

Subject Index

- A**
- Alloying additions, effects on
 - constitution, 28–29
 - Alloying elements, 210–211
 - segregation, 43
 - α -particle, production, 84
 - Alumina, insulating layer, 59
 - Annealing, 205–207
 - Arrhenius plots
 - dissolution rate, 59–60
 - hydrogen diffusivity, 63–64
 - ASME Boiler and Pressure Vessel Code
 - Section VIII, 2
 - ASME Code Case N-47, 2, 199
 - ASTM E 706, 81
 - ASTM E 693, 81
 - Auger electron spectroscopy (AES), 42
 - Austenitic stainless steels
 - helium effects, 213
 - hydrogen diffusivity, 63–64
 - in-reactor creep-rupture, 135
 - irradiated, microstructure, 98–99
 - limitations for fusion, 2
 - Austenitization, effect on displacement
 - damage effects, 146
 - Austenitization temperature, effect on
 - ductile-brittle-transition
 - temperature, 145
- B**
- Beryllium neutron multiplier, 61
 - Bolts, high chromium martensitic steels, 11
 - Boron
 - doping problem, 163
 - effect on size and density of voids, 95–96
 - helium bubbles and, 161
 - irradiated steels, helium effects, 158–162
 - segregation, 43
 - Brazing, 78–79
 - Breeder outside tube, 17–18
 - Bubbles, 82
 - Burgers vectors, 81–82, 97, 113
- C**
- Carbide particles
 - as source of cracks, 146
 - spherical, 153
 - ν -Carbide phase, 106–107
 - Carbide precipitation, 35
 - Carbon, as alloying element, 210
 - Casings and valve bodies, 11
 - Cavities, 82
 - formation at prior austenite grain
 - boundaries, 185
 - growth rates, 98
 - irradiation produced, 98–99
 - CETA steels, irradiated, Charpy curves, 139–140
 - 10 CFR Part 61, 3
 - Charged particle irradiation, effect on
 - precipitate phase, 105
 - Charpy curves
 - before and after irradiation, 139–140
 - compared to fracture toughness curves, 168–169
 - comparison of unirradiated and irradiated, 151–152
 - cyclotron-injected helium, 162
 - irradiated MANET II and CETA steels, 139–140
 - ODS steels, 155
 - Charpy impact curves
 - annealing and, 205
 - unirradiated and irradiated, 159
 - Charpy impact properties, irradiated Cr-Mo steels, 149
 - Charpy impact tests, 168
 - Charpy impact toughness, irradiation
 - effects, heat treatment and, 144
 - Charpy properties, tantalum effect, 153
 - Charpy V-notch ductile-brittle transition
 - curves, heat treatment effects, 46–50, 46–48
 - Charpy V-notch impact transition curves, 48–49, 51
 - Chi phase, 39, 107–108
 - Chromium
 - as alloying element, 211
 - composition profile across prior
 - austenite grain boundaries, 44
 - effect on constitution of Fe-Cr-C alloys, 28–29
 - role in phosphorus segregation, 45
 - segregation, 43
 - Chromium-rich ferrite, precipitation, 105–106
 - Cleavage fracture toughness, Laves and ν
 - phases, 143
 - Clusters, 81
 - Coffin frequency modified endurance
 - approach, 181
 - Coffin-Manson relation, 178–179
 - Cold cracking, 75–77
 - Compressive hold periods, effects on
 - fatigue endurance, 183–184
 - number of fatigue cycles to failure, 183
 - Continuous-cooling-transformation
 - diagram, 32–33
 - fusion welding, 75, 77
 - Continuum damage mechanism, 200
 - Corrosion, aqueous, water coolant, 56–58
 - Corrosion rates, 57–58
 - lithium-lead, 59
 - Cracking, critical hydrogen
 - concentrations, 65, 68
 - Cracks, carbide particles as source, 146
 - Creep, 51–53
 - definition, 113
 - see also* Irradiation creep
 - Creep coefficient, 115
 - in-pile creep, 120
 - temperature dependence, 115, 118
 - Creep compliance, 115
 - Creep deformation, 200
 - Creep-fatigue, 183–185
 - Creep-fatigue crack growth interaction
 - equation, 201
 - Creep resistance, high chromium
 - martensitic steels, 7
 - Creep-rupture, 51–53
 - in-reactor, austenitic steels, 135
 - post-irradiation, 136
 - Cr-Mo steels
 - hydrogen embrittlement, 65–66
 - irradiation hardening by fission
 - neutrons, 122–127
 - Cyclic behavior, subgrain size effects, 187
 - Cyclic-hardening relationship, 187
 - Cyclic softening, 185–186, 191
 - thermal fatigue-tested, 196
 - Cyclic strength, 185–188
 - Cyclic stress-strain constants, 187
 - Cyclic stress-strain curves, 187–188
 - Cyclic stress-strain response, predicted
 - and experimental, 187–188
 - Cyclotron-injected helium, 162–163
- D**
- Defect cluster, 81–82
 - Deuterium-tritium fuel cycle, 82
 - Diametral strain, as function of
 - fluence, 116–117
 - hoop stress, 116–118
 - Diffusion, hydrogen isotope effects, 63–64
 - Diffusion coefficient
 - apparent, temperature dependence, 63–64
 - effective, 63
 - Diffusion welding, 75
 - Dimensional stability, 13
 - see also* Swelling
 - Dislocation channel deformation, 127
 - Dislocation loops, 81–82, 97, 143
 - irradiation-produced, 123
 - Dislocations, 113
 - Displacement damage effects, 139–156
 - austenitization effect, 146
 - chemical composition effect, 149–155

