Subject Index

A

Acicular precipitate, duplex microstructure, 177
A508 Class 2 steel, silicon content effect on ferrite nose position, 71, 73
Alloy 51, 238
creep strength, 253
γ' phase volume fraction, 257
stress rupture, 252–254
Alloy 69, 238
Alloy 143
creep, 213–214
γ' precipitate and dislocation structure, 206
influence of initial γ size on creep curves, 207–208
lamellar structures, 207, 209
lattice mismatch, 211
Mo content effect, 213
Alloy chemistry, 271
development, 116
elements, loss or gain, 26
Alloy W–545, 278, 280, 282
Alpha–2, 176
Aluminides. See Nickel and nickel-iron aluminides
Aluminum
alloys, 183, 199–200
oxide formation, 287
residual element, 61, 63–64
Analytical electron microscopy, 165
dislocation substructure, 176, 178
duplex microstructure of acicular precipitate, 176–177
electron diffraction capability, 176
gas turbine materials, 171, 174–179
Annealing, 238
Antimony, residual element, 65–66
Arsenic, residual element, 65–66
ASME Boiler and Pressure Vessel Code, Section VIII, 96, 101
ASTM A 508, 51–52
ASTM A 788–85, 48
Atomization, 183–184, 193–194
centrifugal, 187–188
gas. See Gas atomization mode, cumulative powder size fraction dependence on, 189
ultrasonic gas, 188–189
vacuum, 187
Attack parameter, 276–278
Austenitic stainless steels, 116–157
alloy chemistries of small heats of PCA modifications, 146–147
cold-worked, 123
crystal structures and compositions of phases, 12–13
D9 type, 119
helium embrittlement resistance, 129–137
higher Ti + Nb and Nb levels, 146, 150
high-temperature strength characteristics, 154–156
histograms of elemental composition, 138–139
phase stability and formation during neutron irradiation, 137–146

Copyright © 1988 by ASTM International
www.astm.org
Austenitic stainless steels—

Continued

phosphide precipitation, 151–154
with tailored precipitation character­
istics, 146–154

tensile yield strength, 155–156
void, 117–118
void swelling resistance, 117–129
bubble evolution as function of
dose, 124, 128
critical cavity size, 125
delay of void formation, 119, 121
design window, 120, 122
differences in void and fine MC
formation, 124, 126–127
as function of fluence, 120
helium effects, 120, 123, 129
irradiation-induced solute seg­
regation, 125, 129
macroscopic description, 119–120
precipitate effects, 125, 129
ratio of dislocation of cavity
sink strength, 125
silicon and titanium effect, 119
swelling expectations for fu­
sion, 122

B

B3 pretreatment, 133–136
Bainite, 110
Baker-Nutting diagram, 88, 92
Beta phase, 176
Boride, 165
Borocarbine, 68
Boron
microalloying, intergranular frac­
ture, 223–226
residual element, 67–70
segregation behavior, 223, 225
Boundary migration, 243
Braid, 290, 296
composite, 292–294
cross-sectional regions, 297
Burgers vectors, 176

