# Subject Index

# A

A36 steel comparison of rectangular and square crack-tip opening displacement fracture specimens of, 470-94 experimental procedures, 473–74 experimental results, 474-84 finite-element analysis procedures, 484 finite-element results, 484–90 material properties, 472-73 A508 steel, ductile fracture of, 8 A710 steel. 61 metallurgical aspects of plastic fracture and crack arrests in, 497-536 crack arrest tests, 502, 506 fracture toughness tests, 502, 508-13, 515 materials, 499 mechanical property tests, 499, 502, 506, 507 metallographic and fractographic examination, 506 metallurgical analysis, 508-13 micromechanisms of crack arrest in HY-80 steel, 515-17, 526, 534 tension tests, 499 Acoustic emission techniques, 61 ALIBABA program, 336 Alternating-current potential drop (ACPD) method, 419 Analysis comparison between experimental and analytical results of crack growth initiation studies on surface cracks, 59–81 analytical approach for J-integral for surface-cracked specimens, 62-65, 68-69, 71, 73evaluation process, 73-76, 78 material and test procedures, 61-62 defect, constitutive behavior and continuum toughness considerations for weld integrity analysis, 82-92

computational modeling, 87–89 continuum material toughness, 83–84 material characterization, 85–87 welded T-section geometry, 85

- evaluation of crack growth based on an engineering approach and dimensional analysis, 40-57
  - engineering approach, 43-53, 57-58
  - key curve method, 53-58
  - material and specimen preparation, 41– 52
  - test details, 42-43
- nonlinear work-hardening crack-tip fields by dislocation modeling, 107–19 monotonic loading, 108–13, 115 unloading behavior, 115–16
- numerical comparison of global and local fracture criteria in compact tension and center-crack panel specimens, 24-39
- plasticity near a blunt flaw under remote tension, 93–106 elastic-plastic results, 99, 102–5
  - numerical formulation, 95-99
- validation of ductile fracture local criterion based on simulation of cavity growth, 7-23
  - critical cavity growth ratio, 14-15
  - experimental program, 9-11, 14
  - measuring process zone size, 15, 17
  - numerical procedure, 14-15, 17-18
  - simulation of stable crack growth, 17– 19
- Applications
  - comparison of rectangular and square crack-tip opening displacement fracture specimens of an A36 steel, 470– 94

experimental procedures, 473-74 experimental results, 474-84

- finite-element analysis procedures, 484 finite-element results, 484–90
- material properties, 472-73

- Applications (cont.)
- crack growth instability in piping systems with complex loading, 371-89
  - applications, 384, 386-87
  - fully plastic and perfectly plastic hinge behavior, 382
  - stability analysis, 372-81
  - stability criteria comparison, 382-84
  - system compliance, 381-82
- critical depth of an internal or external flaw in an internally pressurized tube, 390-403
  - critical crack depth, 400
  - elastic material behavior, 392-94
  - elastic-plastic material behavior, 394-96
  - experimental study, 396-97, 399
  - finite-element models, 391-92
- elastic-plastic assessment of cladded pressurized-water- reactor vessel strength, 454–69
  - comparison of, to conventional analysis, 466-67
  - features of thermomechanical stressstrain field, 465-66
  - finite-element analysis of defect behavior, 461-63, 465
  - material behavior, 457-58
  - modeling of cladding operation and initial residual stress state, 458, 460-61 nonlinear analysis, 458
- failure assessment diagram, 261–79 dimensional analysis, 266–73
  - failure assessment via R6 procedure, 263-64
- geometry and material effects, 264-66
- initiation and growth of complex cracks in nuclear piping under pure bending, 433-53
  - elastic-plastic fracture mechanics analysis, 445-47, 449-51
  - eta-factor analysis of complex-cracked pipe, 445-47, 449
  - material property characterization
  - pipe fracture experiments, 436, 438-39, 443, 445
  - predictive J-estimation scheme analyses, 449-51
- methodology for ductile fracture analysis based on damage mechanics, 332–54 application of, to cracked structures, 346–48
  - ductile fracture characterization of structural steels, 336, 339
  - ductile fracture model, 333-36

- prediction of the inclusion content effect on ductile fracture, 341-43
- prediction of the temperature effect on ductile fracture, 343-45
- theoretical derivation of the equations of the ductile fracture model, 349–53 modified *J*-integral, 306–31
  - apparent stored energy in, 313-15
  - calculation of, 315-17
  - general formulas for, 307-9
  - energies, 311-13, 317-18
- physical interpretation of, 309–11
- prediction of critical crack size in plastically strained welded panels, 415–32 comparison of actual and predicted critical defect sizes in budge panels, 425–
  - 28
  - CTOD tests, 419, 421-23
  - flawed Pellini bulge tests, 418-19
  - J-estimation formulas for shallow cracks in full plastic strain fields, 424–25 materials, 416–17
  - materials, 410–17
  - propagation resistance, 428-31 small specimen tests, 417-18
- procedures for handling self-equilibrating secondary stresses in the deformation plasticity failure assessment diagram approach, 280–305
- stable crack growth and fracture instability predictions for type 304 stainless steel pipes with girth weld cracks, 320–31
- tearing instability and arrest, 359-70
- use of ductile tearing instability proceduretemperature limit curves, 404–14 acceptance criteria, 406
  - assessment point evaluation, 409
  - DPFAD curve generation, 407-9
  - elastic-plastic fracture mechanics analytical model, 406–10
  - instability pressure prediction, 410
  - J-integral formulation, 406–7
  - technical approach, 405-6
  - thermal stress, 410–12
- Applied stress/net section plastic collapse stress ratio, 280, 287, 289, 300, 302-3
- ASTM eta-factor method, for calculating *J*-*R* curves, 53, 58, 171, 172, 174, 176, 182, 183
- ASTM  $J_{Ic}$  standard, 177
- ASTM Test E 8-82: 499
- ASTM Test E 399: 474, 477
- ASTM Test E 399-81: 471
- ASTM Test E 399–83: 60, 126, 145, 192, 416, 539, 597–99, 611

