## Subject Index

### A
- Advanced-cure phenomenon, 102, 103, 105, 129–30
- AES. See Auger Electron Spectroscopy (AES)
- Air, crack growth in, 432, 437
- Alpha-beta interface cracking (IFC), role of hydrogen in, 401, 407, 413, 417–18
- Alpha cleavage, role of hydrogen in, 418, 421
- Aluminum alloy
  - fractographic analysis
  - of damage mechanisms in, 189–210
  - of environmental effects on high-strength, 424–45
- Ambient air, crack growth rate in, 424, 432, 437
- Angleplied laminates, fracture characteristics of, 101–30
- ASTM Standards:
  - E 8-85: 197
  - E 23-82: 336, 351–52
  - E 399-83: 71
  - E 647-83: 337, 386
- Auger Electron Spectroscopy (AES), to study corroded fracture surfaces, 373
- Austenistic stainless steels, ductile-to-brittle transition in, 350–64
- Autotempered martensite, 344–45

### B
- Basicity, effect of, on toughness, 301
- Basicity index, 296, 299
- Beach markings, 12n, 20
  - in chromium steam turbine blading steel, 334
- Brittle cleavage plans, and radiation exposure, 229–30

### C
- Carburization, 318, 320
- Carburized steel, fractographic investigation of fatigue damage in, 317–33
- Case-core interface, in carburized steel, 332
- Case-core separation, in carburized steel, 324–27
- Case hardening, in carburized steel, 318
- Charpy specimens
  - and crack propagation, 296
  - fractography of, 302–10
  - impact testing of, 336–37
  - shear lips in, 12; *illus.*, 12
  - toughness characterization of, 299, 301–2
- Chevron markings, and assessment of crack propagation direction in, 8, 15; *illus.*, 9, 10
- Clam shell markings, 12n, 14, 20; *illus.*, 13
Clay particulates, and crack propagation, 177–87
Cleavage fracture, 15; *illus.*, 16
Cleavage planes, 276, 279
Composite(s). *See also* Particulate composites
characterization of impact damage development in graphite/epoxy laminates, 238–57
correlations between micromechanical failure processes and delamination toughness of graphite/epoxy systems, 68–87
determination of crack propagation directions in graphite/epoxy structures, 154–72
fractographic investigation of stacking sequence on the strength of notched laminated, 131–53
fracture characteristics of angleplied laminates fabricated from overaged graphite/epoxy prepreg, 101–30
fracture surfaces of irradiated, 217–36
Composite Fracture Characterization program, 102, 103
Computer-assisted fractography, 263–64
image processing and analysis, 264–65
Constitutive model, concept of damage-dependent, 190, 200–10
Continuum mechanisms, 192
Cooley-Tukey algorithm, 267
Corroded fracture surfaces, fractography in the failure analysis of, 366–79
Corrosion fatigue fracture morphology, 348
Crack growth direction, use of hackles in determining, 93
Crack-opening displacement (COD), measurement of, 135
Crack-pinning mechanism, in filled polymers, 178, 184–85, 187
Crack propagation. *See also* Fatigue crack propagation
in carburized steel, 327, 332
in filled polymers, 177–87
in graphite/epoxy structures, 154–72
and hackle separation, 165, 167, 172
in high-strength aluminum alloy, 424–45
microstructural aspects of crack propagation in filled polymers, 177–87
mode of, 359
use of chevron markings to assess direction of, 8; *illus.*, 9, 10
Cross-ply interfaces fracture surfaces, 161–63, 168–70

D
Damage-dependent constitutive model, evaluation of, 190, 200–10
Damage mechanisms
in graphite/epoxy laminates, 238–57
in short-fiber metal matrix composites, 189–210
DCB test, 44, 47
d-c power spike, 267
Delamination. *See also* Interlaminar fractures
correlations between micromechanical failure processes and toughness, of graphite/epoxy systems, 68–97
influence of, on notched strength, 151
Digital fractographic pattern characterization, 288, 290
illus., 289, 290
Digital fractographic pattern classification, 275
cleavage planes, 276, 279; illus., 280, 281, 282
fatigue striations, 279, 282; illus., 283, 284, 285
intergranular facets, 282, 285, 288; illus., 286, 287, 288
microvoid coalescence dimples, 275–76; illus., 277, 278, 279
Digital imaging analysis, fractographic feature identification and characterization by, 263–91
Digital image acquisition, 266–71
Dimple zone formation, 359
Discontinuous growth bands (DGB), 27–28
Ductile systems
fracture characteristics of, 93, 95
fracture surface characteristics of, 79
and the formation of hackles, 77, 90–93
Ductile-to-brittle transition in austenitic stainless steels, 350–64