C

Calcium, residual element, 67–68
Carbide
formation, 88, 92
morphologies, 111
species as function of tempering
parameter, 88, 95
Carbide-free acicular bainite, 110–111
Cavitating grain boundaries, versus
life fraction consumed, 34
Cavity
critical size, 125
microstructures, thin foils, 141–142
growth, 31–33
Central Electricity Generating
Board, research and devel­
opment, 5–6
Centrifugal atomization, 187–188
Ceramic matrix, 290
CG–27, 278, 280–281
internal oxidation of aluminum, 286
oxidation and corrosion behavior, 285
Charpy 54 J transition temperature, 107
versus ultimate tensile strength, 89, 96
Charpy fracture, 54–55
Charpy impact energy, 60–61, 95
Cleanliness, effect of Mn content, 71
Clean steel, 47, 50, 53, 71
Cleavage fracture stress, 20
Climb by-pass models, 30
Clinch River breeder reactor, tube­
sheet forgings, 74, 76–78
CMSX–2
creep, 218
\gamma' size effects, 215
creep curves, 207–208
lamellar structures, 207, 210
lattice mismatch, 211–212
Cobalt-base alloys, composition, 274
Coble creep, 29–31
Cold cracking, prevention, 104
Composite materials, 290
stiffness matrix, 296
Compressive strength, concrete, 8
Concrete, 3, 8–9
Consolidation, high temperature aerospace materials, 194–195
Continuous filament system, 291
Copper, 65, 75, 78
Corrosion attack parameter, 276–278
oxide dispersion strengthened alloys, 265–267
resistance, 238, 257
Cr$_2$O$_3$, 278, 285
Crack growth, low chromium ferritic steels, 103–104
initiation, 34–36
nucleation, 34–35
opening displacement versus intergranular failure to, 70
stainless steels, 21
propagation, 36
Cracking cold, 104
hot, 106
post-weld reheat, 105
Creep, 22–34, 83, 202, 222, 238
anisotropy, nickel-base superalloys, 213–214, 218–219
climb by-pass, 30
2.25Cr–1Mo steel, 111
curve, Cr-Mo steels, 100–101
embrittlement, 47
endurance equation, 37
ferritic steels, 24
grain size dependence, 30
IC–264, 230, 233
irradiation effects, 26–28
loss or gain of alloying elements, 26
low chromium ferritic steels, 96–101
nickel and nickel-iron aluminides, 227, 229
oxide formation, 26–27
properties, stainless steel welds, 25
resistance, 271
secondary rate, 29
strength, INCONEL alloy MA 6000, 253
threshold stress, 29
viscous, 30
Creep crack growth, 24–25
Creep deformation, stainless steels, 31
Creep-fatigue, 37–38
Creep mechanisms cavity growth, 31–33
deformation, 29–31
remnant life assessments, 33–34
Creep rate Cr-Mo steels, 99, 101
as function of hafnium concentration, 227, 229
Creep rupture ductility versus rupture time, 72
oxide dispersion strengthened alloys, 249–258
stainless steels, 22–24
Critical radius theory, 125
Critical resolved shear stress, 16
(Cr,Mo)$_2$CN carbides, 88, 92
Cr-Mo steel, 83
Charpy 54 J transition temperature versus ultimate tensile strength, 89, 96
composition and microstructure, 86
welding, 105–106
creep rate, 99, 101
creep strain versus time, 99–100
development, 84
hexenenary phase diagram, 72
Cr-Mo steel—Continued
hydrogen attack resistance, 83
modified, 84
rupture strength, 97–98
ultimate tensile strength, 89
rupture strength versus Larson-Miller parameter, 97–98
strain-controlled fatigue, 101–102
ultimate tensile strength, versus temperature, 89, 96–98
see also Ferritic pressure vessel steels; specific steels
2.25Cr-1Mo steel, 59, 109–111
Al-N particle, 64–65
Al-Si and Si deoxidation, 64
carbide formation, 88, 92
copper particles extracted from ferrite matrix, 76–77
continuous cooling diagrams, 88
effect of boron on ferrite nose position, 67, 69
embrittlement, 108
grain boundary cavities and precipitate-free zone, 24
hardenability, 86
modified, M₃C carbide, 109
phosphorus effect, 59–60
quenched-and-tempered, 110
rupture stress, 64
strain-controlled fatigue curves, 103
tempering sequence, 88
yield strength versus copper content, 76, 78
3Cr-1Mo-1Ni steel, transmission electron micrographs, 86, 88, 90–91
3Cr-1.5Mo-0.5Ni steel
carbide species as function of tempering parameter, 89, 95
carbon extraction replica, 88, 93
creep curve, 100–101
creep strain versus time, 99
3Cr-1Mo steel, embrittlement, 106–108
3Cr-1.5Mo steel, 103, 108–109
9Cr-1Mo steel, 16, 20
12Cr-Mo-V-Cb-N, 49
3Cr-1.5Mo-0.1V-1.5Mn steels, continuous cooling diagrams, 88
9Cr-1Mo-V-Nb steel, crack growth, 103–104
Cr-Mo-V steel, 49
tensile ductility, 66–67
3Cr-1.5Mo-V steel, strain-controlled fatigue curves, 102
2.25Cr-1Mo-V-Ti-B steel, 100–101, 103
18Cr-8Ni austenitic stainless steels, compositional modifications, 10