ASTM Test E 813-81: 2, 9, 10, 30, 60, 61, 126, 144, 147-48, 154, 170, 171, 192, 221, 246, 257, 416, 436, 471, 502, 540, 546, 553, 600 ASTM Test E 1152-87: 2, 362

# B

Bauschinger effect, 116, 118

Bending

- initiation and growth of complex cracks in nuclear piping under pure, 433–53 elastic-plastic fracture mechanics analysis, 445–47, 449–51
  - eta-factor analysis of complex-cracked pipe, 445-47, 449
  - material property characterization
  - pipe fracture experiments, 436, 438-39, 443, 445
  - predictive J-estimation scheme analyses, 449-51
- Blue brittleness, 343
- Blunt flaw
  - plasticity near, under remote tension, 93-106
    - elastic-plastic results, 99, 102-5
  - numerical formulation, 95–99
- British Standard 5447: 471, 474, 477
- British Standard 5762: 193
- Bulge panels, comparison of actual and predicted critical defect sizes in, 425-28

# С

Cavity growth validation of ductile fracture local criterion based on simulation of, 7–23 critical cavity growth ratio, 14–15 experimental program, 9–11, 14 measuring process zone size, 15, 17 numerical procedure, 14–15, 17–18 simulation of stable crack growth, 17– 19

Cavity growth ratio, 8, 14-15

Center-crack panel specimens

numerical comparison of global and local fracture criteria in, 24–39

comparison of J and CTOD, 32-33

- computation of fracture parameters, 30-31
- J and local criterion for cleavage fracture, 33-35
- J and local criterion for ductile fracture, 35–38

local cleavage criterion, 26–27 local ductile criterion, 27-28 numerical simulation, 29-32 theoretical relationships between  $J_{Ic}$  and local criteria under small-scale yielding conditions, 28-29 Cladded pressurized-water-reactor vessel strength elastic-plastic assessment of, 454-69 comparison of, to conventional analysis, 466 - 67features of thermomechanical stressstrain field, 465-66 finite-element analysis of defect behavior, 461-63, 465 material behavior, 457-58 modeling of cladding operation and initial residual stress state, 458, 460–61 nonlinear analysis, 458 Cleavage fracture, J and local criterion for, 33–35 Committee on Safety in Nuclear Installations (CSNI), 321 Compact tension panel specimens numerical comparison of global and local fracture criteria in, 24-39 comparison of J and CTOD, 32-33 computation of fracture parameters, 30 - 31J and local criterion for cleavage fracture, 33-35 J and local criterion for ductile fracture, 35–38 local cleavage criterion, 26-27 local ductile criterion, 27–28 numerical simulation, 29-32 theoretical relationships between  $J_{Ic}$  and local criteria under small-scale yielding conditions, 28-29 Complex-cracked pipe, eta-factor analysis of, 445-47, 449 Computational modeling, 87–89 Computed crack-tip opening angle (CTOA), 234Constitutive relations, 349 Continuum damage mechanics, 333 Continuum material toughness, 83–84 Continuum thermodynamics, 349–50 Continuum toughness, for weld integrity analysis, 82-92 Crack(s) assessment of, growing in welds, 215-17 initiation and growth of complex, in nu-

clear piping under pure bending, 433– 53 Crack(s), initiation and growth of complex, in nuclear piping under pure bending (cont.) elastic-plastic fracture mechanics analvsis, 445-47, 449-51 eta-factor analysis of complex-cracked pipe, 445–47, 449 material property characterization pipe fracture experiments, 436, 438–39, 443, 445 predictive J-estimation scheme analyses, 449–51 Crack arrest metallurgical aspects of, in high-strength steel, 497-586 crack arrest tests, 502, 506 fracture toughness tests, 502, 508-13, 515 materials, 499 mechanical property tests, 499, 502, 506.507 metallurgical analysis, 508-13 metallographic and fractographic examination, 506 micromechanisms of crack arrest in HY-80 steel, 515-17, 526, 534 tension tests, 499 micromechanisms of, in HY-80 steel, 515-17, 526, 534 Crack arrest tests, 502, 506 Crack branching, 249 Crack deflection, 249 Crack growth evaluation based on engineering approach and dimensional analysis, 40-57 engineering approach, 43–53, 57–58 key curve method, 53-58 material and specimen preparation, 41-52 test details, 42-43 Crack growth initiation studies comparison between experimental and analytical results of, on surface cracks, 59 - 81analytical approach for J-integral for surface-cracked specimens, 62–65, 68-69, 71, 73 evaluation process, 73-76, 78 material and test procedures, 61-62 Crack growth instability in piping systems with complex loading, 371-89 applications, 384, 386-87 fully plastic and perfectly plastic hinge behavior, 382

