
Index

1080 steel, 305, 306
4150 steel, 328, 330, 335
4340 steel, 333, 334–335, 336
4360 steel, 328, 329, 330–332
6-6-2 steel, 284, 285

A

activation energy, 29–30
age hardening, 342. *See also* precipitation hardening (PH)
age-hardening alloys, 292, 349–350
aging, 352. *See also* precipitation hardening (PH)
allotropy, 1, 37. *See also* polymorphism (allotropy)
Alloy Phase Diagram Center, 11
Alloy Phase Diagram International Commission (APDIC), 11
alloy phase diagrams
 applications overview, 289–292
 industrial applications (*see* alloy phase diagrams-industrial applications)
 limitations of, 300–301
 uses, 290–292
alloy phase diagrams-industrial applications
 age-hardening alloys, 292
 austenitic stainless steel, 293–294, 295, 296
 carbide cutting tools, 299
 electric motor housings, 297–299
 hacksaw blades, 295–296
 hardfacing, 296
 heating elements, 297
 performance, 297–300
 permanent magnets, 293
 processing, 293, 295–296
 solid-state electronics, 299–300
alloying elements, 396
alloys

 chemical potential, 62–63
 course of freezing, 220–223
 four phase reactions, 225–227
aluminum alloys
 age hardening, 292
 CALPHAD, 269
 electric motor housings, 299
 gas-metal systems, 232
 general precipitation, 110
 liquid-solid phase transformations, 30
 precipitation hardening, 339, 345, 346, 352–358
aluminum-silicon eutectic system, 91–93
amorphous materials, 371
amorphous structure, 371
analytical electron microscopy (AEM), 254
anion, 368
annealing
 crystalline imperfections, 394
 definition of, 409
 equilibrated alloys, 244
 gas porosity, 442
 grain boundaries, 412–413
 heat treatments, prediction of, 292
 homogenization, 244
 low SFE, 425
 lower bainite, 333
 nucleation-controlled peritectic structures, 123–124
 precipitation, 246
 twins, 421
annealing twins, 421
antiphase boundaries (APBs), 174–175
Arrhenius equation, 28–30
as-cast ingots, 91
ASM International, 11
as-quenched martensite, 309
ASTM International, 416–417
atomic packing factor (APF), 372, 377, 380, 383–384

auger electron spectroscopy (AES), 254
 austempering, 326–327
 austenite
 austempering cycle, 327
 austenitic stainless steel, 293
 bainite formation mechanisms, 333
 bainitic microstructures, 327, 328
 lower bainite, 331
 martensite in steels, formation of, 310–313
 martensite morphology, 313
 martensitic structures, 307–308, 309–310, 316
 nickel-base superalloys, 358
 nonequilibrium cooling–TTT diagrams, 303–304
 phase transformations, 283–285
 shape memory alloys, 324
 upper bainite, 328–330
 austenite grain boundaries, 152, 158, 159
 austenitic stainless steel, 293–294, 425
 austenitization, 304
 Avogadro's number, 55, 60
 Avrami equation, 35–36
 AZ91 (Mg–Al–Zn alloy), 110, 111

B

backscattered electron (BSE), 256
 Bain, Edgar C., 325
 Bain strain, 311, 321
 bainite. *See also* bainitic structures
 formation of, 306
 bainitic structures
 austempering, 326–327
 bainite formation mechanisms, 333–334
 bainite transformation start temperatures, 327
 bainite versus ferritic microstructures, 327–328, 329
 cementite particles, 328
 ferrite-carbide bainites, 334–336
 lower bainite, 330–333
 overview, 325–326
 TTT diagram, 325–326
 upper bainite, 328–330, 331
 basal planes, 373, 375
 beryllium-copper alloys, 339, 345, 346
 billets, 289
 binary alloy. *See also* eutectic alloy systems
 definition of, 20
 long/short range order, 176
 peritectoid transformation, 143
 solidification of, 106
 binary isomorphous systems
 overview, 75–79
 phases, predicting chemical compositions of, 79

 phases, prediction of, 79
 phases, prediction of amounts of, 80–84
 binary solutions
 Gibbs free energy, 52–54
 ideal solutions, 54–56
 overview, 51–52
 binary systems
 introduction, 2–4
 isomorphous systems (*see* binary isomorphous systems)
 overview, 73–75
 stable equilibria for, 75
 bismuth
 electric motor housings, 298–299
 performance, 297
 peritectic transformations, 127
 theorem of Le Châtelier, 7
 bivariant equilibrium, 18
 blooms, 289
 body-centered cubic (bcc)
 allotropic transformations, 37
 iron, 24
 body-centered cubic (bcc) system, 376–377
 bond energy, 365
 bonding—in solids
 covalent bonding, 368–370
 ionic bonding, 368
 metallic bonding, 366–368
 overview, 365–366
 secondary (or van der Waals) bonding, 370
 boron, 21, 23, 24, 26, 396, 440
 Bragg angle, θ , 391
 Bragg's law, 391–392
 brasses, 173–174
 Bravais lattices, 372, 373
 bulk metallic glass formability (BMG), 271–274
 Burgers circuit, 398, 399
 Burgers vector, 398, 399, 406, 407, 423
 burning of the alloy, 290–291

C

CALPHAD (CALculation of PHase Diagrams). *See also* computer simulation
 Gibbs energies, 286–287
 industrial alloys, 268–270
 limitations, 285–287
 overview, 263–264
 steels, 269
 capillary effect, 349
 carbide cracking, 162
 carbide cutting tools, 299
 carbon
 austenitic stainless steel, 293
 bainitic microstructures, 327
 carbide cutting tools, 299

