

Index

0-9

- 3',4'-epoxycyclohexylmethyl-3,4-epoxycyclohexane carboxylate, [73](#), [74f](#)
- 4,4'-diaminodiphenyl methane (DDM), [75](#), [77](#), [78f](#)
- 4,4'-tetradiglycidyl diaminodiphenol methane, [75](#), [75f](#)

A

- Acid oxidation, [113](#)
 - inorganic acid oxidation, [113](#)
 - organic acid oxidation, [116](#)
- Acrylic precursors, [32](#), [32t](#)
 - cellulosic precursors.
See Cellulosic precursors
 - PAN-based precursors.
See Polyacrylonitrile (PAN)-based precursors
 - PAN precursors, [33](#)
 - pitch precursors. *See* Pitch precursors
- Acrylonitrile butadiene styrene (ABS) resins, [89](#)
 - and SCF composite, tensile properties of, [90f](#)
 - chemical structure of, [89f](#)
- Acrylonitrile monomer (AN monomer), [32](#)
- Activated carbon cloth, [243t](#)
- Activated carbon fibers (ACFs), [16](#), [242](#)
 - acidic ACFs (A-ACFs), [249](#)
 - adsorption isotherms of propylamine on, [250f](#)
 - adsorption rate of Cr(VI), [119](#), [120f](#)
 - ammonia removal efficiency of, [112f](#)
 - anodic oxidation of, [119](#)
 - as adsorbents, [243](#)
 - chemical composition of, [122t](#), [247t](#)
 - CO₂ adsorption capacity of, [18f](#)
 - Cu-plated, [246](#), [247](#)
 - FT-IR spectra of, [119f](#)
 - gas-adsorption capacity, [111](#)
 - mechanical properties of composite samples, [115t](#)
 - micro/mesopore volume ratios, [18f](#)
 - micropore properties, [249t](#)
 - multimetal ions, removal of, [114f](#)
 - pore shape and structure of, [17f](#)
 - pure (ACF0), [107](#)
 - rayon-based, [107](#)
 - structural characteristics of, [111t](#)
 - textural parameters of, [255t](#)
 - virgin ACFs (V-ACFs), [249](#)
- Advanced Composites Materials Association, [241](#)
- Aircraft, carbon fiber-reinforced composites in, [259–260](#), [260t](#)
 - fighter aircraft, [259](#), [260](#)
 - transport aircraft, [260](#)
- Air oxidation, [87f](#), [106–108](#)
- Air purification, [247](#)
- Allotropes, [1–3](#), [3f](#)
- Ammonium bicarbonate (NH₄HCO₃), [42](#)
- Ammonium carbonate ((NH₄)₂CO₃), [117](#)
 - interfacial shear stress under, [118t](#)
- Ammonium hydrogen carbonate (NH₄HCO₃), [117](#)
 - interfacial shear stress under, [118t](#)
- Ammonium sulfate ((NH₄)₂SO₄), [42](#)
- Amorphous polymers, [193](#)
- Anhydrides, [77](#)

- Anodic oxidation, 42, 42f
 Anodization. *See* Anodic oxidation
 Aqueous dispersion polymerization, 36
 Ascorbic acid (AA), 129
 ASTM test method D3174, 140
 Atomic force microscopy (AFM), 148
 image of Cellion 6000 carbon fibers, 150f
 Auger electron spectroscopy, 147
 Autoclave curing, 217, 218
 benefits of, 218
 popular autoclaves, 217f
 Automobiles, carbon fiber-reinforced
 composites, 262–264, 266f
 CNG cylinders manufactured
 using, 265f, 266f
 for turbine blades, 267f
 in Boeing 787, 263f
 in racing boats, 266f
 Axially aligned polymer nanofibers, 309f
- B**
 Bamboo fibers, 4
 Benzoyl peroxide (BPO), 199
 BET method, 248
 BET-specific surface
 area (BET SSA), 108, 112, 255, 257
 Bicomponent spinning, 301, 302f
 Bismaleimide resins, 204
 Bisphenol-A (BPA)
 dicyanate (DCBA), 70, 71f
 vinyl ester, 201f
 Bulk Molding Compound (BMC), 218,
 222, 231
 Bulk polymerization, 36
- C**
 Carbon
 black oil, 55t
 -carbon (C/C) composites (CCCs), 279, 328
 cloth, 251
 CO₂oxidation, 112
 -epoxy resin (C/Ep), 107
 types of, 3f
 Carbon fiber composites, manufacturing
 process for, 185
 actual mold cavity comparison, 235
 benefits of identifying processes, 186
 closed molding , 218, 222, 223
 See also Closed molding process
 differences, 236
 factors influencing, 186
 matrix, types of. *See* Polymers;
 Thermoplastic resins; Thermoset resins;
 Thermoset resins
 method comparison, 234
 open molding, 209, 221
 See also open molding process
 orphan alternative method , 237
 See also Closed modeling process
 process evaluation, 237
 raw materials for, 234
 reinforcements, types of, 186–191
 strength required, 235
 thickness as issue, 236
 Carbon fiber industry
 by 2020, 22
 market trends, 24
 technology development trends, 21–23
 utility development trends, 22–24
 Carbon fiber paper (CFP), 128, 251
 mechanical and electrical properties of,
 252t
 Carbon fiber-reinforced cement–matrix
 composites (CFRCCs), 270
 flexural strength of, 271f
 Carbon fiber-reinforced composites,
 application, 258, 259
 aircraft structural applications, 258–262
 See also Aircraft, carbon
 fiber-reinforced
 automobiles, 263–266
 construction, 270–273
 marine applications, 264
 sport applications. *See* Sport applications,
 of carbon fiber-reinforced composites
 wind turbine blades, 266, 267
 Carbon fiber-reinforced metal (CFRM)
 matrix, 318
 Carbon fiber-reinforced plastic (CFRP), 263
 matrix, 318
 rackets in, 269f
 tennis racket, 269f
 Carbon fibers (CFs), 2, 31, 69, 105
 and matrix interface, 105
 classification of, 6–7, 7t
 combination of basic structural units
 into microdomains, 20f
 commercial availability, 16, 17
 compound annual growth rate (CAGR), 23f
 correlation of orientation, 8f
 definition, 5
 electrode (CFE), 129
 fluorination, 124, 128
 high-resolution O_{1s} profiles of, 323f
 horizontal section plot of, 150f
 industry. *See* Carbon fiber industry
 market trends, 23f
 mechanical characteristics of, 23f