stability analysis, 372-81 stability criteria comparison, 382-84 system compliance, 381-82 Crack growth resistance curves, 11 effect of fracture micromechanisms on, in irradiated zirconium, 537-62 experimental procedure, 539-51 fracture surface, 542, 546, 555, 559 fracture toughness tests, 539–40 J-resistance curves, 541–42, 546, 553 metallography, 541, 542 microtwins, 554-55 Crack layer theory, 590–91 Crack-opening angle calculations, 184, 186 Crack-opening displacement testing, 471 Crack size prediction of critical, in plastically strained welded panels, 415-32 comparison of actual and predicted critical defect sizes in budge panels, 425-28 crack-tip opening displacement (CTOD) tests, 419, 421–23 flawed Pellini bulge tests, 418-19 J-estimation formulas for shallow cracks in full plastic strain fields, 424–25 materials, 416–17 propagation resistance, 428-31 small specimen tests, 417–18 Crack-tip opening displacement (CTOD) comparison of, and J, 32-33 comparison of rectangular and square, in A36 steel, 470–94 experimental procedures, 473-74 experimental results, 474-84 finite-element analysis procedures, 484 finite-element results, 484-90 material properties, 472-73 estimation of, 31 measurement of, 10 Crack-tip opening displacement (CTOD) test, 416, 419, 421-23, 471, 498 applicability of, 450 Critical cavity growth ratio estimation of, 19–20 measuring, 14-15 Critical depth of internal or external flaw in internally pressurized tube, 390-403 critical crack depth, 400 elastic material behavior, 392-94 elastic-plastic material behavior, 394-96 experimental study, 396-97, 399 finite-element models, 391–92

Critical void growth criteria, 29

CTOD (See Crack-tip opening displacement)

Cyclic J-integral, 115–16

### D

Damage mechanics methodology for ductile fracture analysis, 332 - 54application of, to cracked structures, 346 - 48ductile fracture characterization of structural steels, 336, 339 ductile fracture model, 333-36 prediction of the inclusion content effect on ductile fracture, 341-43 prediction of the temperature effect on ductile fracture, 343-45 theoretical derivation of the equations of the ductile fracture model, 349-53 David Taylor Naval Ship Research and Development Center (DTNSRDC), 321 computational results for analysis of pipe experiment at, 325, 327-28 Deformation J, determination of, 140-41Deformation plasticity analysis of, 320 *J*-integral structural response for, 282–83 Deformation plasticity failure assessment diagram (DPFAD) analysis procedure, 405-6 curve generation, 407-9 handling self-equilibrating secondary stresses in, 280-305 Deformation theory J, 308-9Dimensional analysis evaluation of crack growth based on, 40-57 engineering approach, 43-53, 57-58 key curve method, 53-58material and specimen preparation, 41-52 test details, 42-43 Direct-current potential drop (PD) method, 539 Dislocation modeling nonlinear work-hardening crack-tip fields by, 107–19 monotonic loading, 108-13, 115 unloading behavior, 115–16 Ductile-brittle transition region combined statistical and constraint model for. 563-83 active volume, 568-70

crack-tip stress field, 565-68 fracture stress tests, 572 fracture toughness tests, 572-73 lower-bound toughness, 579–81 predicting fracture toughness distributions, 571-79 predicting transition curves, 573-76 scatter in toughness data, 576–81 test material, 571 toughness predictions, 570-71 Ductile fracture analysis, 332-54 application of, to cracked structures, 346-48 ductile fracture characterization of structural steels, 336, 339 ductile fracture model, 333-36 prediction of the inclusion content effect on ductile fracture, 341-43 prediction of the temperature effect on ductile fracture, 343-45 theoretical derivation of the equations of the ductile fracture model, 349-53 characterization of, in structural steels, 336, 339 J and local criterion for, 35-38 prediction of inclusion content effect on, 341-43 prediction of in low-alloyed steels, 7-8 prediction of temperature effect on, 343-45 Ductile fracture local criterion experimental and numerical validation of, 7–23 critical cavity growth ratio, 14-15 experimental program, 9-11, 14 measuring process zone size, 15, 17 numerical procedure, 14–15, 17–18 simulation of stable crack growth, 17– 19 Ductile fracture model parameters calibration, 333–36 theoretical derivation of equations of, 349-53 Ductile tearing analysis, acceptance criteria for, 406 Ductile tearing instability procedure in establishing pressure-temperature limit curves, 404–14 acceptance criteria, 406 assessment point evaluation, 409 DPFAD curve generation, 407–9 elastic-plastic fracture mechanics analytical model, 406-10 instability pressure prediction, 410

Ductile tearing instability procedure, in establishing pressure-temperature limit curves (cont.) J-integral formulation, 406–7 technical approach, 405-6 thermal stress, 410–12 Dugdale plastic zone model, 266, 274 Dynamic tear test, 417

