Subject Index

A

ABBOR computerized test system, 222, 224, 226
Aging, 344
in forging industry, 575–576
isothermal, 134
optimum temperature, 361
Alloys (See also Steels)
high-temperature, 453–454
optimizing mechanical properties, 346–364
processing improvements, 19–25
Alpha-gamma transformations, 419, 421 (illus), 424
Alumina inclusions, 283
Aluminum
additions, 283, 392, 395–396
in ESR forgings, 142, 525
fine-grained heats, 290
grain size and, 277, 281, 424
low, 37
nitride, 290
role, 42
shear stress of, 495, 497, 498–499 (illus)
treatment, 282–286, 290
American Society of Mechanical Engineers (ASME)
Code Case 1943 for Grade 91, 315
Code Section I, 304
Code Section III, Div. 1, 445
Code Section VIII, 304
Divs. 1 and 2, 296–297

Diamond Jubilee annual meeting, 19 standards, 276
Anchor
body, 546–547
connector, 541
Annealing, post-forging, 388
Antimony content
embrittlement and, 165–167
limits, 38
role, 42
Argon-oxygen decarburization (AOD), 36, 42, 306, 347
AOD-vacuum arc remelting, 347, 354
Arsenic content
embrittlement and, 165–167
limits, 38
role, 42
Association of Technical Supervisory Bodies (TUV), 413
ASTM Committee A–1 on Steel
Special Task Force on Large Forging, 20–21, 24
Subcommittee A01.06, 20, 573, 576, 578, 579, 581

ASTM Standards
A 182–82a: 303
A 213–83: 303
A 262: 446
A 293: 13, 21
A 335–81a: 303
A 336–83: 533
A 370–77: 527, 576
A 387/A 387M–83: 303
A 388–55T: 578
ASTM Standards (continued)
   A 388–80: 553
   A 428–71 (1980): 554, 555 (illus)
   A 470–82: 21, 125, 204
   A 470–84: 579
   A 638–82: 533
   B 557–84: 349, 354
   E 8–85: 347
   E 45–81: 533
   E 399–83: 180, 204, 349, 527
   E 647–83: 205
   E 813–81: 180, 204, 316, 320, 527, 530
ASTM STP 463, 199
ASTM Symposia
   68th Annual Meeting, 21
   Temper Embrittlement in Steels (STP 407), 24
ASTM-ASME Joint Committee on the Effect of Temperature on the Properties of Metals, 12
   Data and Publication Panel reports, 12–13
Austenite (See also Steels, austenitic)
   secondary, 148, 149
   transition, 168

B
Bainite, 189, 201–202
Basic-electric arc-furnace (BEF) process, 36–37, 42, 281
Bore magnetic particle tests, 220, 224, 229
Bore sonic tests, 224–229
development of, 25, 26, 222
Bore visual tests, 220, 224, 229
Brinell hardness, 160–162, 308, 309 (illus)
British- Standards Institution (BSI) standards, 276, 282