- Charpy V-notch test, 163
- covalent bonds, 369–370
- ductility, 162
- effect on pearlite, 163–164
- eutectoid structures, 149–158
- Fe-Cr-Ni system, 227, 229
- ferrite, 146–148
- ferrite-carbide bainites, 334
- ferrite-pearlite steels, 160
- interstitial compounds, 26
- interstitial defects, 396
- interstitial solid solutions, 23–24
- iron-base alloys, 132–133
- iron-carbon eutectoid reaction, 146
- isothermal transformation curves, 315–316
- lower bainite, 333
- martensite, 307, 310–311, 313–314
- martensite, tempering of, 316–320
- martensitic structures, 308
- performance, 297
- solid-state transformations, 146
- substitutional alloying elements, 165–166
- titanium alloys, 277, 279, 280
- upper bainite, 329–330
- carbon steels, 5, 144, 325–326
- cast irons
 - graphite, 146
 - gray cast iron, 98, 99
 - white cast iron, 101
- casting
 - definition of, 429
 - ingot casting, 90–91
- casting alloys, 90–91
- castings
 - aluminum-silicon alloys, 93
 - center-equiaxed zone, 435–436
 - grain size control, 33, 440
 - heterogeneous nucleation, 33
 - inclusions, 443
 - ingot casting, 429
 - inverse segregation, 439
 - porosity, 425, 442, 443
 - segregation, 239, 437
 - wrought metals, 425
 - wrought products, 425
- cation, 368
- cell (use of term), 100
- cellular precipitation, 112–114
- cellular transformations, 36
- cementite (Fe_3C)
 - bainite, 306
 - bainitic microstructures, 327
 - cementite-ferrite microstructures, 328
 - cracks, 162
 - equilibrium, 5
 - eutectoid structures, 149–158
 - ferrite-carbide bainites, 334
 - iron-carbon eutectoid reaction, 143, 145
 - pearlite colony, 152–154
 - pearlite nodules, 152
 - plates, 161, 162, 164
 - proeutectoid cementite, 159–160
 - softening, 319
 - steels, 146
 - substitutional alloying elements, 165
 - tempered martensite, 310
 - upper bainite, 328, 329
 - Widmanstätten cementite plates, 161
- cementite plates, 161, 162, 164
- center-equiaxed zone, 435–436
- centigrade temperature scale, 4
- Charpy V-notch impact test
 - ferrite-pearlite steels, 163–164
 - 4340 steel, 335, 336
 - low-carbon fully ferritic steel, 157
- chauffage*, 38
- chemical potential, 56–58
- chemical thermodynamics, 41
- ChemSage, 268
- chill zone, 434
- Clausius, Rudolf, 42
- Clausius-Clapeyron equation, 8, 50
- cleavage fracture, 164, 335
- closed system, 2, 42
- clusters, 31, 328, 343, 350, 430
- coarsening
 - eutectoid structures, 153
 - nickel-base superalloys, 358
 - precipitation hardening, 345, 346, 349
 - softening, 319
 - spinodal transformation structures, 182
- coherent interface, 348
- coherent precipitation, 346
- cold work brasses, 174
- cold working, 173, 409, 429
- columnar zone, 435
- composition scale, 4
- computer simulation
 - CALPHAD, limitations of, 285–287
 - computational methods, 266–267
 - databases, 270–271
 - Gibbs energy minimization, 266–267
 - industrial alloys, application of CALPHAD to, 268–270
 - industrial applications (*see* computer simulation-industrial applications)
 - overview, 263–264
 - PanNi database, 276
 - phase equilibria, 267–268
 - thermodynamic models (*see* thermodynamic modeling)
- computer simulation-industrial applications
 - example: bulk metallic glass formability (BMG), 271–274
 - example: dilation-austenite to ferrite/austenite to martensite, 283–285

- computer simulation-industrial applications (continued)
 - example: nickel-base superalloys, 274–277, 279
 - example: titanium alloys- β transus and β approach curves, 277–282
 - overview, 271
- congruent melting phase, 171
- congruent transformations, 260–262
- conjugate phases, 75, 208, 210
- constitutional supercooling, 432–433
- continuous precipitation, 110, 111
- cooling curves, 241–243
- coordination number (CN), 372, 377
- copper-nickel alloys
 - clad coinage, 81–83
 - coring segregation, 85
- copper-nickel system, 25, 76–77, 81, 82
- coring segregation, 84–85, 90, 108–109, 214, 291, 438
- coupled zone of eutectics, 107–108, 109
- covalent bonding, 368–370, 402
- critical (or consolute) temperature, 135
- crucibles, 240
- crystal defects, 346
- crystal systems, 371–372
- crystalline imperfections
 - line defects, 397–400
 - overview, 394
 - point defects, 394–397
- crystalline structure
 - body-centered cubic system, 376–377
 - crystal systems, 371–372
 - face-centered cubic system, 372
 - hexagonal close-packed system, 372–373, 375–376
 - overview, 371
 - space lattices, 371
 - X-ray diffraction, 391–393
- crystalline system calculations
 - atomic packing factor, 377
 - body-centered cubic system, 379–380
 - coordination number, 377, 379, 383, 384
 - cubic systems, 377
 - face-centered cubic system, 380–382
 - hexagonal close-packed system, 382–384
 - simple cubic system, 378–379
- crystallographic directions
 - cubic crystal structures, 389
 - hexagonal crystal structures, 389–391
 - Miller-Bravais system for hexagonal crystal structures, 389–391
- crystallographic equivalent planes, 388
- crystallographic planes, 386–389
 - Miller indices—cubic systems, 386–388
 - Miller-Bravais indices—hexagonal crystal systems, 388–389