- nickel layer plating behaviors on, 325, 326*f*
- origin and history of, 4
- oxidation of. *See* Oxidation of carbon fibers
- paper (CFP), 128
- plasma treatment, 120, 121
- polymer coating, 128
- precursors. *See* Precursor fibers
- properties of, 272*t*
- radiation, 122, 123
- SEM micrographs of, 272, 321
- sizing. *See* Sizing, of CFs
- specific resistivity, 324*f*
- stabilized and as-spun fibers, 298*f*
- structure of, 18, 19
- surface contour plot of, 149*f*
- surface free energy of, 319*f*
- with and without organoclay reinforcement, 297*t*
- XPS profiles of, 322*f*
- Young's modulus for, 8*f*
- Carbon fibers, evaluation of, 139
 - atomic force microscopy (AFM), 148
 - Auger electron spectroscopy, 147
 - coefficient of thermal expansion, 157
 - electrical resistivity, 156
 - elemental analysis, 140
 - filament diameter, 152
 - moisture content, 151
 - oxidative resistance, 151
 - Raman spectroscopy, 146, 146*f*, 147, 147*f*
 - scanning tunneling microscopy (STM), 148
 - specific heat, 159
 - tensile properties, 160
 - thermal conductivity, 159, 160
 - thermal stability, 151
 - thermal transition temperature, 159
 - titration, 151
 - X-ray diffraction (XRD), 146*f*
 - X-ray photoelectron spectroscopy (XPS), 140, 144
- Carbon fibers, for energy storage
 - catalysts, 258
 - fuel cells, 251
 - lithium battery, 256
 - molecular sieves, 257
 - supercapacitor, 254
- Carbonization
 - cellulosic precursors, 52, 53*f*
 - gases evolved during, 40*t*
 - of pitch precursor fibers, 62
 - PAN-based precursors, 39
- Carbon molecular sieves (CMS), 257
- Carbon nanofibers (CNFs)
 - and activated carbon fibers (CNFs/ACFs), 328
 - changes in CA of, 336*f*
 - cyclic voltammogram, 338*f*
 - SEM images of, 331, 332, 333*f*, 335*f*
 - TEM images of, 332, 334*f*, 335*f*
- Carbon nanotubes (CNTs), 129, 310
 - See also* Yarns
 - and carbon black (CNTs/CB), 328
 - and carbon fibers (CNTs/CFs), 328
 - and carbon nanofibers, TEM images of, 306
 - and carbon papers (CNTs/CPs), 328
 - and PAN nanofibers, TEM images of, 306*f*
 - carbon nanofibers from, by dry methods, 312*f*
 - carbon nanofibers from, by wet methods, 310–312, 311*f*
- Carbon whisker, 5
 - field emission scanning electron micrographs of, 7*f*
- Carboxylic acids, 33
- Cast aluminum molds, 228
- Catalytic chemical vapor deposition (CCVD), 329
 - filaments, 2
- Cellulose, 4, 45–52
 - carbonization of, 52
 - polymer, chemical structure of, 51*f*
 - thermal degradation of, 13*f*
- Cellulose acetate rayon, saponified, 49, 50*f*
- Cellulose xanthate, 48
- Cellulosic precursors, 32
 - carbon fibers manufacture, 51–54, 53*f*
 - rayon precursor. *See* Rayon precursors
 - stages of, 45
 - stress graphitization, 45
- Charpy impact test, 83*f*, 174, 175, 175*f*
- Chemical vapor deposition (CVD), 129
- Chitosan, 62
- Chopped strand mat, 210, 213
- Closed molding process, 218
 - compression molding, 230
 - extrusion, 233
 - injection molding, 232
 - pultrusion, 225, 226
 - reaction injection molding (RIM), 232, 233
 - resin transfer molding, 219, 220, 224
 - See also* Resin transfer molding (RTM)
 - thermoforming, 227, 228
 - vacuum-assisted resin transfer molding (VARTM), 224, 225
 - vacuum bagging, 228, 229
- CNC cut model, 209