C
Calcium-argon blowing (CAB) process, 418, 420 (illus), 423
Carbides, 201–202
   chromium, 72, 539
distribution and shape, 193, 194, 195 (illus), 196, 201
effect of tempering temperature on, 191 (illus)
grain boundary, 531
   inclusions, 334, 337 (illus)
titanium, 539
Carbon
   check/ladle ratio, 217
distribution, 49 (illus), 51 (illus), 405–406
effects on embrittlement, 430, 431 (illus), 438
   extractive replicas, 334
   in flaws, 163
   segregation, 46, 51–53, 206–207, 296, 368, 380
   segregation ratio, 52–56
   variation in, 217–218
Carbonitrides, 277
Carbon-molybdenum rotor forgings, 157–177
Central zone remelting (CZR), 125
Charpy impact energy, 133–134, 310, 311 (illus), 326–327
Charpy impact tests, 131, 207, 308–311
   of hot forging dies, 585
   of nuclear reactor shell, 382, 383 (illus)
   of superconducting magnets, 530
Charpy V notch energy values, 102
   of new ingots, 375, 377 (table)
Check analysis/ladle analysis, 217 (table)
Chlorides, 259
Chromium (See also Steels, Cr-Ni-Mo)
   carbides, 72, 539
   content, 145–146, 148, 153, 241, 242
Cleavage, mixed mode (See also Cracks; Flaws; Fractures), 585
Compression strength, 478–479, 480
Computer-controlled forging system, 459–462
preform, 469–472
Cold expansion, 144, 250 (illus), 260, 269
Coolant circuit (nuclear reactor), primary, 385–397
Cooling rate, 91
  cracking during, 154
  critical, 193
  effects, 62, 66–67, 72, 93, 133, 196, 197
  FATT and, 102
  as function of forging properties, 193
  for large-diameter rotor forgings, 180
  toughness and creep strength and, 79
Cooling transformation, continuous, 90, 111 (illus)
Cooling treatment, step, 117–118, 134, 343
Copper content
  control of, 141
  limits, 43–44
Corrosion
  attack on nuclear cooling pump, 388
  behavior of 18-18-alloy, 266
  fatigue, resistance to, 243–244, 258–272
  tests, integranular, 446
Corrosion-resistant alloys, 349–354, 359–364
Corrosive agents, 259
Crack initiation
  of 18-18 alloy, 266
  with start-stop cycles, 230, 231–233
Crack propagation
  of 18-18 alloy, 266
  growth rates, 174, 210–211, 232
  rapid, 183
  resistance to in nuclear turbine forgings, 208
  from service-induced flaws, 158, 171, 173
  stable extension, 320
  transgranular, 172 (illus), 176
Crack shrinkage, 391
Crack size, critical, 233
Cracks, hydrogen-induced flake (See also Hydrogen, flake cracking), 407, 573–582
Crank web, 511 (illus), 513, 515 (illus), 518
Crankshafts
  connector inclination angle, 516–519
  forging operation, 506–509
  fully forged, 504–509
  long-stroke, 504–519
Creep properties, 137–139
  ductility, 71–73, 137–138, 312
  of modified Cr-Mo forging, 313–315, 340–341
  rupture strength
    of Cr-Mo-Ni-W-V steel, 120–122
    of Cr-Mo-V steels, 108
    in HP rotor, 83, 85
    in HP-LP rotor, 59–73
    niobium and, 86
    temperature and, 78–79
Creep rupture tests, 12
  of Cr-Mo-Ni-W-V steel, 120, 122
  of differentially heat-treated rotors, 82
  of HP-LP rotors, 62, 66, 70, 72, 73
  long-time, 142
  in retaining rings, 252
Creep strength tests, 256
Creep tests of saddle forging, 313–315
Cryogenic mechanical properties, 523–539

D

DATAQ computerized boresonic system, 222, 224, 226
Dehydrogenation, 281, 284
Deoxidation (See also Sulfur, deoxidation; Vacuum carbon deoxidation), 392–396
  in electroslag refining, 442
Deoxydizers, 283–286
Dephosphorization, 44
Desulfurization, 392, 394–396, 442, 446
Dies
  hot forging, 583–592
  types, 463
Discontinuities, 558–572
  sources of, 17
Disks, shrunk-on construction, 203
Dome (nuclear), cover, 399
Ductile-to-brittle transition, 148
Ductility
  of 18-18 alloy, 260
  improvement in, 21–23
  in long-time creep tests, 142
Electroslag hot topping practice, 29, 36, 42, 125, 443
Elements, effects on “A” segregation, 45–56
Embrittlement
  from ferrite, 246–247
  hydrogen, 243–244, 573–582
  long-term, 119
  nickel content and, 214
  reducing level of, 24–25
  relaxation, 390
  service-induced, 159
  temper, 39–40, 42
  effects, 91–93
  of HP-LP rotors, 59
  parameters influencing, 426–434
  resistance to, 343, 345
  sensitivity, 66
  sensitizing to, 39, 43
  toughness and, 168–169
  from tramp elements, 165–167
  temperature-induced, 396
Energy sources, 143
Equivalent flat bottom hole (EFBH) diameters, 554–555, 557
Erhardt process, 467
Exothermic hot topping, 36
Expansion tests, 241
Fatigue
  from flaws, 175
  of hot forging dies, 583–592
  in retaining rings, 242, 243
  in-service, 260
Fatigue (See also Fatigue tests), 259
corrosion (See Corrosion fatigue)
  crack growth rate, 210, 211 (illus)
  low-cycle behavior, 587–590
  properties
    high-cycle and low-cycle, 135–139
    of modified Cr-Mo forgings, 341
  Fatigue tests
crack growth, 315–316
low-cycle, 135, 205, 212 (illus), 587–588
rotating beam high-cycle, 135