D

- databases
 - multicomponent, 269–270
 - solution, 270–271
 - substance, 270
 - thermodynamic, 263–264, 269
- Debye-Scherrer powder method, 392
- degassing fluxes, 442
- degrees of freedom
 - diffusion couples, 254
 - magnesium, one-component diagram for, 18–19
 - phase equilibria, calculation of, 267, 268
 - phase rule, 5–6
 - ternary isomorphous systems, 203, 204–205
- delta iron, 37
- dendrites
 - and eutectics, 106–108
 - size of, 440
- dendritic growth, 430–432, 433, 435
- differential scanning calorimetry (DSC), 249–251
- differential thermal analysis (DTA), 244, 249
- diffraction effects, 185, 391
- diffractometer methods, 393
- diffusion
 - alloying elements, 165–166
 - aluminum alloys, 352
 - bainite formation mechanisms, 333
 - bainitic microstructures, 327
 - carbon, 132
 - climb, 395
 - coarsening, 345
 - couples, 253–256
 - crystalline imperfections, 394
 - diffusion couple (DC) amplifier, 249
 - eutectics spacing, 140
 - homogenization, 244
 - intermediate phases, 172
 - iron-base alloys, 132
 - lever rule, 119
 - liquid metals, 430
 - macrosegregation, 440
 - martensite, 309, 311
 - martensitic structures, 307
 - nickel-base superalloys, 358–359
 - nonferrous martensite, 320
 - pearlite, 306
 - pearlite growth, 150–152, 153–154, 156
 - peritectic cascades, 127–130
 - peritectic transformations, 126
 - point defects, 394, 395
 - precipitation hardening, 352
 - reaction layers (envelopment), 223
 - SDAS, 440
 - softening, 319

solid-state phase transformations, 33, 34
 spinodal decomposition, 183–185
 undercooling, 306
 vacancies, 348, 349, 395
 vacancy diffusion, 408
 work hardening, 409
 diffusion couple (DC) amplifier, 249
 diffusion couples, 253–256
 diffusion coupling, 103, 108
 diffusion multiple, 255–256
 diffusion-controlled creep, 358–359
 dihedral angle, 419, 420
 dilatometry, 244, 249, 251–252
 dilute solution models, 265, 269
 directionally-solidified (DS), 101
 discontinuous precipitates, 345
 discontinuous precipitation, 110, 111, 112–114
 dislocation-generated APBs, 181
 dislocations
 as-quenched martensite, 320
 carbide cracking, 162
 climb, 406–407
 edge dislocation, 397–398, 399–400
 extended, 424
 glide (or slip), 406
 glissile dislocation, 408
 grain boundaries, 412, 415
 heterogeneous nucleation, 33, 346
 lattice invariant deformation, 312–313
 line defects, 397, 398, 400
 line dislocations, 408
 liquid state, 429
 martensite plates, 322
 negative, 398
 plastic flow and, 403–408, 409
 point defects, 395, 396
 positive, 398
 precipitation hardening, 340, 343, 344
 screw dislocation, 398–400, 408, 411
 semicoherent interfaces, 348, 418
 semicoherent precipitates, 348
 sessile dislocation, 407–408
 SFE, 423–425
 small-angle grain boundaries, 411
 superlattice dislocations, 181
 vacancies, 395
 dislocations (definition), 396
 double-aging treatments, 360
 Driver-Harris Company, Inc, 297
 ductility
 alloying, 20
 austempering, 327
 carbon content in steels, 146, 162
 crystal structure, 365
 CuZn, 172
 ferrite-carbide bainites, 334, 335
 fully pearlitic steels, 157, 158

grain size, 415, 440
 hcp structure, 406
 hydrogen, 24
 hypereutectoid steels, 160
 Laves phases, 27
 lead, 136
 line defects, 397
 martensite, 310
 martensitic steel, 318
 phase diagram limitations, 301
 plastic deformation, 401
 point defects, 396
 pure metals, 19
 SDAS, 440
 second phase particles (lead), 418
 silicon additions, 93
 slip systems, 385
 solubility, 367
 tempering, 307, 316–317
 work hardening, 409
 Duralumin alloys, 292

E

edge dislocation, 397–398. *See also* line defects
 elastic deformation, 315, 398, 401
 electric motor housings, 297–299
 electrical resistance measurement, 244, 252, 253
 electron backscatter diffraction (EBSD), 256
 electron beam welding, 296
 electron diffraction, 246, 247, 318
 electron microscopy, 245–246
 electron phases, 25–26
 electron probe microanalysis (EPMA), 246, 247, 254
 Ellingham diagram, 233–235
 embryos
 liquid-solid phase transformations, 31, 32–33
 precipitation hardening, 343
 endothermic, 44, 58
 energy-dispersive spectrometry (EDS), 254
 energy-dispersive X-ray microanalysis (EDX), 246
 enthalpy
 definition of, 43
 thermodynamics, 41
 entropy of fusion, 51
 envelopment, 216, 223
 equilibrated alloys
 analysis of quenched samples (static method), 245–248
 analysis of samples (dynamic method), 249–253
 overview, 244–245