#### Е

Elastic-plastic assessment

- of cladded pressurized-water-reactor vessel strength, 454–69 comparison of, to conventional analysis,
  - 466 67
  - features of thermomechanical stressstrain field, 465–66
  - finite-element analysis of defect behavior, 461–63, 465
  - material behavior, 457–58
  - modeling of cladding operation and initial residual stress state, 458, 460–61 nonlinear analysis, 458
- Elastic-plastic fracture
  - separation of energies in, 594-612 plastic energy dissipation rate, 607, 610-11
  - specimen size dependence, 604, 607
- Elastic-plastic fracture mechanics (EPFM) analysis of, 406-10, 445-47, 449-51 development of, 1
  - estimation scheme for, 401
  - evaluation of stainless steel tungsten/inert-gas welds, 214-43
    - assessment of cracks growing in welds, 215 - 17
    - finite-element analysis, 228-30, 232, 234 - 37
    - J estimation analysis of welded pipe, 236-37
    - J-resistance curves, 220-25, 228
    - materials and experiments, 220-25, 228
    - nonproportional loading and definition of general crack-tip parameters, 217-18
    - 3T compact specimen results, 230, 232, 234
    - tensile properties, 220
    - three-dimensional considerations, 218-19
    - through-wall crack in the TIG weld of a pipe, 235-36
    - TIG-welded compact specimens, 228-30

test standardization for, 2

- Elastic-plastic fracture toughness (EPFT) parameters
  - evaluating steel toughness using, 144-68 comparison of elastic-plastic fracture toughness parameters, 154, 167
    - comparison of J calculation methods. 148, 154
    - experimental procedures, 145, 147-48 fracture toughness parameters, 154, 167 influence upon metallurgical comparisons, 167-68
- Energies, 311–13
  - related to fracture process, 317-18
  - separation of, in elastic-plastic fracture, 594-612
    - plastic energy dissipation rate, 607, 610-11
  - specimen size dependence, 604, 607
- Energy density, 83
  - maximum value of, 84
- Energy density ratio, 84
- Energy rate method, to calibrate modified J, 131
- Energy-related quantities (ERQ), determination of, 317-18
- Engineering approach, evaluation of crack growth based on, 43-58
- EPRI Handbook, estimate of eta, 132–33
- Estimation methods, 320
- Eta-factor analysis, of complex-cracked pipe, 445-47, 449
- Experimental results
  - comparison between analytical studies of crack growth initiation studies on surface cracks, 59-81
    - analytical approach for *J*-integral for surface-cracked specimens, 62-65, 68-69, 71, 73
    - evaluation process, 73-76, 78
    - material and test procedures, 61-62
- Experimental validation
  - of ductile fracture local criterion based on simulation of cavity growth, 7-23 critical cavity growth ratio, 14–15 experimental program, 9-11, 14 measuring process zone size, 15, 17 numerical procedure, 14-15, 17-18 simulation of stable crack growth, 17-19
- External flaw
- critical depth of, in internally pressurized tube, 390-403 critical crack depth, 400

  - elastic material behavior, 392-94

elastic-plastic material behavior, 394– 96 experimental study, 396–97, 399 finite-element models, 391–92

# F

Failure assessment diagram, 261-79 dimensional analysis, 266–73 failure assessment via R6 procedure, 263-64 geometry and material effects, 264-66 Fatique precracking, 204–6 Fe-3Si steel kinetics of fracture in, under mode of loading, 584-93 crack layer theory, 590–91 damage distribution, 586 experimental procedures, 584, 586 kinetics of fracture, 586-88, 590 results on crack layer propagation, 586-88, 590 stability analysis, 591–92 Finite-element analyses, 177-78 computational results, 178-79 crack-opening angle calculations, 184, 186 J-resistance curves from finite-element method (FEM) analysis, 179, 181-84 3T compact specimen results, 230, 232, 234 TIG-welded compact specimens, 228-30 First International Elastic-Plastic Fracture Symposium, 1 Fracture kinetics of, in FE-3Si steel under Mode I loading, 584–93 crack layer theory, 590-91 damage distribution, 586 experimental procedures, 584, 586 kinetics of fracture, 586–88, 590 results on crack layer propagation, 586-88, 590 stability analysis, 591-92 local approach of, 332–54 application of, to cracked structures, 346–48 ductile fracture characterization of structural steels, 336, 339 ductile fracture model, 333-36 prediction of the inclusion content effect on ductile fracture, 341-43 prediction of the temperature effect on ductile fracture, 343-45 theoretical derivation of the equations of the ductile fracture model, 349-53

separation of energies in elastic-plastic, 594-612 plastic energy dissipation rate, 607, 610-11 specimen size dependence, 604, 607 Fracture criterion, independent parameters of, 14 Fracture instability predictions, for Type 304 stainless steel pipes with girth weld cracks, 320-31 Fracture mechanics analysis of piping systems in nuclear power plants, 371-89 applications, 384, 386-87 fully plastic and perfectly plastic hinge behavior, 382 stability analysis, 372–81 stability criteria comparison, 382-84 system compliance, 381-82 on welded joints, 191-213 analysis of specimens after testing, 209– 11 CTOD specimen geometry and notch location, 193-96 fatigue precracking, 204-6 HAZ testing, 196-201 machining, 203-4 relevant welded joints, 192-93 reporting of test results, 211 straightening before notching, 204 test procedures, 206-9 weld metal testing, 201-3 Fracture micromechanisms on crack growth resistance curves of irradiated zirconium, 537-62 experimental procedure, 539-51 fracture surface, 542, 546, 555, 559 fracture toughness tests, 539-40 *J*-resistance curves, 541–42, 546, 553 metallography, 541, 542 microtwins, 554–55 Fracture parameters, computation of, 30-31 Fracture process, energies related to, 317-18 Fracture toughness effect of prestrain on the J-resistance curve of HY-100 steel, 244-58 elastic-plastic fracture mechanics evaluations of stainless steel tungsten/inertgas welds, 214-43 assessment of cracks growing in welds, 215 - 17finite-element analysis, 228-30, 232, 234 - 37