Ferrites
austenitic, 253–255
cracking, 587–588
chromium, 255
effect on embrittlement, 430 (table, illus)
proeutectoid, 168

Ferroalloys, 247

Ferrous oxide slag, 442–443, 446

Finite-element method (FEM), 64, 65 (illus), 66

Flanges, 399, 402 (illus), 404–405, 406 (illus), 408 (illus)

Flaws (See also Cracks; Fractures; Inclusions)
critical size, 175, 231, 233
detectable size, 213
indication, 170–172
internal, 558–560
metallurgical analysis of, 157–177
service-induced, 158–159
size prediction, 163, 176, 177

Forge material, shear resistance, 476–503

Forge processing improvements, 19–25

Forging
against rigid anvil, 497–499
automatic ring preform, 465–467
center core, 66, 69, 446–448
classification by process, 454, 455–456 (tables)
computer-controlled preform, 469–472
cooled down, 388
dies, 583–592
equipment, 453–475
of ERS ingot, 443–444
failure analysis, 583–592
force requirements, 476–503
hot dies, 583–592
isothermal and hot die, 456–462

of long-stroke crankshafts, 504–519
low-sulfur (See Low-sulfur melting practices)
machine, 501–503
mandrel, 543
nuclear reactor technology, 385–397
precision, 462–465, 592
preform, 465–467, 469–472
reverse extrusion, 543
single tool, 500 (illus), 501
solid, 543, 546
speed, 484–486, 502
techniques, 453–475
technology, 385–397
TR method, 504–519
warm die, 454

Forging evaluation techniques
advances in, 25–28

Forging presses (See also Forging, equipment; specific presses)
automatic cogging, 469
automatic preform, 469 (illus), 471 (illus)
high-speed energy screw-type, 473–475

Forging Symposium in Terni, Italy, International, 386

Forgings (See also Rotor forgings; Steels)
alloy steel
heat/corrosion resistant, 349–354, 359–361
specialty, 347, 354–358
stainless, 347–349, 358–359
cleanliness, 31
fabrication, 306–308
general industrial
equipment and process, 453–519
manufacture and application, 523–549
testing and assessment, 553–592
high-sensitivity, immersion testing of, 553–572
hydrogen in, 573–582
impression die, 454
Forgings (continued)

heavy pressure vessel, 367–384, 402–409
modified 9Cr-1Mo steel, 303–327
nuclear reactor stainless steel, 439–449
for nuclear steam supply system components, 398–409
optimizing mechanical properties, 346–364
pressure vessel and nuclear processing, 367–449
seamless shell course forgings for, 275–300
steels for pressure retaining components, 303–364
sample, 66–68
for tension leg platform anchoring system, 540–549
turbine and generator
general retaining rings, 237–272
improvements in, 9–32
rotor assessment, 157–234
rotor manufacture, 59–103
rotor steel production processes, 35–44, 45–56
steels for rotors, 107–154
Fractography, 583–585, 587–590
Fracture behavior, 585–592
Fracture mechanics analysis, 159
of large generator rotor, 231–233
linear, 173–175
linear elastic, 229
of 3.5Ni rotor forgings, 183–187
Fracture surface appearance, 583, 585–587
Fracture toughness
of Cr-Mo-Ni-W-V steels, 121–122
of Cr-Mo-V steel, 134–135
effect of grain size on, 286–287
of 18-18 alloy, 164–166
of hot forging dies, 585–587
improvements in, 15, 30–31, 395
J-integral, 316–321
of 3.5Ni steel, 178–202
in nuclear reactors, 391, 392, 395
of retaining rings, 242–243, 264–266
specimen thickness and, 102–103
of superconducting magnets, 536–537, 538
after welding simulation, 287–290
Fractures (See also Cracks; Flaws)
brittle, 169, 187
ductile dimple, 183
intercrystalline, 242, 585, 590
mixed-mode, 183, 187, 585
quasicleavage, 187
transcrystalline to intercrystalline, 242
French laboratory Cr-Mo evaluation, 328–345
French Nuclear Code (RCC.M), 382
French Nuclear Program, 88
plants, 267
Friction effects, 481–484, 502–503