- equilibrium
 - definition of, 45
 - introduction, 4–5
 - temperatures, effect of pressure on, 48–50
 - true equilibrium, 11
 - equilibrium freezing
 - alloys, 212–214
 - peritectic alloys, 119–121
 - solid-solution alloys, 206–207
 - etching, 328, 412, 438
 - eutectic alloy (definition), 87
 - eutectic alloy systems
 - aluminum-silicon, 91–93
 - eutectic morphologies (*see* eutectic morphologies)
 - lead-tin, 94–96
 - overview, 87–91
 - eutectic grain (use of term), 100
 - eutectic microstructures, 100–101
 - eutectic morphologies
 - coupled zone of eutectics, 107–108, 109
 - dendrites and eutectics, 106–108
 - eutectic microstructures, 100–101
 - eutectic structures (*see* eutectic structures, solidification and scale of)
 - fibrous eutectics, 97–98
 - irregular eutectics, 100
 - lamellar eutectics, 97–98
 - overview, 97
 - regular eutectics, 98, 100
 - single-phase instability, 106–107
 - terminal solid solutions (*see* terminal solid solutions)
 - two-phase instability, 107
 - eutectic phase diagrams, 69, 71–72
 - eutectic reaction (definition), 87
 - eutectic structures, solidification and scale of
 - irregular eutectic growth, 105–106
 - overview, 101–102
 - regular eutectic growth, 102–105
 - eutectoid ferrite, 158
 - eutectoid transformation, 143, 165, 300, 325
 - exothermic, 44, 58
 - extended dislocation, 424
- F**
- F*A*C*T, 268
 - face-centered cubic (fcc)
 - allotropic transformations, 37
 - binary isomorphous systems, 77
 - binary systems, 2
 - cubic systems, 377
 - equilibrium in heterogeneous systems, 65
 - fcc system, 380–382
 - Fe-Cr-Ni system, 229
 - intermediate phases, 172
 - iron-carbon eutectoid reaction, 145
 - liquid state, 429
 - nickel-base superalloys, 358
 - face-centered cubic (fcc) system, 372, 423, 425
 - faceted phases, 98
 - FactSage, 268
 - Fahrenheit scale, 4
 - family planes, 388
 - Fe-Cr-Ni system, 191, 227–229
 - Fe-Nd-B, 292, 293
 - ferrite
 - to austenite, 283–285
 - austenitic stainless steel, 293
 - bainite formation mechanisms, 333
 - bainitic microstructures, 327–328
 - eutectoid structures, 149–158
 - ferrite-carbide bainites, 334–336
 - formation of, 37
 - iron-carbon eutectoid reaction, 145, 146–148
 - lower bainite, 331–333
 - martensite formation, 307–308, 310, 317, 319
 - nonequilibrium cooling–TTT diagrams, 306
 - peritectic reactions, 133
 - proeutectoid ferrite, 158–164
 - stabilizing elements, 227–229
 - upper bainite, 328–330
 - ferrite iron, 37–38
 - ferrite laths, 329–330, 331
 - ferrite-carbide bainites, 334–336
 - ferritic versus bainite microstructures, 327–328, 329
 - Frank-Read spiral mechanism, 407
 - free energy and phase transformations, 27–28
 - free energy-temperature diagrams, 233–235
 - free-energy hump, 45
 - Frenkel mechanism, 395, 396
- G**
- gamma iron, 37
 - gas porosity, 442, 444
 - gas-metal systems
 - free energy-temperature diagrams, 233–235
 - isothermal stability diagrams (*see* isothermal stability diagrams)
 - overview, 231–232
 - predominance area diagrams, 235, 237–238
 - general precipitation, 110, 111
 - Gibbs, Josiah Willard, 260
 - On the Equilibrium of Heterogeneous Substances*, 43
 - Gibbs energies (CALPHAD), 286–287
 - Gibbs energy change
 - austenite to martensite, 284
 - gas-metal systems, 231–232
 - substance databases, 270
 - Gibbs energy minimization, 264, 266–267, 268