D
Damage volume, 23
Deformation, 29–31
Dendritic microstructures, finescale, 190
Densification mechanism map, 194
Directionally solidified alloys, 202
Discrete fiber system, 291
Dislocation
distribution, 217
substructure, 176, 178
Dissimilar weld metal joints, 25–26
Dortmund-Hoerder degassing, 56
Ductility, 222
boron addition effect, 223–224
IC-145, 228, 230
INCONEL alloy MA 6000, 263
nickel and nickel-iron aluminides, 198, 237

E
Electric arc furnaces, 56–57
Electron microprobe analysis, 165
gas turbine materials, 170–171
Stirling engine, 278, 280–281
Electroslag hot-topping, 57
Electroslag refining, 47, 50, 56–57, 76
Elongation
    effect of chromium additions, 232
    as function of temperature, 259, 261
    see also Ductility

Embrittlement, 52–55
    dynamic, 222, 228–232, 237
    nickel aluminides, 223
    see also specific types of embrittlements

Endurance ratio, INCONEL alloy MA 6000, 263

Endurance testing, Stirling engine, 283–284, 286

Energy dispersive X-ray analysis, 167

ESHT. See Electroslag hot-topping ESR, 47, 50, 56–57, 76

F

Fabrication, 222
    nickel and nickel-iron aluminides, 232–234

Fabric geometry model, 290, 296–297

Failure strain, 295

Fast breeder reactors, 117, 119

Fatigue, 34–38
    crack initiation, 34–36
    crack propagation, 36
    creep-fatigue, 37–38
    high cycle
        INCONEL alloy MA 754, 264
        INCONEL alloy MA 956, 264–265
        INCONEL alloy MA 6000, 262–263
    low chromium ferritic steels, 101–103
    low cycle
        INCONEL alloy MA 754, 264–265
        INCONEL alloy MA 956, 264–266

INCONEL alloy MA 6000, 263–264
    mechanisms of environmental influence, 38, 40–41
    oxide dispersion strengthened alloys, 262–265
    Fatigue crack growth, graphite, 7
    Fatigue resistance, 238
    Fe₂O₃, 278
    δ-Ferrite, 10–11

Ferrite steel welds, HAZ microstructure, 16

Ferritic pressure vessel steels
    creep, 96–101, 111
    fatigue, 101–103
    crack growth, 103–104
    hardenability, 110
    heat treatment effect on microstructure, 86, 88–89
    hydrogen effects, 108–109
    hydrogen embrittlement, 106–108
    low chromium, 83–112
    materials and initial processing, 85–87
    stress rupture, 96–101
    temper embrittlement, 106–108
    tensile strength, 89, 94–96
    toughness, 89, 94–96
    weldability and weldment properties, 104–106

Ferritic steels, 3
    creep, 24
    creep strength and composition, 39
    environmental interactions, 16, 18
    fracture toughness, 18, 20–21
    sulfide characteristics, 17
    tensile properties, 16–18
    yield stress changes, 18

Fiber architecture, 290–298
    categories, 291
    continuous filament system, 291
    control of microstructure, 297
    discrete fiber system, 291
Fiber architecture—Continued
effect on properties of composites, 292–293
failure strain, 295
fiber volume fraction, 297
flexural strength effect, 292–293
fully integrated structure, 291
inherent bending strain, 295
microstructure analysis, 293–296
planar interlaced system, 291
processing science base for microstructural control, 293–297
stiffness matrix, 296
translation efficiency effect, 292
Fiber orientation, 290, 297
Fiber reinforcement, 167, 291
Fiber volume fraction, 290–291, 297
Flexural strength, fiber architecture, effect, 293
Formability, 238
FP/AL-Li composites, 285, 296
Fraction of rare gas release, 9
Fracture
appearance transition temperature, 53–54, 106–107
behavior, 222
boron addition effect, 223–224
mode, 228, 231, 246
toughness, 18–21
Fully integrated structure, 291

