites, 170 | |
| 7.3.3 | Flammability Properties of EVA/Organoclay-Based Nanocomposites, 171 | |

- 7.3.4 NMR Investigation and Fire Retardant Mechanism of EVA Nanocomposites, 173
- 7.3.5 Intercalation Versus Exfoliation of EVA Nanocomposites, 174
- 7.3.6 Combination of the Classical Flame Retardant Filler Alumina Trihydrate with Organoclays, 174
- 7.3.7 Coaxial Cable Passing the UL-1666 Fire Test with an Organoclay/ATH-Based Outer Sheath, 176
- 7.4 Carbon Nanotube Nanocomposites, 177
 - 7.4.1 General Properties of Carbon Nanotubes, 177
 - 7.4.2 Synthesis and Purification of Carbon Nanotubes, 177
 - 7.4.3 Flammability of EVA–MWCNT and EVA–MWCNT–Organoclay Compounds, 177
 - 7.4.4 Crack Density and Surface Results of Charred MWCNT Compounds, 179
 - 7.4.5 Flammability of LDPE Carbon Nanotube Compounds, 179
 - 7.4.6 Cable with the New Fire Retardent System MWCNTs–Organoclays–ATH, 182
- 7.5 Summary and Conclusions, 186
References, 186

8 Nanocomposites with Halogen and Nonintumescent Phosphorus Flame Retardant Additives 191

Yuan Hu and Lei Song

- 8.1 Introduction, 191
 - 8.1.1 Polymer–Organoclay Nanocomposites, 191
 - 8.1.2 Conventional Halogen and Nonintumescent Phosphorus-Containing Flame Retardants, 192
- 8.2 Preparation Methods and Morphological Study, 193
 - 8.2.1 Melt Compounding and Solution Blending, 194
 - 8.2.2 in situ Polymerization Method, 198
 - 8.2.3 Summary of Synthetic Methods, 200
- 8.3 Thermal Stability, 201
- 8.4 Mechanical Properties, 204
- 8.5 Flammability Properties, 206
 - 8.5.1 Cone Calorimetry, 208
 - 8.5.2 LOI and UL-94 Tests, 216
- 8.6 Flame Retardant Mechanism, 222
 - 8.6.1 Combination of Nanocomposites and Halogen Flame Retardant Additives, 224

| | | |
|-----------|--|------------|
| 8.6.2 | Combination of Nanocomposites and Nonintumescent Phosphorus Flame Retardant Additives, 225 | |
| 8.7 | Summary and Conclusions, 227 References, 228 | |
| 9 | Thermoset Fire Retardant Nanocomposites | 235 |
| | <i>Mauro Zammarano</i> | |
| 9.1 | Introduction, 235 | |
| 9.2 | Clays, 237 | |
| 9.2.1 | Cationic Clays, 237 | |
| 9.2.2 | Anionic Clays, 237 | |
| 9.3 | Thermoset Nanocomposites, 239 | |
| 9.4 | Epoxy Nanocomposites Based on Cationic Clays, 240 | |
| 9.4.1 | Preparation Procedures, 240 | |
| 9.4.2 | Characterization of the Composite, 244 | |
| 9.4.3 | Thermal Stability and Combustion Behavior, 247 | |
| 9.5 | Epoxy Nanocomposites Based on Anionic Clays, 255 | |
| 9.5.1 | Preparation Procedures, 256 | |
| 9.5.2 | Characterization of the Composite, 261 | |
| 9.5.3 | Thermal Stability and Combustion Behavior, 261 | |
| 9.6 | Polyurethane Nanocomposites, 271 | |
| 9.6.1 | Preparation Procedures, 271 | |
| 9.6.2 | Characterization of the Composite, 272 | |
| 9.6.3 | Thermal Stability and Combustion Behavior, 272 | |
| 9.7 | Vinyl Ester Nanocomposites, 274 | |
| 9.7.1 | Preparation Procedures, 274 | |
| 9.7.2 | Characterization of the Composite, 274 | |
| 9.7.3 | Thermal Stability and Combustion Behavior, 276 | |
| 9.8 | Summary and Conclusions, 277 References, 278 | |
| 10 | Progress in Flammability Studies of Nanocomposites with New Types of Nanoparticles | 285 |
| | <i>Takashi Kashiwagi</i> | |
| 10.1 | Introduction, 285 | |
| 10.2 | Nanoscale Oxide-Based Nanocomposites, 286 | |
| 10.2.1 | Nanoscale Silica Particles, 286 | |
| 10.2.2 | Metal Oxides, 288 | |
| 10.2.3 | Polyhedral Oligomeric Silsequioxanes, 289 | |
| 10.3 | Carbon-Based Nanocomposites, 295 | |
| 10.3.1 | Graphite Oxide, 295 | |

| | | |
|-----------|--|------------|
| 10.3.2 | Carbon Nanotubes, 299 | |
| 10.4 | Discussion of Results, 315 | |
| 10.4.1 | Flame Retardant Mechanism, 315 | |
| 10.4.2 | Morphology, 316 | |
| 10.4.3 | Thermal Gravimetric Analysis, 318 | |
| 10.5 | Summary and Conclusions, 318 | |
| | References, 319 | |
| 11 | Potential Applications of Nanocomposites for Flame Retardancy | 325 |
| | <i>A. Richard Horrocks and Baljinder K. Kandola</i> | |
| 11.1 | Introduction, 325 | |
| 11.2 | Requirements for Nanocomposite System Applications, 326 | |
| 11.3 | Potential Application Areas, 331 | |
| 11.3.1 | Bulk Polymeric Components, 331 | |
| 11.3.2 | Films, Fibers, and Textiles, 334 | |
| 11.3.3 | Coatings, 343 | |
| 11.3.4 | Composites, 344 | |
| 11.3.5 | Foams, 347 | |
| 11.4 | Future Outlook, 348 | |
| | References, 349 | |
| 12 | Practical Issues and Future Trends in Polymer Nanocomposite Flammability Research | 355 |
| | <i>Alexander B. Morgan and Charles A. Wilkie</i> | |
| 12.1 | Introduction, 355 | |
| 12.2 | Polymer Nanocomposite Structure and Dispersion, 356 | |
| 12.2.1 | Synthesis Procedures, 356 | |
| 12.3 | Polymer Nanocomposite Analysis, 365 | |
| 12.3.1 | Nanoscale Analysis Techniques, 366 | |
| 12.3.2 | Microscale Analysis Techniques, 371 | |
| 12.3.3 | Macroscale Analysis Techniques, 372 | |
| 12.4 | Changing Fire and Environmental Regulations, 373 | |
| 12.5 | Current Environmental Health and Safety Status for Nanoparticles, 376 | |
| 12.6 | Commercialization Hurdles, 377 | |
| 12.7 | Fundamentals of Polymer Nanocomposite Flammability, 379 | |
| 12.8 | Future Outlook, 383 | |
| | References, 388 | |
| | Index | 401 |