E

EDS. See Energy dispersive spectrometry (EDS)
Electron microscopy, for investigating weld surfaces, 298
Electron probe microanalysis (EPMA), to study weld structure, 311
Embritting agent, 419
End notch flexure (ENF) test for delamination testing, 42, 72
Endoxing, 367
Energy dispersive spectrometry (EDS)
to study charpy fracture surfaces, 302, 306, 308, 310
to study corroded fracture surfaces, 368
Engineering plastics and composites
fast fracture and sustained loading in, 16–20
fatigue mechanisms and transitions in, 24–31, 33–34
Engineering solids, fracture surface micromorphology of, 5–34
Environmental effects
characterization of impact damage development in graphite/epoxy laminates, 238–57
fractographic aspects of, on the fatigue crack propagation mechanism in high-strength aluminum alloy, 424–45
fracture surfaces of irradiated composites, 217–36
Environmental hydrogen gas-induced cracking, role of hydrogen in, 401
EPMA. See Electron probe microanalysis (EPMA)
Epoxy composites. See Graphite/epoxy composites
Epoxy resin, fatigue fracture surface of, 33–34

F

Fabrication techniques for metal matrix composites, 191
Face-centered cubic (FCC) crystal structures, fatigue striations in, 22
Failure analysis
  fractography in, of corroded fracture surfaces, 366–79
  implications of, 93
  use of hackles to identify shear loading state, 96–97
Fast fracture
  in engineering plastics, 16–20
  in metal alloys, 15–16
Fatigue crack growth tests, 336–37
Fatigue crack propagation. See also Crack propagation
  in carbonized steel, 318
  micromechanisms of major/minor, in Inconel 718, 383–98
Fatigue damage, fractographic investigation of, in carburized steel, 317–33
Fatigue fracture
  beach markings on surfaces of, 12, 14–15; illus., 13
  in chromium steels, 340–41, 346–48
Fatigue mechanisms and transitions in engineering plastics and composites, 24–31, 33–34
  in metal alloys, 20–24
Fatigue striations, 20–23, 279, 282
Fatigue testing method, 321
Ferrous alloys
  fractography in the failure analysis of corroded fracture surfaces, 366–79
  fractography of pressure vessel steel weldments, 295–316
  fractographic investigation of fatigue damage in carburized steel, 317–32
  fractographic studies of the ductile-to-brittle transition in austenitic stainless steel, 350–64
  fracture morphology of 13% chromium steam turbine blading steel, 334–48
  Fiber-reinforced composite materials, use of, as high-performance structural materials, 217
Fibrils, 17
Filled polymers, microstructural aspects of crack propagation in, 177–87
Fourier transform, development of digital techniques of image reconstruction using, 263–91
Fourier transform power spectrum, 267; illus., 268
  calibration of, 272, 275
Fractal dimension, correlation between fracture toughness and, 265
Fractographic analysis, of hydrogen-assisted cracking in alpha-beta titanium alloys, 400–22
Fractographic aspects of the effect of environment on the fatigue crack propagation mechanism in a high-strength aluminum alloy, 424–45
Fractographic imaging analysis
  digital image acquisition, 266–71
  fractographic image feature calibration, 271–75
  image processing software, 266
  technique of, 265–66
  theoretical fractographic models, 266
Fractographic investigation of the influence of stacking sequence on the strength of notched laminated composites, 131–52, 153
Fractography
definition of, 1
establishment of, as science, 154
in the failure analysis of corroded
fracture surfaces, 366–79
of fatigue damage in carburized
steel, 317–33
of pressure vessel steel weldments,
295–316
techniques of, 1
use of, in failure analysis, 263–64
Fracture energy, in filled composites,
178, 179, 182, 183, 187
Fracture morphology
of 13% chromium steam turbine
blading steel, 334–48
mixed Mode I and II fracture, 54–
65
Mode I fracture, 44–48
Mode II fracture, 48–54
Fracture steps, confirmation of, by
SEM fractography, 181,
187
Fracture surfaces
cleaning of, 6–7
in cross-ply interfaces, 168–70
of irradiated composites, 217–36
in laminate composites, 144–49
Fracture surface micromorphology
in engineering solids, 5–6
macroscopic features
chevron markings, 8, 15; illus., 9,
10
fatigue bands and ratchet mark-
ings, 12, 14–15; illus., 13, 14
shear lips, 9–12
microscopic appearance
fast fractures and sustained
loading, 15–20; illus., 16,
17, 18, 19, 20
fatigue mechanisms and transitions,
20–31, 33–34; illus.,
22, 23, 25, 26, 28, 29, 31, 32,
33; table, 30
preparation procedures, 6–7
Fracture toughness, correlation be-
tween fractal dimension
and, 265