g', 202–203, 238
alloys, secondary recrystallization, 243
directional coarsening, 204–205
lattice mismatch effect, 211
matrix
INCONEL alloy MA 6000, 247
ordered, 229
undersaturated, 213
particle shearing, 215–216
phase, 137, 141, 255
coalescence, 253
coarsening and rafting, 255
morphology, 255–256
size variation with rupture life, 255–256
precipitates, 184, 243
and dislocation structure, 206
shape, 204
size effects, nickel-base superalloys, 207–209, 215
solvus temperature, 243
Gas atomization, 185–186
process control system, 193
sensor needs for feedback control, 193
ultrasonic, 188–189
Gas-cooled reactors, 6
Gas turbine materials, 165–181
analytical electron microscopy, 171, 174–179
cast blades, 167, 169
development procedure, 166
electron microprobe analysis, 170–171
future analytical development needs, 179
image analysis, 170
mu phase, 174–176
oxide rafts, 170, 172–173
precipitate phase, coarsening on dislocation mobility, 179, 181
scanning electron microscopy, 167–170
titanium alloys, 176
ultra-fine array of dispersoid, 179–180
yttrium effects, 169
Gatorizing, high temperature aerospace materials, 192
G phase, 137, 140–141
Grain aspect ratios, 244, 246
Grain-boundary cohesion, 223
Grain-boundary fracture, 222
Grain growth, 238
Granular bainite, 110–111
Graphite, 3, 7–8
Graphitization, 64

**H**

Hafnium additions, 226, 229
Hairpin tubes, 286–287
Hardenability, 47
  2.25Cr–1Mo steel, 86, 110
  boron effect, 68
Hardening, 111, 225–230
HAZ microstructure, ferrite steel
  welds, 16
Heat treatment, microstructure effect, 86, 88–89
Heavy forgings, residual elements. See Residual elements
Helium
  bubble formation, 135
  embrittlement, 117
  embrittlement resistance, 129–137, 156
  B3 pretreatment, 133–136
  bubble formation, 135
  design window, 132–133
  grain boundary carbides, 132–133
  tensile elongation, 132
  tensile properties, 130–132
induced suppression of void formation, 129
induced void suppression, 141
microstructural evolution effect, 140–142
production via nuclear transmutation reactions, 117, 119
RIS effect, 143
suppression of irradiation-induced phase formation, 143
void formation enhancement, 129
void swelling effects, 120, 123
Helium-induced extended transients, 123
High temperature aerospace materials, 183–200
atomization, 193–194
centrifugal atomization, 187–188
consolidation, 194–195
densification mechanism map, 194
dependence of cumulative powder size fraction on atomization, 189
dispersion-strengthened aluminum alloys, 199–200
effect of process parameters on droplet and preform characteristics, 196–197
fine-scale dendritic microstructures, 190
gas atomization, 185–186
Gatorizing, 192
historical profile, 184
hot extrusion, 191
hot forging, 192
hot isostatic pressing, 190–191
interface between powder metallurgy and rapid solidification, 189–190
liquid and partially solidified droplets in transit to substrate, 196
ordered intermetallics, 197–199
Osprey process, 195
post-consolidation thermomechanical processing, 192
rotating electrode process, 186–187
spray deposition, 195–197
titanium alloys, 200
ultrasonic gas atomization, 188–189
vacuum (soluble gas) atomization, 187
High-temperature strength, austenitic stainless steels, 154–156
Holloman-Jaffee parameter, 18
Hot consolidated powder, 240–243
Hot cracking, 106
Hot extrusion, high temperature aerospace materials, 191
Hot forging, high temperature aerospace materials, 192
Hot isostatic pressing, 179, 190–191, 194
HS–188, hydrogen permeability coefficient, 285
Hydrogen
low chromium ferritic steel effects, 108–109
residual element, 58–59
service, temperature-pressure regimes, 108–109
Hydrogen attack, 83, 108
Hydrogen embrittlement, 53, 83, 106–108
Hydrogen flaking, 47, 50, 53, 58–59
Hydrogen permeability, 271
coefficient, 275, 283–285
Stirling engine, 280, 283