- Displacement damage effects (*continued*)
 fluence and temperature effect, 139–144
 heat treatment effect, 144–148
 melting practice effect, 148–149
 oxide dispersion-strengthened steels, 155–156
 reduced-activation steels, 143
 shift as function of helium concentration, 160–161
 shift as function of irradiation temperature, 161
 shift versus irradiation dose, 159
 Dissolution rate, Arrhenius plots, 59–60
 Double austenitizing treatments, 33
 Dual-beam irradiations, 96–98
 Ductile-brittle-transition temperature
 austenitization temperature effect, 145
 chromium content effect, 151
 comparison, F17, EM 12 and EM-10 steels, 142–143
 9Cr-1MoVNb steel, 141–142
 effect of
 aging temperature and time, 49, 51
 prior austenite grain size, 144
 delta-ferrite and, 48
 fracture toughness, 168
 as function of
 displacement damage, 144–145
 irradiation temperature, 154
 temperature, 152
 high chromium ferritic/martensitic steels, 14
 irradiated steel, helium effects, 156–157
 irradiation-induced increase, 147
 relation to irradiation hardening, 143–144
 shift, 209
 as function of fluence, 148
 as function of helium concentration, 160–161
 as function of irradiation temperature, 148, 161
 and strength increase due to irradiation, 139–140
 versus irradiation dose, 159
 tempering temperature effect, 147
 Ductile failure, highly dimpled, 127
 Ductility, δ -ferrite and, 142
 Ductility exhaustion, 200
 Duplex steels, 210
- E**
- Elastic strain range, 188–189
 Electron irradiation, 96–97
 Elongation, 122–123
 effect of single- and dual-beam irradiation, 131–132
 as function of
 fluence, 126
 irradiation temperature, 125
 steel with and without boron, 131
 EM12 steel
 compared with EM10, 210
 irradiation-creep coefficient, 120
 Explosive welding, 75
- F**
- Fast breeder reactors, 11–14
 components and materials, 12–14
 oxide dispersion-strengthened steels, 14
 radiation damage, 11–12
 void swelling, 12–13
- Fatigue, *see* Strain-controlled low-cycle fatigue; Stress-controlled high-cycle fatigue
 Fatigue crack growth, 197–199
 Fatigue crack growth rate, 199–201
 Fatigue transition life, 177–178
 Fe-Cr alloys, irradiation-induced phases, 106–107
 α' -Ferrite, 39–40
 precipitation, 105–106
 δ -Ferrite, 210
 formation suppression, 30–31
 improved ductility and toughness, 142
 Ferrite-forming elements, 28
 Ferritic steels
 comparison of ion, electron, and neutron irradiation, 96
 low- and reduced-activation considerations, 2–3
 low-swelling character, 96
 non-transformable, resistance to elevated-temperature helium embrittlement, 137
 optimization, 212–213
 radiation-induced segregation, 103–105
 reduced-activation, 3
 sodium-cooled, 12, 14
 spherical carbide particles, 153
 stress-strain curves, 122–123
 F82H steel
 activation property, 20–21
 activation response functions, 21–22
 Fission reactors, neutron-energy spectra, 82–83
 Fracture, quasi-cleavage, 146–147
 Fracture behavior
 radiation-induced segregation, 158
 thermal stability, 45–47, 53
 Fracture mode, effects of hydrogen charging and aging, 65–66
 Fracture stress, 153, 167
 Fracture toughness, 167–176
 conventional high-chromium steels, 168–173
 dependence on mode III load component, 67
 as function of
 crack angle, 173–174
 temperature, 169–170
 initiation, increase with increasing chromium and tempering temperature, 169
 MANET I steel, 173
 other approaches, 175–176
 reduced-activation steels, 173–175
 static, 168
 thermomechanical treatment, 169
 TIG weldments, 173
 Fracture toughness curves, compared to Charpy curves, 168–169
 Fusion
 advantages and limitations of martensitic steels, 1–2
 limitations, austenitic stainless steels, 2
 Fusion materials research, simulation techniques, 85
 Fusion neutron environment, irradiation damage, 82–83
 Fusion reactors, 14–23
 hydrogen isotope effects, 68–69
 reduced-activation steels, 18–23
 activation property, 20–21
 composition, 19
 impurity concentrations, 21
 parameters, 19
 systems and components, 15–17
 tritium breeding blanket concepts, 16–18
 Fusion welding, 71–77
 defects, 74–77
 microstructural characteristics, 71–74
 processes, 71
 Fusion zones, microstructures, 71–73
- G**
- Gas tungsten arc welds, micro-hardness profiles, 73
 Gas turbines, high chromium martensitic steels, 5
 G phase, 107–108
 Grain boundary composition, during tempering, effect of molybdenum, 43
- H**
- Hardening, 208–209
 detrimental effects, 209
 ductile-brittle-transition temperature and, 143–144
 fission neutrons, 122–128
 conventional Cr-Mo and reduced activation steels, 122–127
 oxide dispersion-strengthened steels, 128
 helium effects, 129–133
 by 14 MeV neutrons, 128–129
 Hardness
 helium effects and, 160
 martensite, 33
 tempering effect, 146
 Heat-affected zones
 liquation cracking, 74–75
 microstructures, 71–73
 schematic diagram, 72
 simulated, microstructures, 168–173
 Helium
 cyclotron-injected, 162–163
 effect on swelling, 94–96
 Helium bubbles, 157–158
 boron and, 161
 at grain boundaries, 135
 intergranular, stress-induced growth, 135
 prior austenite grain boundaries, 136–137
 Helium effects, 156–162, 209, 213
 boron-doped steels, 158–162
 hardening, 129–133
 nickel-doped steels, 156–158
 past and future, 163
 Helium embrittlement, elevated-temperature, 135–138
 resistance to, bcc iron-based alloys, 135–137
 High-chromium ferritic steels
 allowable impurity concentrations, 21
 ductile-brittle transition temperature, 14
 limitations, fast breeder reactors, 14
 High-chromium martensitic steels, 5–23
 allowable impurity concentrations, 21
 boiler components, 7, 10
 compositions, 6, 8–9
 creep resistance, 7
 development, 7