Fracture toughness, elastic-plastic fracture mechanics evaluations of stainless steel tungsten/inert-gas welds (cont.) J estimation analysis of welded pipe, 236 - 37J-resistance curves, 220–25, 228 materials and experiments, 220-25, 228 nonproportional loading and definition of general crack-tip parameters, 217-18 3T compact specimen results, 230, 232, 234 tensile properties, 220 three-dimensional considerations, 218-19 through-wall crack in the TIG weld of a pipe, 235-36 TIG-welded compact specimens, 228-30 evaluating steel toughness using various elastic-plastic parameters, 144-68 comparison of elastic-plastic fracture toughness parameters, 154, 167 comparison of J calculation methods, 148, 154 experimental procedures, 145, 147-48 fracture toughness parameters, 154, 167 influence upon metallurgical comparisons, 167-68 evaluation of attempts to predict large crack growth J-R curves from smallspecimen tests, 169-90 computational results, 178–79 crack-opening angle calculations, 184, 186 experimental procedures, 170–71 finite-element analysis, 177-84, 186 J-resistance curves by the ASTM etafactor method, 172, 174, 176 J-resistance curves by the finite-element method analysis, 179, 181-84 fracture mechanics tests on welded joints, 191-213 analysis of specimens after testing, 209– 11 CTOD specimen geometry and notch location, 193–96 fatigue precracking, 204–6 HAZ testing, 196-201 machining, 203-4 relevant welded joints, 192-93 reporting of test results, 211 straightening before notching, 204 test procedures, 206-9 weld metal testing, 201-3

geometry effects on the *R*-curve, 123–43 background, 126–27 calibration of modified *J*, 131–32 EPRI handbook of eta factor, 132–33 materials and specimens, 127–29 normalization schemes, 134, 137, 139– 41 *R*-curve test results, 133–34 testing practice, 129–31 Fracture toughness tests, 502, 508–13

## G

- GE/EPRI procedure, 449, 450
- Generalized energy release rate, 317
- Geometry effect, 124
  - on the *R*-curve, 123–43 background, 126–27 calibration of modified *J*, 131–32 EPRI handbook of eta factor, 132–33 materials and specimens, 127–29 normalization schemes, 134, 137, 139– 41 *R*-curve test results, 133–34

testing practice, 129–31

- Girth weld cracks, stable crack growth, and fracture instability predictions for Type 304 stainless steel pipes, 320-31
- Global fracture criteria
  - in compact tension and center-crack panel specimens, 24-39
    - comparison of J and CTOD, 32–33
    - computation of fracture parameters, 30-31
    - J and local criterion for cleavage fracture, 33-35
    - J and local criterion for ductile fracture, 35–38
    - local cleavage criterion, 26–27

local ductile criterion, 27–28

- numerical simulation, 29-32
- theoretical relationships between  $J_{\rm Ic}$  and local criteria under small-scale yielding conditions, 28–29

#### H

Heat-affected zones

general assessments of, 197–99

specific assessments of cracks, 199–201 testing, 196–206

- Hencky equations, 94
- Hole growth, quantitative measurements of,
  - 8

- Huber-von Mises-Henky initial yield criterion, 228
- Hutchinson-Rice-Rosengren (HRR) stress singularity, 565-66
- Hutchinson-Rice-Rosengren (HRR) type asymptotic stress field, 218

HY-80 steel

- metallurgical aspects of plastic fracture and crack arrests in 497–536 crack arrest tests, 502, 506 fracture toughness tests, 502, 508–13,
  - 515 materials 400
  - materials, 499
  - mechanical property tests, 499, 502, 506, 507
  - metallographic and fractographic examination, 506
  - metallurgical analysis, 508-13
  - micromechanisms of crack arrest in HY-80 steel, 515-17, 526, 534
  - tension tests, 499
- HY-100 steel, effect of prestrain on J-resistance curve of, 244-58

# I

Inclusion content effect, prediction of, on ductile fracture, 341-43 Instability analysis approach, 330 Instability pressure prediction, 410 Internal flaw critical depth of, in internally pressurized tube, 390-403 critical crack depth, 400 elastic material behavior, 392-94 elastic-plastic material behavior, 394-96 experimental study, 396-97, 399 finite-element models, 391-92 Internally pressurized tube critical depth of internal or external flaw in, 390-403 critical crack depth, 400 elastic material behavior, 392-94 elastic-plastic material behavior, 394-96 experimental study, 396-97, 399 finite-element models, 391–92 Irwin model, 265, 266

# J

calculation of comparisons of, 148, 154 influence of, 148, 154

J

for cleavage fracture, 33–35 comparison of, and crack tip opening displacement, 32-33 for ductile fracture, 35–38 engineering usage of, as a fracture analysis parameteer, 416  $J_{\rm p}$ -resistance curves, 225, 228  $J_{\rm Ic}$ loss of constraint and variability of, 75-76 theoretical relationships between, and local criteria under small-scale yielding conditions, 28-29J-controlled crack growth regime, proof of, 306 J-estimation analysis, 215, 449-51 for shallow cracks in full plastic strain fields, 424-25 for welded pipe, 236-37 J-integral, 1, 9, 20, 244, 396-97 advantage of characterization, 107-19 monotonic loading, 108-13, 115 unloading behavior, 115-16 as the crack-driving force parameter, 396 definition of, 115 formulation of, 406-7 modified (See Modified J-integral) for surface-cracked specimens, analytical approach for, 62–65, 68–69, 71, 73 value determinations in, 102 Johnson expression, 171 J-resistance curves, 220-25, 228, 330 ASTM test for determining, 2, 172, 174, 176 determination of, 397 effect of prestrain on, in HY-100 steel, 244 - 58evaluation of independence in, 123 from finite-element method analysis, 179, 181 - 84from small-specimen tests, 169-90 computational results, 178-79 crack-opening angle calculations, 184, 186 experimental procedures, 170-71 finite-element analysis, 177-84, 186 J-resistance curves by the ASTM etafactor method, 172, 174, 176 J-resistance curves by the finite-element method analysis, 179, 181-84