- Coal tar pitch precursors, 55
 - aromatic hydrocarbon components in, 56
 - Cobalt (Co) catalysts, 14, 329
 - Coefficient of thermal expansion
 - in-plane, 159*f*
 - of carbon fibers, 157, 158
 - of composites, 160
 - Commercial fibers, 299
 - Composite materials, 139
 - Composite molds, 228
 - Composites, evaluation of.
 - See* Surface free energy
 - Composites, evaluation of, 160
 - coefficient of thermal expansion, 161
 - creep, 173
 - fatigue, 173
 - flexural behavior, 169
 - fracture toughness, 175, 177
 - impact behavior, 174
 - interfacial properties in, 177
 - Poisson's ratio, 162
 - rheological analysis, 162
 - shear strength, 166–168
 - surface free energy.
 - See* Surface free energy
 - tensile behavior, 165, 166*f*
 - tensile tests, 165*f*
 - thermal conductivity, 161–163, 163*f*
 - uniaxial compressive behavior, 170
 - Compound annual growth rates (CAGR), 22
 - of carbon fibers, 23*f*
 - Compressed natural gas (CNG), 263
 - cylinders, using fiber-reinforced composites, 265*f*
 - cylinders, wet-filament winding process for, 266*f*
 - Compression molding, 230
 - bulk molding compound (BMC), 231
 - dough molding compound (DMC), 231
 - meeting demands, 231
 - sheet molding compound (SMC), 230
 - Contact angle (CA), 336
 - Controlled pyrolysis, 31, 241
 - Copper (Cu) nanoparticles, 244
 - Cotton threads, 4
 - Courtaulds Co, 24
 - Creep, 173
 - Crumbs, 47
 - Curing, 194 *See also* Autoclave curing
 - Curing agents
 - alkali curing agents, 77
 - amine-based, 78, 79*f*
 - amine-type, 77
 - anhydride-based, 79, 80, 80*f*
 - catalytic curing agents, 77, 79
 - epoxy curing agents, 76, 77
 - Curramonium rayon, 49, 50*f*
 - Cyanate Ester (CE) resins, 69, 70, 204
 - curing of, via cyclotrimerization, 71*f*
 - IFSS data of, 71*f*
 - synthesis of monomers, 70*f*
 - Cyclic voltammogram, 338*f*
 - Cytec Co., 24, 25*t*, 26*t*
- D**
- Diaminodiphenol methane (DDM), 77, 78*f*
 - Diamond, 1
 - crystal forms of, 2*f*
 - Dicumyl peroxide, 88
 - Diethyltoluene diamine (DETDA), 75
 - Differential Scanning Calorimeter (DSC), 194
 - Diglycidyl ether of bisphenol-A (DGEBA), 72, 72*f*, 201
 - critical stress intensity factor (KIC) of, 73, 73*f*
 - Diglycidyl ether of bisphenol-F (DGEBF), 72, 73, 73*f*
 - Diglycidyl ether of tetrabromobisphenol-A, 73, 73*f*
 - Di(*t*-butylperoxy) cyclohexane, 88
 - Donac, 26*t*
 - Dopamine (DA), 129
 - Double cantilever beam (DCB), 168
 - Dough molding compound (DMC), 230
 - D-R plot method, 248
 - Drying, 43, 43*f*
- E**
- Edison, Thomas Alva, 4, 31, 44, 241
 - electric lamp containing carbon fiber filament, 5*f*
 - Einstein's relationship, 142
 - Electrical resistivity, 156–158
 - of Ni-plated carbon fibers, 157*f*
 - Electrochemical oxidation , 117–120
 - See also* Activated carbon fibers (ACFs)
 - electrolytes, 117
 - fragmentation experiments, 118
 - interfacial shear stress under, 118*t*
 - Electroless Ni plating, 320
 - anodic reaction, 321
 - cathodic reaction, 321
 - steps of, 324
 - Electrolytic metal coating for electric devices, 324
 - Electromagnetic interference (EMI), 319
 - Electron diffraction, 18