G
Glass fiber-polypropylene (PP) rein-
forced composite, fracture
surface in, 32–34
Global material characterization, of
fracture toughness, 42
Graphite/epoxy composites, 131–51
applications of, 68, 100, 155
characteristics of overaged, 105,
114–23
corruption of impact damage
development in, 238–57
correlations between microme-
chanical failure processes
and the delamination
toughness of, 68–97
crack propagation direction in,
154–72
cross-ply interfaces fracture sur-
faces, 161–63, 168–70
materials, 156
Mode I tension fractures, 158
Mode 2 shear fractures, 163
test procedure, 156–58
0°/0° interface fracture surface,
158, 160–61, 163–65, 167
fractographic investigation of the
influence of stacking se-
quence on strength of
notched, 153
fracture characteristics of, 104;
illus., 106
angleplied laminates fabricated
from overaged prepreg,
101–30
fresh, 115, 124; illus., 126–27;
table, 124
fracture stresses of angleplied laminate, 104
fracture surfaces of angleplied laminate, 104; illus., 108–9
irradiated, 217–36
microstructural characteristics of, 105; illus., 110–13
SEM fractography of interlaminar fractures in, 41–66

H
Hackles
formation of, in graphite/epoxy systems, 77, 90–93, 246, 251
for determining direction of crack growth, 93
for identifying shear loading state, 96–97
on fracture surface, 19
separation of, and hackle tilt and crack growth direction, 165, 167, 172

HARM, 267
Helmholtz free energy, 192
Hydrogen
effect of, on austenitic stainless steels, 351, 356
in environmental hydrogen gas-induced cracking, 401
in inert-environment sustained load cracking (SLC), 401
in stress corrosion cracking (SCC), 401
Hydrogen-assisted cracking, fractographic analysis of, in alpha-beta titanium alloys, 400–22
Hydrogen charging, impact of, on fractographic features of stainless steel, 361
Hydrogen embrittlement, 335, 351, 376, 379
Hydrogen reduction method, for oxide removal, 367

I
ICAN (Integrated Composite Analyzer) computer code, 125, 128, 129
IFC. See Alpha-beta interface cracking (IFC)
IGC. See Intergranular cracking (IGC)
Image processing, goal of, 264
Image processing software, 266
Image reconstruction, digital techniques of, 264
Imaging analysis, 264
Impact damage development, characterization of, in graphite/epoxy laminates, 238–57
Impact fracture morphology, 348
Impact fractures, 339, 341, 343–46
Inconel 718, micromechanisms of major/minor cycle fatigue crack growth in, 383–98
Inert-environment sustained load cracking, role of hydrogen in, 401
Interfacial delaminations, association of transverse cracks and, 244, 246, 257
Intergranular cracking (IGC), role of hydrogen in, 401, 407, 413, 417–18
Intergranular facets, 282, 285, 288
Intergranular fracture, 15–16; illus., 16
in chromium steel, 335
in corroded fracture surfaces, 368–69, 372–74, 378
microscopic characteristics of, 155
SEM fractography of, in graphite/epoxy composites, 41–66
Interlayered Cycom 1808 laminate, 251–53
Interlaminar fractures. See also Delamination
microscopic characteristics of, in graphite/epoxy laminates, 154–72
SEM fractographs of pure and mixed mode, in graphite/epoxy composites, 41–66
Interleafing, 239–40, 257; illus., 241
Irradiated composites, fracture surfaces of, 217–36