## K

 $K_{IR}$  curve, 405

Key curve (KC) analysis, 316–17, 359, 366 for crack extension estimates, 57–58, 141 Key curve (KC) analysis (cont.) of crack growth, 53–58 validation of, 362

## L

- Lagrangian procedure, 14, 29
- LBB.BCL1 method, 237, 242
- LBB.BCL2 method, 237, 242, 449, 450
- Leak-before-break method (LBB.NRC), 237, 241, 390, 449, 450, 537
  - for analyses of piping systems in nuclear power plants, 371-89
    - applications, 384, 386-87
    - fully plastic and perfectly plastic hinge behavior, 382
    - stability analysis, 372-81
    - stability criteria comparison, 382–84 system compliance, 381–82
- Levy-Mises equations of plasticity, 29
- Linear elastic fracture mechanics (LEFM), 1
- Linear elastic fracture mechanics (LEFM) analysis procedure, 405
- Linear elastic fracture mechanics (LEFM) ordinate, 280
- Local approach
  - of fracture, 332-54
    - application of, to cracked structures, 346-48
    - ductile fracture characterization of structural steels, 336, 339
    - ductile fracture model, 333-36
    - prediction of the inclusion content effect on ductile fracture, 341-43
    - prediction of the temperature effect on ductile fracture, 343-45
    - theoretical derivation of the equations of the ductile fracture model, 349-53
- Local cleavage criterion, 26-27

Local criterion

- for cleavage fracture, 33-35
- for ductile fracture, 35–38
- theoretical relationships between  $J_{ic}$  and, under small-scale yielding conditions, 28-29
- Local ductile criterion, 27-28
- Local fracture criteria
  - in compact tension and center-crack panel specimens, 24-39
    - comparison of J and CTOD, 32-33
    - computation of fracture parameters, 30-31
    - J and local criterion for cleavage fracture, 33-35

J and local criterion for ductile fracture, 35-38local cleavage criterion, 26–27 local ductile criterion, 27–28 numerical simulation, 29–32 theoretical relationships between  $J_{tc}$  and local criteria under small-scale yielding conditions, 28–29 Loss of constraint theory, 471, 490

#### Μ

Material toughness, 83 M correction term, adequacy of, 75 Mechanical property tests, results of, 506, 508 Merkle-Corten analysis, 127 Metallurgical aspects of plastic fracture and crack arrest in two high-strength steels, 497-536 crack arrest tests, 502, 506 fracture toughness tests, 502, 508-13, 515 materials, 499 mechanical property tests, 499, 502, 506, 507 metallographic and fractographic examination, 506 metallurgical analysis, 508-13 micromechanisms of crack arrest in HY-80 steel, 515-17, 526, 534 tension tests, 499 Mode I loading kinetics of fracture in Fe–3Si steel under, 584 - 93crack layer theory, 590-91 damage distribution, 586 experimental procedures, 584, 586 kinetics of fracture, 586-88, 590 results of crack layer propagation, 586-88, 590 stability analysis, 591–92 Models and mechanisms combined statistical and constraint model for the ductile-brittle transition region, 563-83 active volume, 568-70 crack-tip stress field, 565-68 fracture stress tests, 572 fracture toughness tests, 572–73 lower-bound toughness, 579-81 predicting fracture toughness distributions, 571-79 predicting transition curves, 573-76 scatter in toughness data, 576-81

test material, 571

- toughness predictions, 570–71
- effect of fracture micromechanisms on crack growth resistance curves of zirconium-niobium alloy, 537–62 experimental procedure, 539–51
  - fracture surface, 542, 546, 555, 559
  - fracture toughness tests, 539–40
  - J-resistance curves, 541–42, 546, 553
- metallography, 541, 542
- microtwins, 554-55
- kinetics of fracture in Fe–3Si steel under Mode I loading, 584–93 crack layer theory, 590–91 damage distribution, 586
  - experimental procedures, 584, 586
  - kinetics of fracture, 586-88, 590
  - results on crack layer propagation, 586– 88, 590
  - stability analysis, 591-92
- metallurgical aspects of plastic fracture and crack arrest in two high-strength steels, 497–536
  - crack arrest tests, 502, 506
  - fracture toughness tests, 502, 508–13, 515
  - materials, 499
  - mechanical property tests, 499, 502, 506, 507
  - metallographic and fractographic examination, 506
  - metallurgical analysis, 508-13
  - micromechanisms of crack arrest in HY-80 steel, 515-17, 526, 534 tension tests, 499
- separation of energies in elastic-plastic fracture, 594-612
  - plastic energy dissipation rate, 607, 610– 11
- specimen size dependence, 604, 607 Modified J, 124, 127
- calibration of, 131–32
- Modified J-integral, 306–31 apparent stored energy in, 313–15 calculation of, 315–17 general formulas for, 307–9
- energies, 311-13, 317-18
- Monotonic loading, 108-10, 113, 115-16
- Multipass welds, general assessments of, 201-2