- Electron spectroscopy for chemical analysis (ESCA).
 - See X-ray photoelectron spectroscopy (XPS)
- Electrospinning, 302, 303
 - apparatus and mechanism, 303*f*
 - continuous nanofiber manufacturing process by, 305*f*
 - long carbon fibers by, 302–309
 - modified centrifugal electrospinning, 305*f*
 - uniaxially aligned nanofibers, 307*f*
- Emulsion polymerization, 36
- End notched flexure (ENF), 176
- Epichlorohydrin, 72–74, 76
- Epoxy diluents, 76
- Epoxy resins, 43, 69, 72, 192, 194, 201, 202
 - bisphenol-A/F epoxy resins, 72
 - curing mechanism, 78
 - curing process, 77
 - cycloaliphatic epoxy resins, 73
 - epoxy curing agents, 76
 - epoxy diluents, 76, 77*f*
 - novolac epoxy resins, 76
 - novolac resins, 75
 - tetrafunctional epoxy resins, 74, 74*f*
 - trifunctional epoxy resins, 74
- E-rated lumber, 214
- Eucalyptus, 62
- Extrusion, 233
- EXXON (DAU), 55*t*
- F**
- Fabrics, 187
 - braided, 189
 - common fabrics, 188*f*
 - stitched, 188, 188*f*
 - woven, 188
- Faraday's Law, 42
- Fatigue, 171
 - damage index, 173*f*
- Fe
 - catalysts, 14, 329
 - salt, 242
- Fiber alignment, 106
- Fiber debonding delamination, 175
- Fiber fracture, 175
- Fiberite's 977-3, 260
- Fiber-matrix adhesion, 115
- Fiber protection, 106
- Fiber-reinforced cement–matrix composites, 270
- Fibers, 304
- Fiber wettability, 106
- Fibrous form, 3*f*
- Fighter aircraft, 259, 260, 260*f*
 - in B-2 Bomber, 261*f*
 - in US Navy's F/A-18E/F, 261*f*
- Filament winding, 185, 216
 - process of, 216*f*
- Flash spinning technique, 302
- Flexural strength, 169
- Flexure testing, 169
 - flexural strength test, 171*f*
 - four-point bending, 170, 170*f*
 - three-point bending, 170, 170*f*, 171
- Fluorination, 124
 - and physicochemical properties of CFs, 125
 - mechanism of, 126*f*
 - schematic of fluorination reactor, 126*f*
 - SEM images of CFs, 127*f*
- Fluorocarbons, 212
- Formosa Co, 24, 25*t*
- Fowkes' proposition, 178
- Fracture, 175
 - in Ar⁺ ion-irradiated carbon fibers, 181*f*
 - load-displacement ENF curves, 177*f*
 - schematic, 176*f*
- Fuel cells, 251
 - efficiency of, 251
 - nickel coating on, 253, 253*t*
 - proton electrolyte membrane fuel cells (PEMFCs), 252
 - proton exchange membrane fuel cells (PEMFCs), 251
 - schematic of, 250*f*
- Fullerenes, 1
- Functional carbon fibers for smart composites
 - electroless metal coating for electric devices, 319
 - electrolytic metal coating for electric devices, 324
 - metal-coated carbon fibers, 318
 - nanocarbon coating on carbon fibers, 328
- G**
- Gamma ray (γ -ray) radiation, 122
 - on PAN-based carbon fibers (PAN-CFs), 123
 - on polyetherimide (PEI) matrix, 123
- Gaseous oxidants, 106
 - air oxidation, 106–109
 - CO₂ oxidation, 112
 - H₂O oxidation, 112
 - O₂ oxidation, 109
 - O₃ oxidation, 109
- Gas-phase-grown carbon fibers, 15

Gaussian distribution, 248
 General-purpose carbon fibers
 (GP-carbon fibers), 12, 16
 Glass-fiber-reinforced PPS, 98
 Glass-like carbon, 2
 Glassy carbon electrode (GCE), 129
 Graphene, 4, 19, 52, 62, 121, 129,
 332, 336, 337
 and CNTs, 328
 Graphites, 1, 2
 crystal structure of, 6*f*, 19*f*
 graphitization and sketches of, 19, 21*f*
 nanofibers (GNFs), 122
 schematic of structure of, 39*f*
 whiskers, 2, 5
 Graphitization, 39, 41
 cellulosic precursors, 52, 53*f*
 of pitch precursor fibers, 62
 PAN-based precursors, 39, 41
 Grove, William, 251

H
 Halpin-Tsai relationship, 195
 Hand layup, 211*f*
 and volatile organic compounds (VOCs),
 211
 bonding, 213
 fluorocarbons, 212
 laminated construction, 213
 laminar materials, 212, 213
 multi-ply construction, 214
 surface preparation, 213
 Hardeners, 201
 Hardwood kraft lignin, 296, 296*f*
 Heat cure, 77
 Heat deflection temperature (HDT), 74, 195
 Hexcel Co. (carbon fiber producing
 company), 22, 24, 25*t*
 IM7 carbon fiber, 260
 High-modulus (HM) carbon fibers, 6
 High-performance (HP) carbon fibers
 (HP carbon fibers), 12, 16
 classification of, 22*f*
 High-resolution carbon peak, 145*f*
 High-tensile-strength (HT) carbon fibers, 6
 HITCO Co. (USA), 24
 HWKL carbon fibers, mechanical
 properties of, 297*t*
 HWKL/PEO carbon fibers, mechanical
 properties, 297*t*
 Hydrogen (H₂) adsorption, 245, 245*f*
 micropore properties determined using,
 249*t*
 Hydrogen physisorption, 244

I
 Incandescent filaments, 4
 Injection molding, 231, 232
 schematic of, 232*f*
 Inorganic acid oxidation, 113, 116
 Interfacial shear strength (IFSS), 70, 71*f*
 calculation, 168
 effects of deposited CNTs on, 169*f*
 of composites, 168
 Interlaminar shear strength (ILSS)
 of carbon fiber-reinforced composites, 167*f*
 of composites, 167
 short-beam shear test, 167*f*
 Intermediate-modulus (IM) carbon fibers, 6
 Ion-assisted reaction (IAR) method, 124, 125*f*
 Irwin and Kies expression for fracture energy,
 176
 Isophthalic polyesters, 199, 200
 Isophthalic resins, 215
 Isotropic carbon fibers, 6
 Isotropic pitches, 58, 59
 Izod impact test, 174, 174*f*

K
 Kayacarbon, 12
 Kraft process, 14
 Kureha Chemicals, 26

L
 Light RTM process (LRTM), 222, 223
 and RTM processes, 223
 Lignin, 12, 14, 295, 296
 -based carbon fibers, 12, 14
 fiber spools produced from, 15*f*
 Liquid injection molding processes, 218
 London dispersive components, 178, 179, 179*t*
 Low-cost production technique of carbon
 fibers, 295, 300