Gibbs energy-temperature diagram, 233–235

Gibbs free energy

binary solutions, 52–54

overview, 43–45

phase diagrams, 67–72

phase transformations and, 27–28

single-component systems, 45–51

Gibbs free-energy curves, 30, 68, 69–72

Gibbs' phase rule, 5–6

Gibbs triangle, 196–198

Gibbs-Konovalov Rule, 260

glass-forming ability (GFA), 272–274

glide (or slip), 402, 406

glissile dislocation, 408

GP II zones, 354

grain boundaries

austenite, 150, 158

carbide formation, 319

cellular precipitation, 114

discontinuous precipitation, 110

electric motor housings, 298

eutectic alloy systems, 90

grains, 410

heterogeneous nucleation, 33

high-angle grain boundaries, 411–412

liquid-solid phase transformations, 31

low-angle grain boundaries, 411, 412

martensitic structure, 316

nickel-base superalloys, 358

nucleation, 346

pearlite nodules, 152

phase diagram limitations, 301

precipitate formation, 345

precipitate-free zones, 356

proeutectoid cementite, 159, 160

second phase formation, 418–420

shrinkage porosity, 444

slip, as obstacle to, 415

small-angle grain boundaries, 411

spinodal structures, 187

subcrystals, 411

subgrains, 411

surface or planar defects, 410–414

twin boundaries, 422–423

vacancies, 395

grain refinement, 440

grain size

ASTM grain size number, 416–417

castings, 33, 440

chill zone, 434

ferrite-pearlite steels, 160

ferritic steel, 148

grain boundaries, 411

grain refinement, 440

liquid-solid phase transformations, 33

nickel-base superalloys, 360

polycrystalline metals, 415–416

grain-boundary embrittlement, 419

grains, 410

graphite

carbon steels, 5

diamond to, 44

equilibrium, 5

faceted phases, 98

flake graphite, 99

iron-carbon eutectoid reaction, 146

spheroidal graphite cast iron, 98, 99

spheroidal graphite particles, 98

vermicular or chunky, 98

gray cast iron, 98, 99

growth

precipitation hardening, 346, 349

solid-state phase transformations, 33, 34

Guinier-Preston (GP) zones, 346, 350–351, 353–356

H

habit plane, 312

hacksaw blades, 295–296

Hall-Petch coefficient, 415

Hall-Petch relationship, 149, 415

hard ball model, 378, 379

hardfacing, 296

heat-flux DSC, 250–251

heating elements, 297

Hemholtz free energy, 27

Henry's law, 63

heterogeneous equilibria, 5

heterogeneous nucleation, 347–348

liquid-solid phase transformations, 31–32

solid-state reactions, 33

hexagonal close-packed (hcp) system, 38, 372–373, 375–376

high SFE, 425

high-carbon steels, 164, 327

high-dome alloys, 136–137, 140

high-strength low-alloy (HSLA) steels, 164

high-temperature (hot-stage) metallography, 249

high-temperature creep, 276, 359, 408

homogenization

definition of, 91

equilibrated alloys, 244

inverse segregation, 439

peritectic alloys, 121

SDAS, 440

terminal solid solutions, 108, 110

homogenous nucleation, 31, 32, 33, 347–348

hot isostatic pressing, 425, 442

hot pressing, 425

hot work brasses, 174

hot-stage microscope, 245

Hume-Rothery ratios, 26

Hume-Rothery rules, 24–25, 78

hydrogen
 atomic hydrogen, 442
 gas porosity, 442
 molecular, 442
 unwelcome addition, 24
 vacuum degassing, 442
 hydrogen embrittlement, 24
 hypereutectic alloy (definition), 88
 hypoeutectic alloy (definition), 87–88
 hypoeutectoid (definition), 158

I

impurities, 396
 in situ XRD, 245, 249
 incoherent interface, 348
 incongruent melting phase, 171
 ingots, 91, 272, 289, 429, 442
 intergranular
 corrosion, 160
 grain boundaries, 414
 hypereutectoid steels, 160
 pearlite nodules, 153
 precipitate-free zones, 356
 interlamellar spacing, 105, 157, 305, 306
 intermediate phases
 electron phases, 25–26
 intermetallic compounds, 25
 interstitial compounds, 26
 Laves phases, 26–27
 order-disorder transformations (*see* order-disorder transformations)
 overview, 25, 171–174
 spinodal transformation structures (*see* spinodal transformation structures)
 intermetallic compounds, 25, 98, 171, 255, 368
 internal energy, 42
 interstitial carbon, 24, 146–147, 151–152, 166
 interstitial compounds, 26
 interstitial defects, 396
 interstitial sites, 24
 interstitial solid solutions, 20–21, 23–24
 interstitials, 396
 invariant point, 19
 invariant transformations, 143
 inverse lever rule, 9–10, 80–81
 ionic bonding, 368
 iron. *See also* cast irons; cementite (Fe_3C); iron-base alloys; iron-carbon eutectoid reaction
 allotropic transformations, 37–38
 austenitic stainless steel, 293
 bainite formation mechanisms, 333
 binary iron-chromium system, 227–229
 carbide, 5
 covalent bonding, 367

crystalline structure, 372
 crystalline structure as a function of temperature, 1
 equilibrated alloys, 245
 equilibrium temperatures, effect of pressure on, 48–50
 eutectic alloy systems, 90
 eutectic morphologies, 98
 ferrous alloys, 279
 hydrogen solubility, 442
 interstitial solid solutions, 23–24
 iron-molybdenum alloy, 187
 Laves phase formation, 27
 laws of dynamics, 41
 martensitic structures, 308
 nickel-base superalloys, 358, 359
 precipitation hardening, 358
 ternary phase diagrams, 191
 titanium alloys, 277, 279
 iron-base alloys
 peritectic structures in, 130–131, 132–133
 precipitation hardening, 345, 346
 iron-carbon eutectoid reaction
 alloying elements, 165–166
 eutectoid structures, 149–158
 ferrite, 146–148
 hypereutectoid structures, 159–164
 hypoeutectoid structures, 158–164
 overview, 144–146
 iron-carbon system, 90, 144, 160, 165
 isomorphous (definition), 73, 78
 isomorphous alloy systems
 binary isomorphous systems, 75–84
 binary systems, 73–75
 nonequilibrium cooling, 85
 overview, 73
 isomorphous phase diagram, 2–3
 isopleths, 202–203
 isothermal stability diagrams
 alloy system and a gas, 236–237
 one metal and two gases, 235–236
 overview, 235
 predominance area diagrams, 237–238

J

Johnson-Mehl-Avrami equation, 155–156
 Joule, James, 42

K

Kellogg diagrams, 235–236
 kinetics, 28–30
 kink band formation, 423
 Konovalov, Dmitry, 260
 Kurdjumov-Sachs relation, 154, 160