L
Laminate notched strength, 149
Laminate thickness, effect of, on notched strength, 132
Laminate type A
fractographic results, 138–39
fracture surfaces, 144–47
stacking sequence, table, 133
Laminate type B
fractographic results, 139–41
fracture surfaces, 148
stacking sequence, table, 133
Laminate type C
fractographic results, 141–42
fracture surfaces, 148
stacking sequence, table, 133
Laminate type D
fractographic results, 141–44
fracture surfaces, 148–49
stacking sequence, table, 133
Laminated composites. See also Composite(s)
damage tolerant design requirement for, 131–32
fracture behavior of, 131–52, 153
Laminates, fracture characteristics of angleplied, 101–30
Load deflection response of notched specimens, 179; illus., 182

M
“Mackerel” pattern, 19
Major/minor cycle loading, fatigue crack growth tests under, 383–98
Materials Test Systems (MTS) closed-loop servocontrolled hydraulic test system, 321
Metal(s)
fractographic analysis of hydrogen-assisted cracking in alpha-beta titanium alloys, 400–22
fractographic aspects of environmental effects on fatigue crack propagation in high-strength aluminum alloy, 424–45
fractographic feature identification and characterization by digital imaging analysis, 263–91
fractographic investigation of fatigue damage in carburized steel, 317–32
fractographic studies of the ductile-to-brittle transition in austenitic stainless steel, 350–64
fractography in the failure analysis of corroded fracture surfaces, 366–79
fractography of pressure vessel steel weldments, 295–316
fracture morphology of 13% chromium steam turbine blading steel, 334–48
micromechanisms of major/minor cycle fatigue crack growth in Inconel 718, 383–98
Metal alloys
fast fracture and sustained loading in, 15–16
fatigue mechanisms and transitions in, 20-24

Metal matrix composites
constitutive equations for, 191
development of constitutive theory on, 191-97
documentation of constitutive theory on, 197-200
fabrication techniques for, 191
fractographic study of damage mechanisms in short-fiber, 189-210
observation of damage in, 191
physical behavior of, 191
Microcleavage, 347; illus., 347
Microhardness measurement, 321
Micromechanical failure processes, correlations between, and delamination toughness of graphite/epoxy systems, 68-97
Microvoid coalescence, 15, 33; illus., 16
Microvoid coalescence dimples, 275-76; illus., 277, 278, 279
Mixed mode fracture
fractography of, 54, 60-61, 65
shear and compression, 65
Mixed mode loading, 66
Mode I fracture, 158
fractography of, 44, 47-48
Mode II fracture, 163
fractography of, 48, 51-58
Mode I loading, 65-66, 76-77, 90, 91, 92, 93, 96-97
Mode II loading, 66, 77, 90, 91, 92, 93, 96

Nitrogen, crack growth in, 437, 440
Nonferrous alloys
fractographic analysis of hydro-
gen-assisted cracking in alpha-beta titanium alloys, 400-22
fractographic aspects of environmental effects on fatigue crack propagation in high-strength aluminum alloy, 424-45
micromechanisms of major/minor cycle fatigue crack growth in Inconel 718, 383-98
Nonmetallic inclusion, 327, 332
Notch, influence of, on surface cracking, 363
Notched laminated composites, fractographic investigation of the influence of stacking sequence on strength of, 131-52, 153
Notched strength
definition of, 149
influence of delaminations on, 151
Notch-tip damage zone
description of, 135, 138
influence of, on final fracture, 150
X-ray analysis of, 135, 138, 139, 140, 141, 142

O

Optical microscopy, on stainless steels, 352
Optical reconstruction, 264
Oxide formation, as problem in fracture analysis, 367
Oxide removal process, 367