- ductile-brittle transition temperature, 14
- fusion reactors, *see* Fusion reactors
- gas turbines, 5
- limitations, fast breeder reactors, 14
- precipitation, normalized-and-tempered, aged, and creep-rupture tested, 39–40
- stainless characteristics, 5
- steam power plants, 5–6
- turbine components, 10–11
- uses, 5
- see also* Fast breeder reactors
- High-cycle fatigue, *see* Stress-controlled high-cycle fatigue
- High-frequency induction welding, 75
- High-pressure/low-pressure combination rotor shafts, 10
- HT9 steel, hydrogen embrittlement, 64–65
- Hydrogen charging, effects on tensile ductility and fracture mode, 65–66
- Hydrogen cracking, 75–77
- Hydrogen effects, 209
- Hydrogen embrittlement, 64–68
- 9Cr-1Mo steel, 65–66
- HT9 steel, 64–65
- irradiation effects, 68
- MANET steels, 65, 67–68
- manifestation, 63
- mechanisms, 67–68
- reduced-activation steels, 65, 67–68
- Hydrogen isotope effects, 63–69
- fusion reactor systems, 68–69
- solubility, diffusion, and permeation, 63–64
- see also* Hydrogen embrittlement
- Hysteresis loops, 177–178, 185
- I**
- Impact, 46–53
- Impact curves, annealing and, 205–206
- Impact properties, irradiation effects, 139–163
- cyclotron-injected helium, 162–163
- Inherent creep strength, 52
- In-pile creep, creep coefficient, 120
- Interfacial segregation, stress-driven, 45
- Intergranular attack, 56
- Intergranular cracking, 181
- Intergranular fracture, irradiated ferritic steels, 158
- Internal gas pressure, 135
- Interstitials, 97–98
- Inverse Kirkendall effect, 103
- Ion irradiation, 96–97
- Iron-base alloys, body-centered-cubic, resistance to intergranular helium embrittlement, 135–137
- Irradiated steels, welding, 79
- Irradiation, effects on ferritic/martensitic steels, 81–82
- Irradiation creep, 113–120
- ferritic/martensitic steels, 114–120
- measurement techniques, 114
- rate, 113
- steady-state rate, 116
- theory, 113
- Irradiation creep coefficient
- neutron-irradiated steels, 117
- ODS and EM12 steels, 120
- Irradiation creep deformation, 118–119
- Irradiation damage, fusion neutron environment, 82–83
- Irradiation effects, 208–210
- Irradiation embrittlement
- helium effects, 156–162
- see also* Displacement damage effects
- Irradiation experiments, 88–89
- Irradiation facilities, 85–88
- Irradiation resistance, enhanced, 149
- Irradiation simulation techniques, 83–85
- Irradiation studies, 83–85
- Isothermal transformation diagram, 32–33
- J**
- Joining, 71–79
- brazing, 78–79
- dissimilar metal welding, 77–78
- solid state welding, 77
- welding of irradiated steels, 79
- K**
- Knock-on atom, 81
- L**
- Langer equation, 179–180
- Laves phase, 40, 107–110
- cleavage fracture toughness, 143
- irradiation-induced, 143
- phosphorus segregation, 43–44
- precipitates, compositions, 39, 41
- spheroidization, 53
- time-temperature-precipitation diagrams, 39, 41–42
- Life predictions, 199–201
- Linear damage rule, 201