G

“Gatorizing” process, 457–459
Generator (See Nuclear plants, generators; Retaining rings; Steam generators; Turbine-generators)
Generator rotors, large
in-service inspection and evaluation, 219–234
service life, 219
tensile properties, 232
Geothermic power stations, 143–154
German Nuclear Committee (KTA), 391
German specialty steel producers, 410–424
Grain
austenitic growth kinetics, 286
coarsening, 79
fine-grain practice, 277, 299
growth, 419, 421 (illus)
refinement, 253, 392, 419
size, 321–327
controlling, 269, 282, 424
reducing, 86, 449
tensile properties and, 527
size effects, 60–61, 71, 81, 197,
288–289 (illus), 419, 525,
530–531, 536, 539
of FATT, 117–118
on toughness, 286–287

H
Hardenability, 39–40
of Cr-Ni-Mo steel grade, 90
effect of nickel on, 75
effect of temperature on, 78
levels, 108
parameters influencing, 426–427,
431–434, 438
Hardening
surface, 587–588, 589 (table)
through, 192–193
work, 479–480
Hardness (See also Brinell hardness;
Vickers hardness number)
of modified Cr-Mo forging, 308, 326
Heat, geothermic, 143
Heat-resistant alloys, 349–354, 359–364
Heat stability test, 13
Heat treatment (See also Thermal treat-
mant)
of AF1410 alloy, 358
conditions, 62, 91
differential, 70, 74–86
for forged shells with heavy walls,
425–438
effect on mechanical properties, 63
(illus), 64, 68 (illus)
of HY80 steel alloy, 543–544, 546
mechanical properties and, 126–127
of nuclear components, 404–405
postweld (PWHT)
of anchoring system, 546
effects on mechanical properties,
91–93, 99 (table)
embrittlement due to, 95
final, 343
thermal cycle of, 89
quenched tempered (QT), 91, 93, 419,
423–424
of retaining rings, 242
simulation, 216
thick plate, 341–344
water-cooled tempering (WCT), 91,
93
Heating ladle refining process (HLRP),
95, 97
Heavy-section tube sheets, 410–424
Heavy-wall reactor vessels (See React-
TOR vessels)
High-sensitivity tests, 553, 560–572
High-temperature tests, 14
Hot tensile tests, 12
Hot working, 269
Hydraulic presses, 464
Hydrogen (See also Embrittlement, hy-
drogen)
control, 578–579
determining content, 579–581, 582
 elemental, 442
flake cracking, 407, 573–582
flaking, 558, 560, 562 (illus), 565
(illus), 566, 569, 571 (illus),
572
SUBJECT INDEX  601
Hydrogen (continued)

inclusions, 407
low, 37
role, 42
in steel forgings, 573–582

I

Immersion tests, 553, 560–572
Impact properties
in Cr-Mo forgings, 339
in Cr-Mo-V steel, 129–135
effect of impurities on, 95
Impact tests (See also Charpy impact tests), 14
of Cr-Mo-Ni-W-V steel, 114–115, 120
of Cr-Mo-V steel, 129
on HP-LP rotors, 62
Impurities (See Steels, impurities)

Inclusions
aluminum, 283
analysis, 333–334
content, 102
frequency, 170
hydrogen (See also Hydrogen), 407
manganese-silicate, 175–176
manganese-sulfide, 201–202
nonmetallic, 169, 170–171, 172–173
(illus), 231, 292, 407, 558–560, 566
oxide, 17, 334

Ingot

cylindrical, 434–437
in heavy pressure vessel forgings
conventional, 368
manufacturing, 400–402
mechanical properties, 407
new, 368–384
quality of, 405–408
hollow, 291–292, 299, 371
chemical analysis, 378–381
mechanical testing, 382
nuclear reactor shell from, 378–383, 434, 435 (illus)
large
“A” segregation in, 45–56
electroslag remelting, 439–449
size and shape, 46–49
solidification analysis, 17, 18 (illus)
solidification shrinkage, 163–165, 175, 177
In-service inspection tests, 219, 223–234
automated, 222
historical development, 220–221
of nuclear reactors, 399
recommended procedure, 222–223
trends, 223
Ion-nitriding, 587, 588
Isothermal aging, 134
Isothermal forging, 456–462
Isotropy, 245, 391, 418