L

Lagrangian multipliers, 268
 laths, 313, 317, 319, 329
 lattice invariant deformation, 312–313, 321
 lattice parameter method, 247–248
 Laue method, 392
 Laves phases, 26–27
 Law of Conservation of Energy, 42
 lead
 aluminum alloys, 299
 diffraction pattern, 393–394
 electric motor housings, 297–298
 intermediate phases, 171–172
 machinability, 420
 monotectic alloy systems, 135–136, 139–140
 leaded alloys, 136
 lead-tin eutectic system, 94–96
 lead-tin solder alloys, 90, 94–95
 lever rule
 aluminum-silicon eutectic system, 92
 introduction, 8–11
 phases, predicting amounts of, 80–81
 limit of liquid immiscibility, 135
 line defects, 397–400
 line dislocations, 408
 liquid lead, 135
 liquid state
 fcc structure, 429
 hcp structure, 429
 overview, 429–430
 X-ray diffraction, 429–430
 liquid-solid phase transformations, 30–33
 liquidus (definition), 75
 locally constitutionally supercooled, 433
 long-range order, 371
 low SFE, 425
 low-angle grain boundaries, 411
 low-carbon steels, 327, 415
 low-dome alloys, 137, 138
 lower bainite, 330–333
 lower bainite with midrib, 332–333

M

macroscopic deformation, 320–321, 322
 macroscopic slip, 407
 macrosegregation, 437
 magnesium, 16–19, 25, 42, 254
 magnesium alloys, 339
 magnetic analysis, 244, 252–253
 martensite
 as-quenched martensite, 309
 austempering, 326
 to austenite, 283–285
 deformation of, 312
 ferrite-carbide bainites, 334–335

formation of, 307–308
 industrial applications, 283–285
 lower bainite, 331
 nonferrous martensite, 320–323
 phase diagrams, 300–301
 SMA, 324
 in steels, 308–316
 tempered, 310
 tempering in steels, 316–320
 thermoelastic martensite, 324
 upper bainite, 328
 martensite-in steels
 carbon content, 315–316
 formation of, 310–313
 morphology of, 313–314
 nonequilibrium cooling, 307–308
 overview, 308–310
 retained austenite, 314–315
 tempering, 316–320
 martensitic reaction (definition), 309
 martensitic transformation
 in metallic systems-grouped, 323
 nonequilibrium cooling, 307–308
 steels, 33
 Massalski, Thaddeus, 257
 massive transformation, 38
 mechanical twinning, 420, 421
 medium-carbon steels, 164
 metallic bonding, 366–368
 metallic structure
 bonding-in solids, 365–370
 crystalline imperfections, 394–400
 crystalline structure, 371–377
 crystalline system calculations, 377–384
 crystallographic directions, 389–391
 crystallographic planes, 386–389
 metal (definition), 363
 metallic bond (definition), 363
 metalloids, 363
 nonmetals, 363
 periodic table, 363–365
 plastic deformation, 401–409
 semimetals, 363
 slip systems, 384–386
 surface or planar defects, 409–425
 volume defects, 425
 X-ray diffraction-determining crystalline structure, 391–393
 metallography
 equilibrated alloys, 244
 high-temperature (hot-stage) metallography, 249
 nonequilibrium cooling-TTT diagrams, 303, 304
 optical, 245
 quantitative, 245
 unetched and etched samples, 412
 metastability, 5

metastable equilibria, 5
 metastable equilibrium states, 44
 metastable phase diagrams, 5
 Mg_2Sn , 25, 100
 microcracks, 314, 425
 microsegregation, 437–438, 439
 military mode, 308
 Miller indices—cubic systems, 386–388
 Miller-Bravais indices—hexagonal crystal systems, 388
 Miller-Bravais system for hexagonal crystal structures, 389–391
 mixing, free energy of, 52
 molar free energy, 53, 56–57, 62, 65, 66
 molybdenum
 eutectic morphologies, 97
 ferrite strengtheners, 147–148
 iron-molybdenum alloy, 187
 martensite in steels, 319
 multicomponent systems, 131–132
 nickel-base superalloys, 275, 276, 358–359
 spinodal structures, 187
 titanium alloys, 277–278, 281
 monotectic alloy systems
 high-dome alloys, 136–137, 140
 low-dome alloys, 137, 138
 overview, 135–136
 solidification structures, 136–142
 terminology, 135, 136
 monotectoid transformation, 144
 monovariant equilibrium, 19
 MTDATA, 268
 mushy zone, 76, 444

N

National Institute of Standards and Technology, 11
 natural aging, 343, 352
 Nernst, Walter, 43
 neutron diffraction, 246, 247
 Newton-Raphson method, 268
 Nichrome heating elements, 297
 nickel-base superalloys
 CALPHAD, 269, 285
 computer simulation, 274–277, 279
 homogenous nucleation, 346
 industrial applications, 271, 274–277, 279
 precipitation hardening, 339, 344, 345, 346, 358–360
 Nitinol (50Ti-50Ni), 324
 nitrogen
 alloying element in steel, 24
 ferrite, 147
 industrial applications, 271, 277, 279, 280
 interstitial compounds, 26
 interstitial solid solutions, 23

iron-base alloys, 130
 phase equilibria, calculation of, 268
 point defects, 396
 quenching media, 245
 solid solutions, 21
 nonequilibrium cooling
 isomorphous alloy systems, 85
 TTT diagrams, 303–308
 nonequilibrium cooling–TTT diagrams, 303–308
 non-equilibrium freezing, 121
 nonequilibrium reactions
 bainitic structures, 325–336
 martensite in steels, 303–308
 martensite in steels, tempering of, 316–320
 nonequilibrium cooling–TTT diagrams, 303–308
 nonferrous martensite, 320–323
 precipitation hardening (*see* precipitation hardening (PH))
 shape memory alloys, 323–324
 nonferrous martensite, 320–323
 nucleation
 precipitation hardening, 346–348
 solid solutions, 31
 solid-state phase transformations, 33, 34