M
 Machined aluminum molds, 227
 Matrix cracking, 175
 Melt blowing technique, 301
 Melt spinning, pitch precursor fibers, 60
 Mesophase pitches, 59
 Metallocene catalysts, 96, 98
 Methacrylate (MA), 33
 Methyl ethyl ketone peroxide (MEKP), 88, 199
 Methyl methacrylate (MMA), 33
 Mitsubishi Chemical Co. (carbon fiber
 producing company),
 22, 24, 25*t*, 26*t*
 Mitsubishi Rayon Co. Ltd. (Tokyo, Japan), 241
 MoSi₂, 288

- Multiwalled carbon nanotube (MWCNT), 108
characteristics of air-oxidized, 109*t*
characteristics of pristine, 109*t*
TEM images, 108*f*
- N**
- N₂-adsorption isotherms, 107
- Nanocarbon-coated CFs
characteristics of, 330
preparation of, 329–331*f*
- Nanocarbon coating on carbon fibers, 328, 337
See also Nanocarbon-coated CFs
- Nanofiber fabrics, 309
- Nanofiber yarns, 309
- NaOH-treated jute fibers, 300*f*
- Naphthalene, 12
- Natural fibers, 299*t*
- N-benzylpyrazinium hexafluoroantimonate (BPH), 77, 78*f*
BPH-initiated epoxides, polymerization of, 81*f*
- N-benzylquinoxalium hexafluoroantimonate (BQH), 77, 78*f*
- Newtonian fluids, 162
- Nickel/carbon hybrid fibers, 253
- Nickel (Ni) plating process, 320
- Ni-coated carbon nanofibers
behavior viscosity of, 164*f*
storage and loss moduli of, 165*f*
- Ni-plated carbon fibers, 319
deposition behaviors of, 328*f*
electrical resistivity, 254, 254*f*
interlaminar shear stress (ILSS) of, 319, 320*f*
SEM images of, 325*f*
specific electric resistivity of, 328*f*
XRD patterns of, 326, 327*f*
- Nippon Graphite, 26*t*
- N₂ isotherms of fibers, 245
micropore properties determined using, 249
- Nitric acid (HNO₃), 42, 117
interfacial shear stress under, 118*t*
- N₂/77 K adsorption isotherms, 248
- Nomex-derived ACFs, 255
- Non-Newtonian fluids, 162
- Novolac epoxy resins, 76
- Novolac resins, 75, 80
- Nylon 66, 90
- Nylon, 130, 189, 206, 207
and CF composites, tensile and compression properties of, 91*t*
schematic of synthesis of, 91*f*
- O**
- Oak Ridge National Laboratory (ORNL), 14
- Open molding process, 209, 210
autoclave curing, 217, 218
filament winding, 216, 217
hand layup, 211, 214
spray layup, 214–216*f*
tape layup, 216
wet layup, 210, 211
- Optical microscopy, 18
- Organic acid oxidation, 116
- Orthophthalic polyesters, 199
- Orthophthalic resins, 215
- Oxidation, 41 *See also* Thermal stabilization
gaseous oxidation, 41
liquid oxidation, 41
- Oxidation of carbon fibers, 106
acid oxidation. *See* Acid oxidation
electrochemical oxidation, 117, 119
gaseous oxidants. *See* Gaseous oxidants
treatment with nonoxidative agents, 120
- Oxygen (O₂) oxidation, 109, 111, 112
- Ozone (O₃) oxidation, 109, 111, 112
- Ozone method, 110
- P**
- Petoca Materials, 26*t*
- Petoca Oil Company, 62
- Petroleum pitch
Ashland 240 pitch, 55*t*
Ashland 260 pitch, 55*t*
precursors, 54, 55
preparation of, 56–58, 58*f*
- Phenolic polymers, 63
- Phenolic resins, 4, 32, 79, 203, 204
charpy impact strength, 83*f*
evolution of KIC, 82*f*
novolac resins, 80
resol resins, 79, 80
- Photocure, 78
- Phthalic anhydride (PA), 77, 78
- Pitch, 9
fabrication processes, 11*f*
manufacturing processes, 10*f*
melt spinning of, 12, 13*f*
noncarbonized mesophase pitch-based fibers, 20
- Pitch-based carbon fibers
SEM images of, 155*f*
structure of, 157*f*
- Pitch-based precursors, 32
carbon fibers from, 60, 62
coal tar pitch, preparation of, 57, 59, 59*f*
petroleum pitch. *See* Petroleum pitch