J

Japan Steel Works
Internal Pressure Bursting (JIB) test, 205, 210–211
nuclear component forging processes, 399, 404 (illus)
J-integral tests, 527

K

Kerosene-and-whiting tests, 13
Kraftwerk Union (KWU), 399, 400, 410, 413

L

Ladle analysis, 217 (table)
Ladle furnaces (LF), 281
Ladle injection, 36, 42
Ladle refining furnace (LRF), 36–37, 42, 267
Ladle refining process, heating (HLRP), 431
Larson-Miller parameter (LMP) curves, 137, 138 (illus)
Lawrence Livermore National Laboratory, 523
Le Creusot Heavy Forge, 368–384, 426, 430, 431, 437
Liquid melt, residual, 391
Liquid penetrant examination, 536
Longitudinal beam tests, 553, 558–562, 569–570
Low-sulfur melting practices, 29, 126–127, 139–140

M
Magnetic particle tests, 13, 14
of rotor center bore, 66
Magnets, superconducting, 523–539
Manganese levels
decreasing, 37, 90
effect on hardenability, 90, 91 (illus)
effect on liquid density, 53–56
embrittlement and, 429–430, 431 (illus)
low, 44
in retaining rings, 241, 242
role, 38, 39–40
Manganese-silicate inclusions, 175–176
Manganese-sulfide inclusions, 136, 201–202
degradation effects, 391
Manual of Open Die Forgings, 575
Martensite
microstructure, 343, 344
tempered, 189, 192
Mechanical properties (See also under specific materials)
of advanced technology Cr-Mo-V forgings, 124–142
cryogenic, 523–539
improvement, 108
Mechanical testing of anchor system, 544–546
Melting media, 277
Metal Forming Institute, Poznan, 509, 519
Microscopy (See also Scanning electron microscopy), 333–334
Microstructure (See also under specific materials)
effects of, 426–427
investigations, 187–189, 190 (illus), 333–337
Mirror fusion testing facility (MFTF-B), 523–524
Molybdenum
austenitic steels, 250–253
carbides, 72
effect on hardenability, 90, 91 (illus)
effect on liquid density, 53–56
Multiaxial presses, 465

N
Nickel (See also Steels)
content, 145–146, 148, 153
creep strength and, 75
effect of addition, 60–64, 70, 72, 144
embrittlement and, 214
fracture toughness of, 178–202
high, 38
in retaining rings, 241, 242
Niobium
carbides, 62, 72
creep strength and ductility and, 86
effect of addition, 60–64, 70, 72
inclusions, 334
toughness and, 75
Nitrates, 259
Nitrogen
as alloying element, 245–247, 249–255, 256
inclusions, 334
low levels, 37
solubility in steels, 247–249
Nondestructive tests, 220, 224, 231
of ERS ingots, 444–445
of superconducting magnets, 536–537
Nonmagnetic ring material (See Retaining rings, nonmagnetizable)
North Sea Hutton field, 540
Nuclear plants
generators, 258–272
German, 386
Obbrigheim, 386
pressurized water reactor, 87–103
Stade, 386
Nuclear Regulatory Commission, 179
Nuclear steam supply system components, 398–409
Nuclear turbine forgings
fracture toughness, 208, 209–210 (illus)
integrity, 203–218
mechanical properties, 207–213
segregation in, 205–206

O
Oak Ridge National Laboratory (ORNL), 328
Offshore Structures—Det Norske Veritas 1977, Rules of Design Construction and Inspection of, 545
Oxygen
activity, 283–284
decreasing, 36–37
high, 44
Oxysulfides, 418

P
Periphery ultrasonic tests, 14, 26, 220–221, 229
Phosphorus content
chronological evolution, 97, 98 (illus)
distribution, 49 (illus)
effect on carbon segregation, 56
effect on ductility, 137
embrittlement and, 119, 429, 431
in flaws, 163
low, 21, 22 (table), 36–37, 95, 137
role, 40
segregation, 217–218
Pitting, 262
Porosity, 17
micro, 292
shrinkage, 231
in weldings, 256
Power generating industry, 237–257
corrosion resistance in, 258–272
heavy-section tube sheet technology, 410–424
Pressure vessels (See Reactor vessels)
Proof load tests, 537–538
Pump casing, integral forged, 385–397