## Ν

Newton-Raphson iteration approach, 227 Node release technique, 20

for stimulating stable crack growth, 17, 19 Nonlinear work-hardening crack-tip fields by dislocation modeling, 107-19 monotonic loading, 108–13, 115 unloading behavior, 115-16 Nonproportional loading, 217–18 Nuclear plant critical depth of internal or external flow in internally pressurized tube, 390-403 critical crack depth, 400 elastic material behavior, 392-94 elastic-plastic material behavior, 394-96 experimental study, 396-97, 399 finite-element models, 391–92 effect of fracture micromechanisms on crack growth resistance curves of irradiated zirconium in, 537–62 experimental procedure, 539-51 fracture surface, 542, 546, 555, 559 fracture toughness tests, 539–40 J-resistance curves, 541-42, 546, 553 metallography, 541, 542 microtwins, 554-55 fracture mechanics analyses of piping systems in, 371-89 applications, 384, 386–87 fully plastic and perfectly plastic hinge behavior, 382 stability analysis, 372–81 stability criteria comparison, 382-84 system compliance, 381-82 initiation and growth of complex cracks in piping in, under pure bending, 433– 53 elastic-plastic fracture mechanics analysis, 445–47, 449–51 eta-factor analysis of complex-cracked pipe, 445–47, 449 material property characterization pipe fracture experiments, 436, 438–39, 443, 445 predictive J-estimation scheme analyses, 449-51 use of ductile tearing instability procedure in establishing pressure-temperature limit curves, 404–14 acceptance criteria, 406 assessment point evaluation, 409 DPFAD curve generation, 407–9 elastic-plastic fracture mechanics analytical model, 406-10 instability pressure prediction, 410 J-integral formulation, 406–7

Nuclear plant, use of ductile tearing instability procedure in establishing pressure-temperature limit curves (cont.) technical approach, 405-6 thermal stress, 410–12 Nuclear power industry, 1 Numerical comparison of global and local fracture criteria in compact tension and center-crack panel specimens, 24-39 comparison of J and CTOD, 32-33 computation of fracture parameters, 30 - 31J and local criterion for cleavage fracture, 33-35 J and local criterion for ductile fracture, 35-38 local cleavage criterion, 26–27 local ductile criterion, 27–28 numerical simulation, 29-32 theoretical relationships between  $J_{Ic}$  and local criteria under small-scale yielding conditions, 28-29 Numerical validation of ductile fracture local criterion based on simulation of cavity growth, 7-23 critical cavity growth ratio, 14-15 experimental program, 9-11, 14 measuring process zone size, 15, 17 numerical procedure, 14-15, 17-18 simulation of stable crack growth, 17-19 NUREG 1061 approach, 187-88 NUREG model, 265-66

### P

Paris method, 241, 449 Pellini bulge explosion test method, 416, 418 - 19Piping systems crack growth instability in, with complex loading, 371-89 applications, 384, 386–87 fully plastic and perfectly plastic hinge behavior, 382 stability analysis, 372-81 stability criteria comparison, 382-84 system compliance, 381-82 Plastic energy dissipation rate, 607, 610–11 Plastic fracture metallurgical aspects of, in high-strength steel, 497-536 crack arrest tests, 502, 506

fracture toughness tests, 502, 508-13, 515 materials, 499 mechanical property tests, 499, 502, 506, 507 metallographic and fractographic examination, 506 metallurgical analysis, 508-13 micromechanisms of crack arrest in HY-80 steel, 515-17, 526, 534 tension tests, 499 Plastic instability, 76, 78 Plasticity, 308-9, 394 near blunt flow under remote tension, 93-106 elastic-plastic results, 99, 102-5 numerical formulation, 95–99 Plastic strain fields, J estimation formulas for shallow cracks in full, 424-25 POLO-FINITE structural mechanics system, 484 Pop-in, 207-9 Portevin–Le Chatelier effect, 343 Power generation industry, 1 Prandtl-Ruess equations, 98 Pressure-temperature limit curves use of ductile tearing instability procedure in establishing, 404–14 acceptance criteria, 406 assessment point evaluation, 409 DPFAD curve generation, 407–9 elastic-plastic fracture mechanics analytical model, 406–10 instability pressure prediction, 410 J-integral formulation, 406-7 technical approach, 405-6 thermal stress, 410-12 Prestrain, effect of, on J-resistance curve of HY-100 steel, 244-58 Process zone, 491 measuring size of, 15, 17 Propagation resistance, 428–31

# Q

Quantitative metallography, 8

# R

R6 procedure, failure assessment via, 263-64

Ramberg-Osgood approximation to the material flow behavior, 566 power law, 381

power-law hardening stress/strain relationship, 380 power-law stress/strain behavior, 383 relationship, 64 stress-strain constants, 406 stress-strain exponent, 285 stress-strain law, 43 stress-strain relationship, 275 work-hardening constants, 264 R-curve geometry effects on, 123-43 background, 126-27 calibration of modified J, 131-32EPRI handbook of eta factor, 132-33 materials and specimens, 127-29 normalization schemes, 134, 137, 139-41 R-curve test results, 133-34 testing practice, 129-31 R-curve method, 400-2 R-curve test results, 133-34 normalization schemes, 134, 137, 139-41 Remote tension plasticity near a blunt flaw under, 93-106 elastic-plastic results, 99, 102-5 numerical formulation, 95–99 Rice intercept method, 485 Rik's algorithm, 88