- Pitch precursors, 54
 - asphaltenes, 54
 - coal tar pitch precursors, 55
 - composition of, 122*r*
 - naphthene aromatics, 54
 - petroleum pitch precursors, 54, 55
 - pitch-based precursors, 57
 - polar aromatics, 54
 - saturates, 54
- Plasma treatment
 - atmospheric pressure plasma device, 121*f*
 - in ultrahigh modulus (UHM) CFs, 121
 - low-pressure plasma-mixed gas (Ar/O₂) treatment, 122
 - selected systems used in, 121
- Plexiglas disk, 308
- Poisson's ratio, 162
- Polyacrylonitrile (PAN), 4
 - based carbon fiber manufacturers, 25, 26*t*
 - lignin copolymers, 297
 - chemical structure, 37*f*
 - cyclization reaction of, 304*f*
 - fabrication processes, 11*f*
 - fibers, 9, 36, 38, 153*t*
 - manufacturing processes, 10*f*
 - oxidative stabilization, 153*t*
 - polymers, 303
 - precursors, comonomers for, 34*t*
- Polyacrylonitrile (PAN)-based carbon fibers
 - composites, 70, 71*f*
 - production cost of, 296*f*
 - SEM images of, 155*f*
 - structure of, 158*f*
 - types of, 44
- Polyacrylonitrile (PAN)-based precursors
 - carbonization, 39, 41
 - drying, 42, 43
 - graphitization, 39, 41
 - manufacture of carbon fibers from, 36, 37*f*
 - mechanism of cyclization of, 39*f*
 - plant for processing, 38*f*
 - polymerization methods for production of, 35, 36
 - polymerization of, 36
 - sizing, 42
 - surface treatment, 41
 - tensile strength of, 40*f*
 - thermal stabilization, 38
 - winding, 42, 44
- Poly(adipic acid divinyl ester) (poly AADE), 88
 - degree of grafting in, 88*f*
- Polyamides (PAs), 4, 63
 - aliphatic PAs, 90
 - amorphous PAs, 90
 - aromatic PAs, 90
 - copolymer PAs, 90
 - homopolymers, 90
 - PA 6/66, 90
 - PA 66, 90
 - resins, 85, 89, 90
 - semicrystalline PAs, 90
- Poly(ether ether ketone), 208
- Poly(hexamethylenediamine adipamide), 90
- Poly(p-phenyleneacetylene), 12
- Polyaceneophthalene, 63
- Polybenzimidazole, 63
- Polybenzoxazole, 63
- Polybutylene terephthalate (PBT), 83, 85*f*
- Polycaprolactone (PCL), 83, 84*f*
- Polycarbonate, 208
 - Apples original iMac, 208
 - compact disks (CDs), 208
- Polycarbonate (PC) resins, 91, 92
 - schematic of synthesis of, 92*f*
- Polyester resins, 82, 83, 85, 198, 199
 - CF composites, conductivity of, 85*t*
 - cross-linking, 199
 - mechanical properties of, 199
 - unsaturated polyester, 200*f*
- Polyesters, 4, 83, 192, 207, 213
- Polyetheretherketone (PEEK) resins, 89, 92, 93
 - schematic of synthesis of, 93*f*
- Polyetherimide (PEI) resins, 89, 94, 208
 - chemical structure of, 94*f*
 - specific wear rate, 95*f*
- Polyethersulfone (PES) resins, 89, 94
 - chemical structure of, 95*f*
 - transverse flexural properties of, 95*t*
- Polyethylene, 205
- Polyethylene (PE) resins, 89, 96
 - chemical structure of, 96*f*
 - dependence of electrical conductivity on, 97*f*
 - high-density PE (HDPE), 96
 - linear low-density PE (LLDPE), 96
 - low-density PE (LDPE), 96
- Polyethylene terephthalate (PET), 83
 - by dimethyl terephthalate process, 84*f*
 - by terephthalic acid, 84*f*
- Polyglycolic acid (PGA), 83, 84*f*
- Polyimide (PI)
 - aliphatic PIs, 85, 86*f*
 - aromatic PIs, 86*f*
 - chemical structure, 86*f*
 - polymers, 303
 - resins, 85, 87
- Poly(lactic acid) (PLA), 83, 84*f*

- Polymer coating, 128
- Polymerization, 37
- BPH-initiated epoxides, 81*f*
- Polymers
- chemistry, 196 *See also*
 - Thermoplastic resins;
 - Thermoset resins
 - knee stress, 196, 197*f*
 - matrix-dominated property, 196
 - matrix selection, 191
 - overview of, 193
 - Silicone toy behavior, 165
 - stress-strain curve of, 195*f*
 - tension and compression tests, 195
 - thermal properties of, 194, 195
 - viscoelastic properties of, 163
- Polyphenylene, 63
- Polyphenylene sulfide (PPS)
- resins, 89, 97–99, 207, 208
 - schematic of synthesis of, 97*f*
 - variations in friction coefficient of, 98*f*
- Polyphthalamides, 90
- Poly-p-phenylene, 4
- benzobisthiazole (PBBT), 63
- Polypropylene (PP) resins, 89, 98, 99
- atactic, 99*f*
 - bending strength and modulus of, 99, 100
 - chemical structure, 99*f*
 - isotactic (iPP), 97, 99*f*
 - schematic of synthesis of, 99*f*
- Polypropromellitimide, 87*f*
- Polystyrene, 63
- Polyurethane resins, 202, 203*f*
- formation reaction, 203*f*
- Polyvinyl alcohol (PVA) polymers, 4, 63, 303
- Polyvinyl chloride (PVC), 12
- Polyvinylidene, 4
- Polyvinylidene chloride, 63
- Polyvinylpyrrolidone (PVP) nanofibers, 307
- orientation of, 308*f*
- Postcuring, 199
- Precursor fibers, 8–12, 14–16
- aromatic polymers, 12
 - carbon yield comparison, 14*f*
 - controlled pyrolysis, 8
 - fabrication processes, 11*f*
 - lignin-based carbon fibers, 12, 14
 - manufacturing process, 10*f*
 - schematic for preparation of, 9*f*
 - short carbon fibers, 14
 - structural model, during graphitization process, 9*f*
 - thermal degradation of cellulose to carbon, 14*f*
- Pristine carbon fibers (Pristine CFs)
- galvanostatic charge/discharge curves of, 338*f*
 - N₂/77 K isotherms, 332*f*
 - N₂ full isotherms, 334
 - SEM images of, 332*f*
- Proton electrolyte membrane fuel cells (PEMFCs), 252
- Pultrusion, 198, 225–227
- radio frequency (RF) wave generator unit, 226
 - schematic of, 226*f*
- Pyrolysis, 45
- Pyrolytic graphite, 2
- R**
- Raman spectroscopy, 146, 147
- in pitch-based Nippon Graphite Fibers, 147*f*
 - in polyacrylonitrile (PAN)-based fibers, 147*f*
- Rayon, 4, 9
- based carbon fibers, 12
 - SEM images of, 156*f*
- Rayon precursors, 45
- currammonium rayon, 49, 50*f*
 - saponified cellulose acetate rayon, 49, 50*f*
 - viscose rayon, 46–49
- Reaction injection molding (RIM), 218, 232, 233
- schematic, 233*f*
- Reinforcements, for carbon fiber composites
- bidirectional, 190*f*
 - braided fabrics, 189
 - mats, 187
 - multidirectional, 187
 - multiend rovings, 187
 - pseudoisotropic, 190*f*
 - prepregs
 - sandwich construction, 190, 190*f*
 - single-end rovings, 187
 - stitched fabrics, 188
 - unidirectional, 189, 190*f*
 - woven fabrics, 188
- Resin characteristics, 192
- Resin transfer molding (RTM), 191, 192, 198, 219, 220
- background of, 222
 - benefits of, 221
 - current developments, 221
 - in fighter aircraft, 259
 - light RTM (LRTM), 222, 223
 - process of, 220*f*
- Resol resins, 79, 80
- Room temperature cure, 77
- Rovings, 187