Q
Quenching, 388
air and oil, 109, 122
liquid-medium, 160

R
Reactor vessels
boiling water reactor pressure vessel (BWRPV), 399
fabrication problems, 292–298, 299
forging processing and nuclear application, 367–449
heavy-wall, 275–300
new ingot applications, 367–384
pressurized water reactor pressure vessel (PWRPV), 399
specifications, 276–290
Reactors
components, 425
light water (LWR), 399
liquid metal fast breeder (LMFBR), 328–329, 340, 344
petrochemical, 425
pressurized heavy water (PHWR) vessel, 399, 400
primary coolant circuit, 385–397
steam supply system components, 398-409

"Recommended Practices for Ultrasonic Inspection of Large Rotor Forgings," 20-21

Refining processes, secondary, 36

removal of sulfur in, 40

Retaining rings

cold-expanded, 244

corrosion-resistant, 258-272

function and demands, 238-240

future trends in, 271-272

manufacture of, 267-269

materials for, 237-257

mechanical properties, 242-243, 269-271

nonmagnetizable, 237-257, 259-260

resistance to corrosion and embrittlement, 243-244

service conditions, 259

Ring preform forging presses, 466

Rotor failure, technological impact, 35-36

Rotor forgings

evaluation of, 80-84

fracture toughness, 178-202

high-pressure-low-pressure, integral, 59-73

applications, 69-70

high-temperature characteristics, 13

manufacture, 79-80

mechanical properties, 13

metallurgical analysis of flaws in, 157-177

microstructural investigations, 179, 187-189, 190 (illus)

modern technology, 14-17

3.5Ni steel, 178-202

simulated large diameters, 179-180

specification trends, 35-44

Rotor steels, high purity, 37-38

Rupture ductility, trends in, 27 (illus)

Rupture strength, high-temperature trends, 27 (illus)

Scanning electron microscopy, 160

Segregation

"A," 45-56

cleanliness, 129

degradating effects of, 391

high manganese-sulfide inclusions in, 125

carbon (See Carbon, segregation)

dendritic, 189

in ERS ingots, 448

macrosegregation, 291, 370-371, 373

microsegregation, 392

negative and positive, 51-52, 292, 380

in nuclear turbine forgings, 205-206, 207 (illus)

phosphorus, 217-218

ratio, 48 (illus), 49, 50 (illus)

sulfur, 127, 164, 217-218

Shear

bidirectional, 495, 499-501

distribution, 387, 490-494

effect, 486-495

failure, 495

resistance, 476-503

stresses, 488-494

inside distribution of, 495-497

Shear-wave inspections, 553-555, 569-570

Shells

flanges, 402, 404, 406 (illus), 408 (illus)