- Linear damage summation, 200
- Linear elastic fracture mechanics, 198
- Liquid metal embrittlement, 59–60
- Lithium-lead eutectic, corrosion, 58–60
- Lithium, liquid, 18
- Low activation, 3
- Low-alloy ferritic/pearlitic steels, resistance to elevated-temperature helium embrittlement, 137
- Low-cycle fatigue
- effect of temperature, 178–179
- see also* Strain-controlled low-cycle fatigue
- M**
- Magnetic confinement systems, 15
- MANET steels
- activation property, 20–21
- creep and temperature, 52
- effect of hold periods on number of cycles to failure, 184
- fatigue endurance, 67–68
- fracture toughness, 173
- fusion reactors, 15
- hydrogen embrittlement, 65, 67–68
- irradiated, Charpy curves, 139–140
- irradiation hardening, 125–126
- irradiation temperature effect, 139–140
- stress corrosion cracking, 59–60
- tempering curves, 35
- Martensite microstructure, tempered, 160
- Martensitic steels
- advantages and limitations for fusion, 1–2
- hydrogen diffusivity, 63–64
- irradiated, microstructure, 98–99
- low- and reduced-activation considerations, 2–3
- low-swelling character, 96
- optimization, 212–213
- see also* High chromium martensitic steels
- Martensite hardness, 33
- Mean stress, 185
- Mechanical properties, thermal stability, 45–47
- Melting practice, 212
- effect on displacement damage, 148–149
- Metallurgy, 28–37
- constitution, 28–30
- tempering, 33–37
- transformation, 29–33
- Microhardness, gas tungsten arc welds, 73
- Microstructural developments, 39, 41
- Microstructural evolution, 40
- Microstructure
- effects, 210–211
- normalized-and-tempered steels, 141–142
- Midlife weldment cracking, 75
- Molybdenum
- as alloying element, 211
- composition profile across prior austenite grain boundaries, 44
- effect on grain boundary composition during tempering, 43
- role in phosphorus segregation, 45
- Monotonic stress-strain constants, 187
- Monotonic stress-strain curves, 187–188
- N**
- Neutron-energy spectra, fission reactors, 82–83
- Neutron irradiation, 82–83, 209
- effect on precipitate phase, 105
- swelling during, *see* Swelling
- Neutrons, 14 MeV
- hardening by, 128–129
- Next European Torus (NET), 15
- Nickel
- effect on microstructure and properties, 84–85
- helium effects, 96
- on hardening, 129
- irradiation embrittlement, helium effects and, 156–158
- segregation, radiation-induced, 158
- Nuclear fission, 11
- Nuclear fusion, 14–15
- ν phase, cleavage fracture toughness, 143
- O**
- Orowan type of equation, 45
- Outboard blanket segment, 17–18
- Out-of-phase thermomechanical fatigue tests, 196–197
- Oxide dispersion-strengthened steels, 19, 213–215
- Charpy curves, 155
- displacement damage effects, 155–156
- fast breeder reactors, 14
- hardening by fission neutrons, 128
- irradiated, microstructure, 98, 100
- irradiation-creep coefficient, 120
- swelling, 119–120
- P**
- Permeation, hydrogen isotope effects, 63–64
- Phase diagram, HAZ regions, 72