S

Sandwich lamination constructions, 214
 Saponified cellulose acetate rayon, 49, 50*f*
 Scanning electron microscopy (SEM), 18, 244
 images of Cu-plated ACFs, 246*f*
 images of oxygen plasma treated ACFs, 247*f*
 Scanning force microscopy (SFM). *See* Atomic force microscopy (AFM)
 Scanning tunneling microscopy (STM), 148, 149
 atomic-scale STM images, 149*f*
 images of GNF-coated ACFs, 123*f*
 local density of states (LDOS), 148
 Selected area diffraction (SAD), 20
 Semicrystalline polymers, 193
 SGL (carbon company), 25*t*
 Sheet molding compound (SMC), 187, 230
 Short carbon fiber (SCF) content, 90
 fiber corrosion depths of, 93*f*
 -reinforced PEEK composites, 93
 Silane-treated carbon fiber-reinforced cement, 271
 tensile strength of, 272*t*
 Silk, 62
 Single-filament composite (SFC), 168
 pull-out test specimen, 168*f*
 Single walled nanotubes (SWNTs), 310
 Sizing, of CFs, 130
 and polyether sulfone (PES), 131
 definition, 130
 for fiberglass, 130*t*
 interfacial shear strength (IFSS), 131, 132
 interlaminar shear strength (ILSS), 132
 organic solvent-free polyamic acid (PAA) nanoemulsion, 131
 sizing agents, 133*t*
 surface chemical changes, 131
 Small-angle X-ray diffraction, 18
 Small-angle X-ray scattering (SAXS), 20
 Sodium dodecyl sulfate (SDS), 310
 Sodium hydroxide (NaOH), 117
 interfacial shear stress under, 118
 Solution polymerization, 35
 Solvent recovery, 247
 Sp² hybridized orbitals, 2*f*, 19
 Sp³ hybridized orbitals, 2*f*, 19
 Sport applications, of carbon fiber-reinforced composites, 267
 golf shaft, 268, 270*f*
 rackets in CFRP, 267, 268
 Spray layup, 214, 216
 advantage of, 215
 process, 215*f*

Stabilization

 cellulosic precursors, 51, 52
 of pitch precursor fibers, 60, 61
 Stoner's thesis, 181
 Stress graphitization, 45
 Structural reaction injection molding (SRIM), 218
 Submicron carbon fibers, 301
 bicomponent spinning, 301, 302*f*
 electrospinning, 302
 flash spinning technique, 302
 melt-blowing technique, 301
 Sulfonic acids, sodium salts of, 34*t*
 Sulfuric acid (H₂SO₄), 42, 117
 interfacial shear stress under, 118*t*
 Surface free energy, 179*t*
 analysis using linear fit method, 178
 and work of adhesion, 177–179, 179*f*
 Surface replica electron microscopy, 18
 Surface-treated CFs
 PP composites filled with, 99
 -reinforced PI composites, 87
 relative percentages of functional groups on, 116*t*
 Surface treatment, 41, 42
 Surface veils, 190
 Synthetic fibers. *See* Precursor fibers

T

Tape layup, 216
 t-butyl peroxybenzoate, 88
 T-300 CF oxidation, 109
 Tetraethyl orthosilicate (TEOS), 330
 Thermal conductivity
 of carbon fibers, 158, 159
 of composites, 162*f*
 Thermal stabilities, 279
 Thermal stabilization, 38
 Thermofforming molds, 227, 227*f*, 228
 benefits of, 228
 infrared ovens, 227
 types of, 227
 Thermogravimetric analysis (TGA), 151
 Thermoplastic polymers, 91
 Thermoplastic resins, 89, 94, 204
 acrylonitrile butadiene styrene resins, 89
 continuous-use temperature for, 198*t*
 molecular arrangements in, 205*f*
 nylon, 207
 polyamide (PA) resins, 90, 91
 polycarbonate (PC) resins, 91, 92, 208
 polyesters, 207
 polyetheretherketone (PEEK) resins, 92, 93
 polyetherimide (PEI) resins, 94, 208