INCOLOY alloy MA 956, 238, 250–251, 253
INCONEL 718, 278, 280
INCONEL alloy MA 6000, 238, 240
γ’ phase, morphology, 255–256
creep rupture, 249, 251–252
creep strength, 253
dispersoid size variation with rupture life, 257
ductility, 263
endurance ratio, 263
formation of coarse grains, 243
γ’ size variation with rupture life, 255–256

IC–50, oxidation rates, 231, 234
IC–63, hot fabricability, 234–235
IC–72, oxidation rate, 232, 234
IC–145, ductility, 228, 230
IC–159, hot fabricability, 234–235
IC–218, oxidation rate, 232, 234
IC–264, tensile properties, 230, 233
Image analysis, 165
gas turbine materials, 170
oxide rafts, 170, 172–173
Impact properties, stainless steel, 18–19
Impact toughness, 9Cr–1Mo, 20
IN–939, corrosion resistance, 257
Inclusions, 47
calcium, 67–68
egg-type, 74–75
Ni–Cr–Mo–V rotor forging steels, 74–75
sulfide, 60–61, 74
INCOLOY 800, distribution of aluminum, 286

INCONEL alloy MA 753, 243
INCONEL alloy MA 754, 238, 243
high cycle fatigue resistance, 264
low cycle fatigue resistance, 264–265
oxidation resistance, 266
secondary recrystallization, 247–248
yield strength, 259
zone-annealed, 247

INGOTS, nickel aluminides, 232–233
Inherent bending strain, 295
Interaction solid-solution hardening, 111
Intergranular failure, 70, 130–131
Intergranular fracture, boron microalloying, 223–226
Intermediate temperature strength improvements, oxide dispersion strengthened alloys, 252–255
Intermetallic compounds, 183–184, 222
Iron-base alloys, 271, 274, 284
Irradiation effects, creep, 26–28
Irradiation-induced phase, 116, 137, 139
Irradiation-induced solute segregation, 116, 125, 129, 137
helium effect, 143
intensity, 140–141
negative effect on MC stability, 144
Irradiation-modified phase, 116, 137, 139
Isothermal annealing, 247–249
Isothermal embrittlement, 53–54

J
J factor, 53–54, 106

K
Kachanov relationship, 23

L
Ladle refining furnace, 47, 57, 59, 68
Lamellar structures
alloy 143, 207, 209
CMSX–2, 207, 210
Larson-Miller equation, 88–89
Larson-Miller parameter, 18, 96–98
versus tensile strength, 89, 94
Lattice mismatch, nickel-base superalloys, 209–212, 221
Laves phase, 141, 143, 150
Ni concentration, 141, 143
Light water reactors, 117
Lithium, additions to aluminum alloys, 200
LRF. See Ladle refining furnace

M
M₃C carbide, 88, 108–109
M₆B₃, 165
M₆C carbide
energy dispersive X-ray spectra, 94
helium embrittlement, 132
neutron irradiation, 137
M₂₃C₆ carbide
energy dispersive X-ray spectra, 94
helium embrittlement, 132
retardation during fusion breeder reactor, 137
Magnetic fusion reactor, 117, 119–120, 123
alloy development, 132
design window, 120, 122
Magnetic particle, indications in Ni-Cr-Mo-V rotor forgings, 74–75
Manganese, as residual element, 70–72
MAR-M200, creep, 213, 218
MAR-M247, 212–214, 218
Martensite, formation, 11
MC
B₃ pretreatment, 133, 135
formation, 124, 126–127
grain boundary, 146, 148–150
interface, clustered fine bubbles at, 144
matrix, formation characteristics, 146, 150–151
as nucleation multipliers, 125
phase composition, 150
Mechanical alloying, 238
powder, 240
Mechanical properties, 83, 183–184, 202, 222
nickel and nickel-iron aluminides, 230–233
relationship with microstructure, 3, 7–38
titanium alloys, 176
see also specific properties
Metallography
nickel and nickel-iron aluminides, 230–233
Stirling engine, 278, 280, 284, 287
Metal matrix, 290
Microalloy region, composition under irradiation, 140
Microcomposition, 116
Mil-S–23194F, 48, 51–52
Misfit dislocations, 207
Mo2C carbides, energy dispersive X-ray spectra, 88, 92
Mu phase, 174–176
MXON alloy, 212
Co effect, 215, 218
γ size effects, 215, 217