S

- Self-equilibrating secondary stresses, handling, in deformation plasticity failure assessment diagram approach, 280– 305
- Sharp crack blunting, mechanics of, 93
- Single-pass welds, general assessments of, 202

Slip-line theory, 94

- Small-specimen tests
  - prediction of large-crack growth J-R curves, 169–90
    - by ASTM eta-factor method, 172, 174, 176
    - computational results, 178-79
    - crack-opening angle calculations, 184, 186
    - experimental procedures, 170-71
- by finite-element analysis, 177-84, 186
- Stable crack growth simulation of, 17–19
  - for Type 304 stainless steel pipes with girth weld cracks, 320-31

Stainless steel pipes, stable crack growth and fracture instability predictions for Type 304, 320-31 Stainless steel tungsten/inert-gas welds elastic-plastic fracture mechanics evaluations, 214-43 assessment of cracks growing in welds, 215 - 17finite-element analysis, 228-30, 232, 234 - 37J estimation analysis of welded pipe, 236 - 37J-resistance curves, 220–25, 228 materials and experiments, 220-25, 228 nonproportional loading and definition of general crack-tip parameters, 217-18 3T compact specimen results, 230, 232, 234 tensile properties, 220 three-dimensional considerations, 218-19 through-wall crack in the TIG weld of a pipe, 235-36 TIG-welded compact specimens, 228-30 Steel (See also A36 steel; A508 steel; A710 steel; FE-3Si steel; HY-80 steel; HY-100 steel) evaluating toughness in, with elastic-plastic fracture toughness (EPFT) parameters, 144-68 comparison of elastic-plastic fracture toughness parameters, 154, 167 comparison of J calculation methods, 148, 154 experimental procedures, 145, 147-48 fracture toughness parameters, 154, 167 influence upon metallurgical comparisons, 167-68 metallurgical aspects of plastic fracture and crack-arrest in high-strength, 497-536 crack arrest tests, 502, 506 fracture toughness tests, 502, 508–13, 515 materials, 499 mechanical property tests, 499, 502, 506, 507 metallographic and fractographic examination, 506 metallurgical analysis, 508-13 tension tests, 499 Stress-intensity factor/fracture toughness ratio, 280, 285-87, 303-4

## Surface cracks

- comparison between experimental and analytical results of crack growth initiation studies on, 59-81
  - analytical approach for J-integral for surface-cracked specimens, 62-65, 68-69, 71, 73
  - evaluation process, 73-76, 78
  - material and test procedures, 61-62
- Surface-cracked specimens, analytical approach for J-integral, 62–65, 68–69, 71, 73

#### T

- Tearing instability and arrest, 359-70
- Tearing modulus, 371, 372
- Temperature effect, prediction of, on ductile fracture, 343-45
- Tension tests, 506, 508
- Thermal loading, 298-99
- Thermal stress, 410
- Thermomechanical stress-strain field, features of, 465-66
- Third International Symposium on Nonlinear Fracture Mechanics, 1
- 3T compact specimen results, 230, 232, 234
- Through-wall crack, in TIG weld of pipe, 235-36
- TIG-welded compact specimens, 228-30
- TIG weld of pipe, through-wall crack in, 235-36
- TITUS code, 29
- TITUS program, 336
- Two-pass welds, general assessements of, 202

#### U

United States Nuclear Regulatory Commission (NRC), 321, 371

#### V

Virtual crack extension technique, 392 von Mises, stress distribution, 489

#### W

Weakest link statistics, in predicting the fracture toughness of ferritic steels in ductile-brittle transition region, 563-83
Weakest link theory, 471-472
Weibull distributions, 480, 484
Weibull model, 480
Weibull statistical distribution, 28

Weibull's theory, 26 Weibull stress, 26-27, 29, 34 Weld(s), assessment of cracks growing in, 215 - 17Welded joints fracture mechanics tests on, 191-213 analysis of specimens after testing, 209-11 CTOD specimen geometry and notch location, 193-96 fatigue precracking, 204-6 HAZ testing, 196-201 machining, 203-4 relevant welded joints, 192-93 reporting of test results, 211 straightening before notching, 204 test procedures, 206-9 weld metal testing, 201-3 Welded panels prediction of critical crack size in plastically strained, 415-32 comparison of actual and predicted critical defect sizes in budge panels, 425-28 CTOD tests. 419, 421-23 flawed Pellini bulge tests, 418-19 J-estimation formulas for shallow cracks in full plastic strain fields, 424–25 materials, 416-17 propagation resistance, 428-31 small specimen tests, 417-18 Welded pipe, J-estimation analysis of, 236-37 Welded T-section geometry, 85 Weld integrity analysis defect, constitutive behavior, and continuum toughness considerations for, 82 - 92computational modeling, 87-89 continuum material toughness, 83-84 material characterization, 85-87 welded T-section geometry, 85 Weld metal testing general assessments of multipass welds, 201 - 2general assessments of single-pass welds, 202 general assessments of two-pass welds, 202 specific assessments of cracks in weld metals, 203-4 Y

Yielding conditions, theoretical relationships between  $J_{Ic}$  and local criteria under small-scale, 28–29 Z

Zirconium

effect of fracture micromechanisms on crack growth resistance curve in irradiated, 537-62 experimental procedure, 539–51 fracture surface, 542, 546, 555, 559 fracture toughness tests, 539–40 *J*-resistance curves, 541–42, 546, 553 metallography, 541, 542 microtwins, 554–55