forged, 425-438

torus and, 399

Silicon

decreasing, 37, 75

deoxidation (SD), 23, 49-52, 139, 392, 395-396, 429-430

effect on ductility, 137

effect on embrittlement, 429

effect on liquid density, 53-56
Silicon (continued)
effect on tensile properties, 93–94, 296
killing, 282–286
low, 38
modified alloy, 354
role, 41
Simulation technique, 179–180, 194–195, 198–202
Solidification
conditions, 368
horizontal-oriented (See Solidification, LSD)
of ingot, 46, 291
liquid density change during, 53–56
LSD (Lingot a Solidification Dirige), 369–375, 384, 434–437
shrinkage, 163–165, 175, 177
vertical and horizontal-oriented, 369
Solution treatment, 269
Sonic tests (See Ultrasonic tests)
Spheroidization, 202
Spring collet, 542–546
Steam-turbine rating trends, 11 (illus)
Steel production (See Steelmaking process)
Steelmaking process
advanced technology, 35–44
effects on “A” segregation, 45–56
effects on rotor specification trends, 35–44
for heavy-wall reactor vessels, 276–290
improvements, 17–19
new processes, 28–31
Steels (See also Alloys; Forgings; specific materials)
A286, 349–365
cryogenic mechanical properties, 523–539
A-508 Class 2, 386, 390
acid open hearth (AOH), 13
AISI 329, 253–255
austenitic, 245–247, 250–255
austenitic Cr-Ni, 144, 388
basic open hearth (BOH), 13
bidirectional shear, 499–501
carbon, 14
segregation of, 51–56
carbon-molybdenum, 157–177
macrostructure and microstructure, 321–326
mechanical properties, 308–326
modified, 303–327
cleanliness, 35, 44, 75, 283, 296
Cr-Mn, 241–243
Cr-Mn-N, 241–243
Cr-Mo, modified
chemical composition, 329
evaluation by French laboratories, 328–345
hardness, 338–339
mechanical properties, 339–341
microstructure, 333–337
transformation points, 329–333
Cr-Mo-Ni-W-V, 107–123
Cr-Mo-V, 14, 28, 31
analysis, 24
compositions, 15–16
in differentially heat-treated forgings, 74–86
ductility, 21–23
mechanical properties, 124–142
nickel/niobium effects on, 62–64
toughness, 59
Cr-Ni-Mo
chemical composition, 150, 153
mechanical properties, 98, 99 (table)
soft-martensitic stainless, 143–154
specification requirements, 89
tensile properties, 152, 154
electric furnace (EF), 13
ferritic-austenitic, 253–255
ferritic chromium, 255
fracture toughness, 178–202
heat/corrosion-resistant, 349–354, 359–361
high-sensitivity, immersion, ultrasonic testing, 553–572
high-temperature, 107, 119–122
hot low-carbon, 499–501
HY80, 543–549
hydrogen effects on (See also Hydrogen), 573–582
impurity levels, 36–37, 195, 375
effects of, 87–103
Inconel 625, 349, 360
mechanical property improvement, 108, 346–364
metallurgical analysis of flaws, 157–177
Mn-Cr-N (18-18 alloy), 259–272
corrosion behavior, 266, 267 (illus)
fracture toughness, 264–266
mechanical properties, 264
Mn-Mo-Ni, 388, 391, 392
in nuclear power stations, 418–419, 423
0.5Mo-2.5Ni-V, 13
3.5Ni, 178–202
Ni-Cr-Mo-V
creep rupture strength and temper embrittlement, 59
segregation in, 217
sensitizing to temper embrittlement, 39
toughness, 40–42, 214–215
Ni-Mo-Cr, 390
Ni-Mo-V, 13, 14, 29–30
analysis, 24
fracture toughness, 23
metallurgical analysis of flaws, 157–177
nitrogen as alloying agent, 245–247, 249–255, 256
nitrogen solubility in steels, 247–249
nonmagnetizable, 240–243
for nuclear steam supply system components, 398–409
optimization of grade, 87–103
optimization of mechanical properties, 346–364
quality, 35
quenched and tempered, 189, 192–196
retaining-ring, 245, 249–255
SA 336 F22 grade, 373–377
chemical composition, 427–431
heat treatment, 425–438
microstructure, 426–427
specialty, 347, 354–358
stainless, 347–349, 358–359
Type 304 stainless, 304, 439–449
cryogenic properties, 523–539
Strain rate, 516–519
Stress (See also Shear, stresses)
corrosion (See also Stress corrosion cracking), 259
flaking and, 576
in-service, 259, 542
relieving, 269, 390, 548, 575
residual, 83–84, 85
tangential, 231
thermal (See also Thermal cracking), 170, 173
transformation, 154
ture, 478, 479 (illus), 501
Stress corrosion cracking, 30, 154
of disks, 203
resistance to, 241, 243–244
Stress corrosion tests, 260
Stress intensity factor, 174
Stress rupture, carbon-molybdenum rotor, 169–170, 176
Stretched zone width (SZW) measurement, 590–592
Sulfides
critical concentrations, 418
inclusions, 136
linear, 17
Sulfur content
chronological evaluation, 97, 98 (illus)
distribution, 448
effect on fatigue, 136
effect on liquid density, 55, 56
effect on mechanical properties, 126–127, 136, 139–140
in flaws, 163
grain growth and, 421 (illus), 423
low, 21, 22 (table), 36–37, 38, 95
print, 163, 167
reduction in, 392, 395–396
role, 40–41
segregation, 127, 154, 217–218
Superalloys, 238
Support struts fabrication, 523–539