N
N–155, 272, 275, 283
Nabarro-Herring creep, 29–31
NASAIR 100
Co content, 217
precipitation, 212
Neutron irradiation, 116–117
phase stability and formation, 137–146
Ni-Al-Nb, stress-strain response, 199
Nickel, 141, 143, 165
Nickel and nickel-iron aluminides, 222–236
alloy design, 233–234
boron-doped, fracture mode, 228, 231
cold and hot fabrication, 232–234
composition ranges, 234–235
correlation of strengthening potency to lattice strain, 225, 228
crack-free weldments, 236
creep, 227, 229–230, 233
ductility, 198, 237
dynamic embrittlement and environmental effects, 228–232
effect of chromium additions, 229, 232
hafnium additions, 226, 229
intergranular fracture and microalloying with boron, 223–226
mechanical and metallurgical properties, 230–233
oxidation resistance, 231, 234
solid solution hardening and strength improvement, 225, 230
stress-strain response, 199
sulfur attack, 236
tensile properties, 230, 233
yield stress, 197–198, 225, 227
Nickel-base alloys, 274, 284
Nickel-base superalloys, 184, 202–219
compositions, 204
creep around 1000°C, 204–214, 205
annoying effects, 212–214
creep anisotropy, 213–214
γ′ size effects, 207–209
lattice mismatch, 209–212
raft formation, 204–207
creep around 760°C
alloying effects, 215, 217–218
creep anisotropy, 218–219
γ′ size effects, 215–216
directional solidification, 202
lattice mismatch, 221
microstructure, 203–204
misfit dislocations, 207
single crystals, 203
Ni-Cr-Mo-V steel, 49, 67
rotor forgings, magnetic particle indications, 74–75
turbine disk steel, low sulfur, yield strength, 76, 78–79
3.5Ni-Cr-Mo-V steel, 49, 53, 72
Nitrogen, residual element, 66–67
Nondestructive evaluation, 49

O

Ordered intermetallics, 197–199
Orowan looping, 215–216
Osprey process, 195
Oxidation, 222, 271
attack parameter, 276–278
resistance, 238
nickel aluminides, 231, 234
oxide dispersion strengthened alloys, 265–267
Oxide, formation, 26–27
Oxide dispersion strengthened alloys, 238–267
boundary migration, 243
boundary motion isotherm, 246–247
composition, 239
configurations of coarse grain initiation and growth, 246
creep rupture, 249–258
intermediate temperature strength improvements, 252–255
structural effects on long-term rupture strength, 255–259
dispersoid morphology after stress rupture testing, 258
effect of alloy design on stress rupture characteristics, 257, 260
fatigue, 262–265
grain aspect ratios, 244, 246
grain size, 242
hot consolidated powder, 240–243
hot corrosion, 265–267
mechanically alloyed power, 240
secondary recrystallization, 243–248
isothermal annealing, 247–248
zone annealing, 244–247
tensile properties, 259, 261–263
see also INCONEL alloy MA 6000, 243
Oxide rafts, image analysis, 170, 172–173
Oxide scale adherence, 286–287
Oxygen, residual element, 66–67

P

Phase
classifications, 137, 139
formation during irradiation conditions, 140–141
stability, aged and irradiated steels, 137–140
Phosphide phase, 144
Phosphide precipitation, 151–154
Phosphorus, residual element, 59–60
Planar interlaced system, 291
Plasma arc melting furnaces, 58
Plastic zone size, 36
Point defects, 116–117
Post-consolidation thermomechanical processing, high temperature aerospace materials, 192
Post-weld heat treatment, 74, 76, 104–105
Post-weld reheat cracking, resistance to, 105
Powder metallurgy, 183–184
Power generation equipment, 3–42
design aspects, 6–7, 39
extrapolation to plant conditions, 42
fabrication, 39
Prealloyed powders, 183–184
Precipitate phase, coarsening on
dislocation mobility, 179, 181
Precipitation, 116, 202
Preform geometries, via spray de­
position, 195
Pressure vessel forgings, 47, 51–52
Pressure vessel steels, 83
development, 84
see also Ferritic pressure vessel
steels
Processing science, 290