N

Particulate composites. See also Composites
applications of, 178
fractographic study of damage mechanisms in short-fiber metal matrix, 189–210
fracture surface in, 30–31, 33
microstructural aspects of crack propagation in filled polymers, 177–87
Patch micromorphology, 18, 29
Ply coupling, 150
Ply orientation, effect of, on progressive fracture of laminates, 103–4
PMMA (polymethyl methacrylate) fatigue fracture surface, beam damage zone, 7; illus., 8
Polymer fracture surfaces, fractographic examination of, 7
Polymer(s), microstructural aspects of crack propagation in filled, 177–87
Pressure vessel steel weldments, fractography of, 295–316

Q
Quantitative fractography, 265

R
Radiation, effect of, on plasticity of epoxy materials, 227
Radiation exposure, 218
Ratchet lines, 15; illus., 14
Real-time delamination fracture
Mode I loading, 76–77
Mode II loading, 77
Replication techniques, 21
Residual stress measurement, 321
"River markings"
in filled polymers, 184
in metal alloys, 15, 23; illus., 16

S
Sand particulates, and crack propagation, 177–87
Scanning electron microscopy (SEM), 324
for fractographic examinations, 5–6, 7
of austenitic stainless steels, 352
of corroded fracture surfaces, 366–67
of filled polymers, 181, 187
of graphite/epoxy composites, 41–66
of hydrogen-assisted cracking in alpha-beta titanium alloys, 408
of irradiated composites, 219
of matrix composites, 199
reducing depth of field in, 15
to study weld structure, 298
Semicrystalline polymers
fast fracture surface appearance of, 19–20
fracture surface in, 29–30
Shear behavior, study of, 42
Shear lips, and assessment of crack propagation, 9–12
Shear loading, use of hackles to identify state of, 96–97
Single-surface stereographic analysis, use of, to obtain fractographic information, 352
Slag basicity, effect of, on weld properties, 296
Slip plane decohesion, 346; illus., 347
Solids, fracture surface micro-morphology in engineering, 5–34
Space exploration, use of composite materials in, 217–18
Stacking sequence, fractographic investigation of the influence of, on the strength of
notched laminated composites, 131–52, 153

Steel
fractographic studies
of ductile-to-brittle transition in austenitic stainless, 350–64
of fatigue damage in carburized, 317–32
fracture morphology of 13% chromium steam turbine blading, 334–48
Strain energy release rate, 47, 48, 51
Strength degradation
and fracture stress, 114
in unidirectional laminate, 124–25
Stress corrosion cracking (SCC), role of hydrogen in, 401, 402, 405, 408
Stress intensity factor, 179
Stress relief annealing (SRA) process, 296
Stress-strain curves, 219, 227
“Stress whitening” zone, 48; illus., 50
Striations, in chromium steam turbine blading steel, 334
Submerged arc (SA) welding process, 295–96
Subsurface crack initiation, 332
Superimposed compression, influence of, on pure shear mode, 65
Sustained loading
in engineering plastics, 16–20
in metal alloys, 15–16
Symposium on Fractography of Modern Engineering Materials, objective of, 1

T
Temper embrittlement, 335, 343–44
Thermodynamics, 192

13% chromium steam turbine blading steel, fracture morphology of, 334–48
Three-rail shear test, for studying shear behavior, 42
Titanium alloys, fractographic analysis of hydrogen-assisted cracking in alpha-beta, 400–22
Transmission microscope, for fractographic examinations, 5, 21
Transverse cracks, association of interfacial delaminations and, 244, 246, 257
Tufting, 20, 73

U
Ultraviolet, 218
Unidirectional laminate, strength degradation in, 124–25

V
Vacuum, crack growth in, 432

W
Wedge plot
development of, to display
Fourier transform power spectrum data, 271
showing cleavage planes, 276, 279; illus., 279
showing fatigue striations, illus., 282, 285
showing intergranular facets, 285; illus., 288
showing microvoid coalescence dimples, 276; illus., 279
Welding flux
effect of, on weld properties, 296
Weld metal toughness, role of metallurgical fractures in determining, 296-97
Weld microcleanliness, 315

X
X-ray analysis
  to obtain fractographic information, 352
  to study notch-tip damage zone, 135, 138, 139, 140, 141, 142
X-ray energy dispersive microanalysis, for studying weld structure, 298
X-ray energy dispersive spectrometry (EDS), for studying weld structure, 302, 306, 308, 310

Z
$0^\circ/0^\circ$ interface fracture surface, 158, 160-61, 163-65, 167