O

Okamoto, Hiroaki, 257
On the Equilibrium of Heterogeneous Substances (Gibbs), 43
 open system, 2
 optical metallography, 245
 optical microscopy (OM), 246, 256
 order-disorder transformations
 antiphase boundaries (APBs), 174–175
 B2 superlattice (FeAl structure), 177–178, 179
 D0₃ superlattice (Fe₃Al structure), 179–180
 dislocation-generated antiphase boundaries, 180–181
 L1₀ superlattice (CuAu I structure), 176
 L1₂ superlattice (Cu₃Au structure), 177, 178
 long-range order, 175–176
 overview, 174
 short-range order, 175–176
 ordering, 176
 Ostwald ripening, 124, 345, 349
 overaged, 343, 354, 356

P

packing factors, 375, 384
 PANDAT, 267, 268, 272
 PanFe database, 283

- PanNi database, 276
- PanTi database, 280, 281
- particle bowing (looping), 340, 341, 343
- particle cutting, 343, 345
- particle hardening, 340–342
- particles
 - deformable, 340
 - nondeformable, 340–341
- partitioning, 165, 166, 276, 327, 333, 437
- peak intensity method, 247
- pearlite
 - eutectoid structures, 150–152
 - fine versus coarse, 162
 - tensile strength, effect on, 160, 162
 - TTT diagrams, 305–306
- pearlite colony, 150–157, 160
- pearlite nodule, 152, 153
- periodic crystalline order, 364
- periodic table, 363–365
- peritectic (definition), 117–118
- peritectic alloy systems
 - equilibrium freezing, 119–121
 - iron-base alloys, 130–131
 - multicomponent systems, 131–133
 - non-equilibrium freezing, 121
 - overview, 117–119
 - peritectic formation (*see* peritectic formation, mechanisms of)
- peritectic cascades, 127–130
- peritectic formation, mechanisms of
 - direct precipitation of β from the melt, 121
 - nucleation-controlled peritectic structures, 123–124
 - overview, 121–123
 - peritectic cascades, 128–130
 - peritectic reactions, 121, 122, 124–126
 - peritectic transformations, 121, 122, 126–127
- peritectic transformation (definition), 121
- peritectoid (definition), 118
- peritectoid (use of term), 166
- peritectoid transformation, 128–129, 143, 166
- permanent magnets, 293
- phase
 - definition of, 1
 - use of term, 15
- phase boundaries, 417–420
 - coherent phase boundary, 417–418
 - incoherent interface, 152–153, 155, 343, 348, 349, 418
 - semicoherent interface, 152, 153, 343, 348, 418
- phase diagram construction errors
 - congruent transformations, 260–262
 - phase-boundary curvatures, 259–260
 - phase-rule violations, 257–259
- phase diagram determination
 - atmospheric contamination, 240
 - construction errors (*see* phase diagram construction errors)
 - cooling curves, 241–243
 - diffusion couples, 253–256
 - equilibrated alloys (*see* equilibrated alloys)
 - overview, 239–241
- phase diagrams
 - alloy constitution and physical properties, 11
 - binary systems, 2–4
 - Clausius-Clapeyron equation, 8
 - composition scale, 4
 - equilibrium, 4–5
 - introduction, 1–12
 - lever rule, 8–11
 - phase rule, 5–6
 - resources, 11
 - temperature scale, 4
 - theorem of Le Chtâtelier, 6–8
 - unary systems, 2
- phase equilibria, calculation of, 267–268
- phase rule, 5–6
 - one-component diagram for, 18–19
 - ternary isomorphous systems, 203–206
- phase rule violations, 257–259
- phase transformations
 - liquid-solid phase transformations, 30–33
 - solid-state phase transformations, 33–36
- phase-boundary curvatures, 259–260
- planar defects, 394, 409–425
- Planck, Max, 43
- plastic deformation
 - definition of, 401
 - dislocations and plastic flow, 403–408, 409
 - overview, 401–403
 - work hardening, 408–409
- point defects, 394–397
- point model, 378
- polymorphic, 37
- polymorphism (allotropy), 1, 36–38. *See also* allotropy
- porosity, 440–443. *See also* volume defects
 - gas porosity, 442, 444
 - shrinkage, 443–444
- powder metallurgy, 240, 244, 425
- power-compensation DSC, 250
- precipitate-free zones (PFZs), 356–358
- precipitation hardening (PH)
 - aluminum alloys, 352–358
 - coarsening, 346, 349
 - common systems, 346
 - growth, 346, 349
 - nickel-base superalloys, 358–360
 - nucleation, 346–348
 - overview, 339
 - particle hardening, 340–342
 - precipitation sequences, 349–352
 - stainless steels, 339
 - theory of, 342–346

precipitation hardening (PH) (continued)
 three-step process, 339–340
 uses of, 339
 precipitation transformations, 36, 112
 predominance area diagrams, 235, 237–238
 proeutectoid ferrite, 158–159, 160, 325
 pure metal
 aluminum, 92
 binary isomorphous systems, 76
 columnar zone, 435
 copper, 79
 dendrites, 432
 DTA signal versus temperature, 249, 250, 251
 freezing curve, 242
 hacksaw blades, 296
 intermediate phases, 171
 lever rule, 8
 one-component (unary) systems, 45
 phase rule, 6
 phases of, 1
 pressure-temperature diagram, 2, 7
 solid solutions, 19–20
 solidification structures, 433
 unary systems, 15
 undercooling, 430
 purple plague, 299–300