T
Technischer Überwachungs-Verein (TUV) standards, 276
Temperature (See also Stress, thermal)
austenizing, 62–63, 64, 66, 67 (illus), 71–73
effect on FATT, 75, 78
effect on hardenability, 431–434, 438
effect, 480–481
on turbine rotor, 12–13, 75, 78–79, 108–122
failure, 590–592
hardening, 146
strength dependence on, 182
tempering, 146–148, 194, 196, 354, 356
transformation, 145, 149, 192–193
in modified Cr-Mo forgings, 329–333
suppression, 144
transition, 168
Tempering study, 347, 348 (table), 354
Tensile properties
in Cr-Mo forgings, 339–340
in Cr-Mo-V steel, 129–135
effect of silicon on, 93, 94 (illus), 296
of modified Cr-Mo forging, 311–313
Tensile strength
trends in, 27 (illus)
ultimate, 94 (illus), 271, 287, 296, 485
Tensile tests, 14
Tension leg platform anchoring system, 540–549
Tension testing standard, 576
Tension tests, 13
of Cr-Mo-Ni-W-V steel, 114
of Cr-Mo-V steel, 129, 154
of HP-LP rotors, 62
of 3.5Ni steel, 181–182
Thermal cracking (flaking) (See also Hydrogen, flaking), 573, 576
Thermal shock, 590
Thermal stability, 83, 85
Thermal treatment (See also Heat treatment), 347, 443–444
Thermomechanical processing, 346–364
Thickness and fracture toughness, 102–103
Tin content
embrittlement and, 119, 165–167
limits, 38
role, 42
Titanium, 525
carbide, 539
Toughness (See also Fracture toughness)
of HP-LP rotors, 59–73
of HY80 alloy, 547–548
properties, 108–109
TR method, 504–519
Trace elements (See also Tramp elements; specific elements)
embrittlement and, 119
reduction, 97, 108
Tramp elements (See also specific elements)
role of, 42
in temper embrittlement, 165–167
Transformation structure, 413, 417–419, 424
Trepanning equipment, center core, 25
Tube sheets, heavy-section, 410–424
Tubes, heavy-walled, 467–469
Tufttride, 587–588
Turbine rotors
Cr-Mo-V forgings, 124–142, 157–177
development programs, 14–15
differentially heat-treated, 74–86
failures, 14
mechanics of, 16–17
full-integral, low-pressure forgings, 203–218
high-pressure, 107–123, 165–170
analysis for flaw indication, 170–172
fracture mechanics of flaws, 173–175
mechanical properties, 166 (table), 167–168
low-pressure, 163–165
mechanical properties, 166 (table)
manufacture of, 149–153
metallurgical analysis of flaws in forgings, 157–177
soft-martensitic stainless Cr-Ni-Mo steel, 143–154
welded polyblock, 87–103
Turbine-generators
history of, 9–12
modern steam, 9–32
in power generation, 238

U
Ultrasonic tests, 20–21 (See also Bore sonic tests; Periphery ultrasonic tests)
of bore surface indications, 160, 162–163
of Cr-Mo-Ni-W-V steel, 11
detecting internal defects, 577–578
of ERS ingot forgings, 445, 447 (table), 448, 449
for flaw size, 160, 162–165, 171–172, 176, 177
high-sensitivity, immersion, 553–572
of large generator rotors, 229–230
of near-bore zone, 158
of rotor center bore, 66, 160
of steel forgings, 553–572
of superconducting magnets, 536–537

V
Vacuum arc degassing (VAD), 373
Vacuum arc remelt (VAR), 347
furnace, 28
Vacuum carbon deoxidation (VCD), 23–24, 41–42, 125
effect on segregation, 49–56, 72
of forged reactor pump casing, 392–396
hardenability and, 86
impurities and, 93, 95
reduction of, 72
in mechanical properties testing, 125–140
in reactor forgings, 281–290, 299
temper embrittlement and, 75, 86
toughness and, 62
Vacuum casting, 575–576
Vacuum induction melted (VIM)–vacuum arc remelting, 347, 349
Vacuum lift process, 578–579, 582
Vacuum stream degassing (VSD), 37, 42, 281, 299
Vanadium
carbides, 72
effect on carbon segregation, 46, 56
in grain size control, 424
Vickers hardness number, 546
Voids, 164
Voids (continued)
  irregularly shaped, 177
  microshrinkage, 292

W
Water (as corrosive), 259
Welded polyblock turbine rotors, 87-103, 198
Welding problems, 256
Weldment examination, 547, 548

Y
Yield strength
  effect, 189, 164, 196
  of 18-18 alloy, 260, 261 (illus)
  ratio to ultimate tensile strength, 271
  of superconducting magnets, 536–537
  in tube sheets, 413–417

Z
Zirconium, 283