- Phosphorus
 composition profile across prior austenite grain boundaries, 44
 segregation, 43
 Plane-strain fracture toughness, 167
 Plastic strain range, 188–189
 development, 191
 Post-weld heat treatment, 2, 71, 75–76
 Precipitate phases, 104–111, 211, 213
 chi, 107–108
 α' -ferrite, 105–106
 G phase, 107–108
 Laves, 107–110
 ν -carbide, 106–107
 σ phase, 107, 110
 Precipitation, 39–42
 normalized-and-tempered, aged, and creep-rupture tested steels, 39–40
 Preferred absorption glide creep, 113
- Q**
- Quasi-cleavage fracture, 146–147
- R**
- Radiation damage, fast breeder reactors, 11–12
 Radiation-induced segregation, 103–105
 fracture behavior, 158
 Ramberg-Osgood equation, 187
 Reduced-activation steels, 3
 activation property, 20–21
 chemical composition effect, 149–150
 chromium content and ductile-brittle-transition temperature, 151
 composition, 21
 displacement damage effects, 143
 effect of tungsten and vanadium, 150
 fracture toughness, 173–175
 hydrogen embrittlement, 65, 67–68
 impurity concentrations, 21
 irradiation hardening by fission neutrons, 122–127
 microstructure, 28–29
 following irradiation, 93–94
 neutron-irradiated, void swelling, 92–93
 parameters, 21
 Reheat cracking, 75
 Ritchie-Knott-Rice model, 147
 Rotors, high-chromium martensitic steels, 10–11
- S**
- Schaeffler-Schneider diagram, 30–31
 Segregation, 42–45
 effect of stress, 45
 σ phase, 107, 110
 Silicon, segregation, 43
 Sinks, 81
 irradiation-produced defects, 98
 Softening rate, 34
 Solid ceramic breeding materials, 61
 Solidification cracking, 74
 Solid state welding, 77
 Solubility, hydrogen isotope effects, 63–64
 Solubility curves, 28–30
 vanadium nitride, 35–36
 Solubility products, 28
 Steam oxidation, water coolant, 58
 Steam power plants, high chromium martensitic steels, 5–6
- Strain-controlled fatigue endurance, 191
 Strain-controlled low-cycle fatigue, 177–193
 creep-fatigue, 183–185
 cyclic strength, 185–188
 as function of total axial strain range, 180
 irradiation effects, 187–193
 strain range, 177–178
 strain rate and frequency, 181
 steel composition, structure, and fabrication, 181–183
 test atmosphere, 180–181
 test temperature, 178–180
 Strain range, 177–178
 mechanical, 194
 versus stress range, 195
 partitioning, 200
 versus number of cycles to failure, 181–182, 188–189
 versus stress range, 188–189
 Strain rate, 181
 Strength, increase due to irradiation, 130
 ductile-brittle-transition temperature shift, 139–140
 Stress amplitude, evolution during strain controlled fatigue tests, 189–190
 Stress-controlled high-cycle fatigue, 192–194
 Stress corrosion cracking, 56
 Stress induced preferential absorption creep, 113
 Stress intensity factor, 167
 Stress intensity factor range, 198
 Stress range
 development, 191
 development during fatigue tests, 189–190
 strain-controlled “in-beam”, 191–192
 effect of temperature, 192–193
 as function of number of fatigue cycles, 191–192
 versus strain range, 188–189
 thermal fatigue-tested steels, 196–197
 versus total mechanical strain range, 195