R

Radiation
damage, 116
resistance, 116
Raft formation
\(\gamma'\) size effects, 207
lattice mismatch, 209–211
nickel-base superalloys, 204–207
Rapid solidification-hot consolida­
tion, 183–184
Rapid solidification processing, 176,
179, 198–199
rate process, 188
Rare earths
oxides, dispersion/precipitation,
179
residual elements, 68, 70
Ratio of dislocation of cavity sink
strength, 125
Recovery-controlled creep, 29–31
Recrystallization, 238
secondary, oxide dispersion
strengthened alloys, 243–248
Reheat cracking, 47
Remnant life assessments, 33–34
Residual elements, heavy forgings,
47–79
aluminum, 61, 63–64
antimony, 65–66
arsenic, 65–66
boron, 67–70
calcium, 67–68
compositions of grades, 48
copper, 65
embrittlement, 52–55
hydrogen, 58–59
manganese, 70–72
nitrogen, 66–67
oxygen, 66–67
phosphorus, 51, 59–60
pressure vessel forgings, 51–52
rare earths, 68, 70
silicon, 70–74
sulfur, 51, 60–62
tin, 65–66
turbine rotor forgings, 48–50
Resolved shear stress increase, 16
Rheinstahl-Heraeus degassing, 56
RIS. See Irradiation-induced solute
segregation
Rotating electrode process, 186–
187
Rupture life, grain aspect ratio ef­
effect, 246
Rupture strength
versus Larson-Miller parameter,
97–98
long-term, structural effects, 255–
259
versus temperature, 251
Rupture stress, versus rupture time,
64

S
Sanicro 32, 278, 280
SC 7–14–6, creep, 213
Scanning electron microscopy, 165
fiber-reinforced composite micro-
structure, 167–168
gas turbine materials, 167–170
size distribution of microstruc­
tural features, 169
X-ray energy maps, 169
Segregation, 47
Shape welding, 58
SiC/SiC composites, 292–293
Sigma phase, 150
Silicon, 70–74, 119
Single crystals, 202–203
Spray deposition, high temperature aerospace materials, 195–197
Stainless steels, 3
  composition effect, 10–11
  creep deformation behavior, 31
  creep rupture, 22–24
  creep strength and composition, 39
  environmental effects, 16
  honeycomb carbide structure, 14
  irradiation effects, 26, 28
  metallurgical variables, 23–24
  properties related to ageing, 11–14
  role of metallurgical variables, 21
  tensile properties, 9–16
  thermal ageing, 11–13, 23
  thermomechanical treatment, 11
  toughness properties, 21
  welds, creep properties, 25
Steel
  chemistries, 87
  clean, 47, 50, 53, 71
  grain size effect, 76–79
  hydrogen content, 56
  ingots, 50
  low alloy, 83
  microcleanliness, 59
  processing history, 85–86
Steelmaking, 47, 49–50
  innovations, 55–58
  installed capacity, 58
Stiffness matrix, 296
Stirling engine, 271–288
  change in specific weight, 273–274
  hydrogen permeation and endurance tests, 280, 283–285
  materials, 273–274
  operation, 271–272
  oxidation and corrosion tests, 275–280
  attack parameter, 276–278
  electron microprobe analysis, 278, 280–281
  metallography, 278, 280
  weight change, 275–277
  X-ray diffraction, 278–279
  schematic, 272
  simulator materials test rig, 273–275
Strain rate, 27
Stress corrosion cracking, 47, 52–53
Stress rupture, 238
  alloy 51, 252–254
  alloy design effect, 257, 260
  2.25Cr–1Mo steel, 105
  3Cr–1.5Mo steel, 105
  INCONEL alloy MA 754, 249–250, 252–253
  INCONEL alloy MA 956, 250–251, 253
  low chromium ferritic steels, 96–101
Stress-strain, 290, 296
Sulfides, 17, 60–61
Sulfur
  attack, nickel and nickel-iron aluminides, 236
  effect on mechanical properties, 76, 78
  residual element, 60–62
Superclean steels, 47