- polyethersulfone (PES) resins, 94
- polyethylene (PE) resins, 96, 97, 206
- polyphenylene sulfide (PPS) resins, 97, 98, 207, 208
- polypropylene (PP) resins, 98, 99, 206, 207
- Thermoset polymers, 193
- Thermoset resins, 69, 197, 198
 - bismaleimide resins, 204
 - continuous carbon nanofibers, 301, 302, 304, 305, 307–309
 - continuous-use temperature for, 198*t*
 - cross-linking of, 198*f*
 - cyanate ester (CE) resins, 69, 70, 204
 - epoxy resins. *See* Epoxy resins
 - phenolic resins, 203, 204 *See also* Phenolic resins
 - polyester resins, 82, 85, 198, 200
 - polyimide resins, 85, 87
 - polyurethane resins, 202, 203*f*
 - properties of, 199*t*
 - vinyl ester (VE) resins, 87, 88, 200, 201*f*
- Thin carbon fibers for extreme industries, 300
 - carbon nanotube (CNT) yarns, 310, 312, 313
 - continuous carbon nanofibers
- Titration techniques, 151
- Toho Tenax Co. (carbon fiber producing company), 22, 24, 25*t*
- TORAYCA®brand of CFs, 132
 - designation of, 133*t*
 - sizing agents of, 133*t*
- Toray Co. (carbon fiber producing company), 22, 24
- Transmission electron microscopy (TEM), 18, 20
- Transport aircraft, 260, 262
 - in Airbus A320, 262*f*
- Trimethylol propane-N-triglycidyl ether, 74*f*
- U**
- Ultrahigh-modulus (UHM) carbon fibers, 6
- Uniaxial compressive behavior, 170, 171
 - compression strength variation, 172*f*
 - scarf-joint specimen geometry, 173*f*
- Union Carbide Corporation (UCC), 4
- Unsaturated polyesters, 192
- Uric acid (UA), 129
- V**
- Vacuum-assisted resin transfer molding (VARTM), 211, 224
 - benefits of, 224*f*
 - process of, 224*f*
- Vacuum bagging, 228
 - consumable materials and equipment required for, 229*t*
 - schematic of, 229*f*
- van der Waal forces, 1, 19, 178
- Vapor-grown carbon fibers (VGCFs), 2, 15, 92, 128
 - elemental analysis of, 140*t*
 - manufacturing processes, 16*f*
 - with supercritical fluids (SCFs), 140
- Vinyl acetate (VAc), 33
- Vinyl amides, 34*t*
- Vinyl compounds, ammonium salts of, 34*t*
- Vinyl esters, 34*t*, 192, 193
- Vinyl ester (VE) resins, 69, 87, 88, 200*f*
 - cured VE, 88
- Vinylidene chloride, 32*t*
- Virgin carbon fibers, 242
 - ACFs as adsorbents. *See* under Activated carbon fibers (ACFs)
 - applications of, 242, 243
- Viscose, 47
- Viscose rayon, 46
 - aging, 47
 - cutting, 49
 - degassing, 48
 - dissolving, 48
 - drawing, 49
 - filtering, 48
 - manufacture of, 46*f*
 - pressing, 47
 - ripening, 48
 - shredding, 47
 - steeping, 46
 - wet spinning, 48
 - xanthation, 47
- Volatile organic compounds (VOCs), 211, 238
- W**
- Washburn's equation, 178
- Washing, 41, 42
 - PAN-based precursors, 39, 41
- Water (H₂O)
 - oxidation, 112, 113
 - purification, 247
- Weibull distribution, 180
- Wet filament winding, 216
- Wet layup, 210
 - advantage of, 210
 - vacuum-assisted wet layup, 211
- Wet spinning, rayon precursor fibers, 48
- Wide-angle X-ray diffraction, 18
- Wide-angle X-ray scattering (WAXS), 20
- Winding, 43, 44*f*

X

- Xanthation, [47](#)
- X-ray diffraction (XRD), [146](#)
 - patterns of carbon materials, [146f](#)
- X-ray patterns, [45](#)
- X-ray photoelectron spectroscopy (XPS), [140](#), [143](#), [144](#), [146](#), [247](#)
 - binding energy assignments, [143t](#)
 - carbon atom undergoing photoelectron emission, [142f](#)
 - information obtained by, [141t](#)
 - profile of C_{1s} region, [144f](#)
 - schematic of processes of, [142f](#)
 - surface functional groups of ACFs, [249f](#)

Y

- Yarns, [304](#)
 - carbon nanofibers from, by dry methods, [312](#), [313](#)
 - carbon nanofibers from, by wet methods, [310–312](#)
- Young's modulus, [44](#), [312](#)
 - of PC/VGCF cast, [92](#), [92f](#)

Z

- Ziegler-Natta catalysts, [96](#)
- Ziegler-Natta polymerization, [98](#)
- Zoltek Co. (carbon fiber producing company), [22](#), [25t](#)