 Stress relaxation, 184
 Stress-relief cracking, 75
 Stress-strain curves
 engineering, 127, 135–136
 ferritic steel, 122–123
 Subgrain size, effects on cyclic behavior, 187
 Submerged arc welds, microhardness, 73–74
 Supercritical power plants, 5–6
 Surface energy, effective, tantalum effect, 153
 Swelling, 82
 during neutron irradiation, 91–100
 helium effects, 94–96
 ion and electron irradiation, 96–97
 mechanisms, 97–100
 reduced-activation steels, 93–94
 effect of chromium, 211
 mechanisms, 97–100
 ODS steels, 119–120
- T**
- Tantalum
 as alloying element, 211–212
 effect
 Charpy properties, 153
 Young’s modulus and effective surface energy, 153
- Tearing modulus, 168, 169–173
 dependence on mode III load component, 67
 Temperature-fluence diagram, 208
 Tempering, 33–37
 curves, MANET I, MANET II steels, 35
 Tensile, 45–47
 Tensile ductility
 effects of hydrogen charging and aging, 65–66
 elevated-temperature helium embrittlement, 136
 HT9 steel, 64–65
 thermal aging effects, 46–47
 Tensile hold periods, effects on fatigue endurance, 183–184
 number of fatigue cycles to failure, 183
 Tensile strength, 122–123
 effect of fluence, 122–124
 Thermal fatigue, 194–199
 effect of hold periods, 196
 endurance, 194
 Thermal stability, 39–53
 creep and creep-rupture, 51–53
 fracture, 53
 impact, 46–53
 mechanical properties and fracture behavior, 45–47
 precipitation, 39–42
 segregation, 42–45
 tensile, 45–47
 Thermal strain, 196, 198
 THERMOCALC, equilibrium phase prediction, 40, 42
 Thermomechanical fatigue, 177, 194–197
 effect of hold periods, 196, 198
 Thermomechanical treatment, 212
 fracture toughness, 169
 TIG weldments, fracture toughness, 173
 Time-temperature-precipitation diagrams, Laves phase, 39, 41–42
 Tokamaks, 15
 plasma-facing components, 15
 Toughness, δ -ferrite and, 142
 Transformation, 29–33
 Transgranular cracks, 181
 Transgranular failures, 128
 Transgranular fracture, 185
 Tritium breeding, 15
 blanket concepts, 16–18
 Tungsten
 as alloying element, 211
 computed kinetics, 41–42
 computed partitioning, 41–42
 effect on reduced-activation steels, 150
 Turbine blades, high chromium martensitic steels, 11
 Turbine components, high chromium martensitic steels, 10–11
 Type IV cracking, 75–76
- U**
- Ultracritical power plants, 5–6
 Upper-shelf energy, as function of displacement damage, 144–145
 USE, 147
- V**
- Vacancies, 82, 97–98
 Valve bodies, 11
 Vanadium

as alloying element, 211
 effect on reduced-activation steels, 150
 Vanadium nitride, solubility curves, 35-36
 Voids, 82
 boron effect on size and density, 95-96
 formation at prior austenite grain
 boundaries, 185
 Void swelling
 electron- and ion-irradiated steels, 91

fast breeder reactors, 12-13
 neutron-irradiated steels, 92-93

W

Water coolant, 56-58
 steam oxidation, 58
 Weight loss, versus exposure time, 59
 Welding, 2
 irradiated steels, 79

Y

Yield stress, 122-123, 130-131
 effect of
 fluence, 122-124
 single- and dual-beam irradiation,
 131-132
 as function of
 fluence, 126, 129
 irradiation temperature, 125