T
Tank degassing, 56
Td-Ni-Cr, 243
Temper embrittlement, 47, 49, 53, 83
  antimony, 65
  arsenic, 65
  composition, 54
  heat treatments used to assess susceptibility, 107
  low chromium ferritic steels, 106–108
  phosphorus role, 59
  tin, 65
Tempering parameter, Charpy V impact energies as function of, 89, 95
Tensile ductility, Cr-Mo-V steel, 66–67
Tensile elongation
  boron addition effect, 224, 226
  B3 pretreatment, 133–134
  steels irradiated in HFIR, 131–132
Tensile properties, 7–18, 238
  concrete, 8–9
  ferritic steels, 16–18
  graphite, 7–8
  nickel aluminide, 230, 233
  stainless steels, 9–16
  uranium dioxide, 8–9
Tensile strength
  austenitic stainless steels, 155–156
  CW Type 316 stainless steel, 130–131
  versus Larson-Miller tempering parameter, 94
  low chromium ferritic steels, 89, 94–96
  steels irradiated in HFIR, 131–132
  versus temperature, 89, 96–98
Texture, 238
Thermally activated glide-controlled creep, 29–31
Thermal phase, 116, 137, 139, 145–146
Thermomechanical processing, 183–184, 238
Threshold stress, 238
Tin, residual element, 65–66
Titanium, 119, 165
Titanium alloys, 200
  dislocation substructure, 176, 178
  dispersion strengthened, 183
  mechanical properties, 176
Titanium superalloy, ultra-fine array of dispersoid, 179–180
Toughness, 21–22
  environmental interactions, 21–22
  low chromium ferritic steels, 89, 94–96
Trepan boring, 50
Tubesheet forgings, Clinch River breeder reactor, 74, 76–78
Turbine rotor forgings, 48–50
Type 304 stainless steel, 21,2 3
Type 316 stainless steel
  COD effects, 21
  cold-worked, 123, 130–131
  creep rupture properties, 23
  fatigue endurance, 35
  grain-boundary carbide and ferrite formation, 15
  impact properties, 18–19
  short-term thermal ageing, 11
  time-temperature-transformation diagram, 14

U
Ultrasonic gas atomization, 188–189
Uniaxial modulus translation efficiency, 293
Uranium dioxide, 3, 8–9

V
Vacuum arc degassing, 57
Vacuum arc double electrode remelting, 58
Vacuum arc refining, 50, 56–57, 76
Vacuum carbon deoxidation, 50, 56, 70
Vacuum degassing, 56, 59
Vacuum oxygen decarburization, 57
Vacuum reladling, 56
Vacuum (soluble gas) atomization, 187
Vacuum stream degassing, 56
Vanadium, effects on early stages of tempering, 89
VAR, 50, 56–57, 76
VCD, 50, 56, 70
VOD, 57
Void
  austenitic stainless steels, 117–118
  suppression, helium-induced, 141
  swelling, 117; see also Austenitic stainless steels, void swelling resistance

W
Waspaloy, 230, 233
Weldability, low chromium ferritic steels, 104–106
Weldment, 104–106, 236
Welds, creep properties, 25–26
  metals, 25–26, 39
  practices, 105

X
X-ray diffraction, Stirling engine, 278–279
X-ray spectrometers, 171

Y
Yield strength
  versus copper content, 76, 78
  equation, 259
  as function of temperature, 259, 261
  low sulfur Ni-Cr-Mo-V turbine disk steel, 76, 78–79
  Ni₃Al, 197–198
Yield stress, 16
  as function of hafnium concentration, 226, 229
  as function of test temperature, 225, 227
  irradiated steel specimens, 18
Yttrium, oxidation resistance, 169
Yttrium oxide, 238

Z
Zone annealing, oxide dispersion strengthened alloys, 244–247