Q

quantitative metallography, 245
 quasi-chemical approach, 58
 quasi-chemical model, 58
 quenching
 aluminum alloys, 352–353, 356
 austempering, 326–327
 copper, 353
 equilibrated alloys, 244, 245
 Fe-Cr-Ni system, 227
 martensitic structure, 316
 nonequilibrium cooling–TTT diagrams, 303, 304
 PFZ widths, 357
 precipitation hardening, 352
 solid-state diffusion couples, 254
 upper bainite, 328
 vacancies, 348, 356

R

randomness (ω), 54
 Raoult's law, 63
 reaction layers, 223
 real solutions
 heterogeneous systems, equilibrium in, 65–67

 overview, 64
 phase diagrams, 67–72
refroidissement, 38
 regular solutions, 60
 repulsion force, 365
 retained austenite, 314–315
 austenite to martensite, 284
 in bainite, 330, 331
 eutectoid plain carbon steel, 316
 hacksaw blades, 296
 iron-carbon martensite, 317
 low-carbon steels, 327
 martensite in steels, 310
 martensitic transformation, 308, 309
 reversion, 345, 349
 Richards, Theodore, 43
 Richard's rule, 51
 rotating single-crystal method, 392
 Rutherford backscattering spectrometry (RBS), 254

S

satellites or sidebands, 185
 scanning electron microscopy (SEM), 246, 256
 Schmid factor, 403
 Schmid's law, 403
 Schottky mechanism, 395, 396
 Schottky partials, 423–424
 screw dislocation, 398–399, 408
 second law of thermodynamics, 10–11
 secondary (or van der Waals) bonding, 370
 secondary dendrite arm spacing (SDAS), 440, 441
 secondary ion mass spectrometry (SIMS), 254
 secondary solid solutions, 25
 segregation
 definition of, 436
 gravity, 437
 inverse, 439–440
 macrosegregation, 437
 microsegregation, 437–438, 439
 normal, 437, 438
 overview, 436–437
 semicoherent interface, 348
 sessile dislocation, 407–408
 shape memory alloys (SMA), 323–324
 shear stress, 401–402
 short-range order, 371
 shrinkage, 443–444
 liquid, 443
 shrinkage porosity, 443–444
 solid, 443, 444
 solidification, 443
 sidebands or satellites, 185
 Sievert's law, 442
 single-phase boundary (SPB) line, 194–195

- sliding (slip) (definition), 384
- slip. *See also* plastic deformation; slip systems
 - ionic bonding, 368
 - kink band formation, 423
 - martensite plates, 322
 - mechanical twinning, 421
 - polycrystalline metals, 414–415
 - precipitation hardening, 340
 - twinning, differences between, 421–422
 - work hardening, 408
- slip direction, 404, 405
- slip planes, 402–403, 404–405, 414–415
- slip systems, 384–386, 404–407
- small-angle grain boundaries, 411
- softening, 307, 319, 343
- SOLGAS, 268
- SOLGASMIX, 268
- solid solutions
 - free energy and phase transformations, 27–28
 - intermediate phases, 25–27
 - interstitial solutions, 23–24
 - kinetics, 28–30
 - liquid-solid phase transformations, 30–33
 - overview, 15
 - polymorphism (allotropy), 36–38
 - solid solutions, 19–23
 - solid-state phase transformations, 33–36
 - substitutional, 24–25
 - unary systems, 15–19
- solidification
 - liquid state, 429–430
 - overview, 429
 - segregation, 436–440
 - solidification interfaces, 430–433
 - solidification structures, 433–436
 - wrought products, 429
- solidification interfaces
 - constitutional supercooling, 432–433
 - overview, 430
 - thermal supercooling, 430–432, 433
- solidification rate
 - dendrite formation, 440
 - dendrite size, 440, 441
 - eutectic microstructure, 104–105
 - eutectic solidification, 103, 108, 109
 - grain size, 440
 - liquid-solid phase transformations, 31
 - multicomponent systems, 131
 - SDAS, 440, 441
- solidification structures
 - center-equiaxed zone, 435–436
 - chill zone, 434
 - columnar zone, 435
 - overview, 433–434, 436
- solid-solution alloys, 206–207
- solid-solution strengthening, 20, 23, 276
- solid-state electronics, 299–300
- solid-state invariant reactions, 143
- solid-state invariant transformations, 143
- solid-state phase transformations
 - diffusion, 33, 34
 - growth, 33, 34
 - nucleation, 33, 34
 - rate of transformation, 35
 - transformation, time required for, 35
- solid-state transformations
 - eutectoid transformation, 143
 - iron-carbon eutectoid reaction (*see* iron-carbon eutectoid reaction)
 - monotectoid transformation, 144
 - overview, 143–144
 - peritectoid structures, 166–169
 - peritectoid transformation, 143–144
- solubility
 - binary isomorphous systems, 77, 78, 82
 - carbon in iron, 146
 - copper-zinc phase diagram, 171, 173
 - electric motor housings, 299
 - eutectic alloy systems, 89
 - eutectic solidification, 102
 - ferrite, 146–147
 - hydrogen in liquid metals, 442
 - intermetallic compounds, 25
 - interstitial compounds, 26
 - lattice parameter method, 247
 - liquid state, 367
 - metallographic method, 246
 - Ostwald ripening, 349
 - peritectic transformations, 126
 - phase boundaries, 417
 - phase diagram applications, 292
 - phase diagram construction errors, 257
 - solid solutions, 20
 - spinodal decomposition, 182
 - substitutional solid solutions, 24–25
 - ternary four-phase equilibrium ($L \rightarrow \alpha + \beta + \gamma$), 218
 - thermodynamic modeling, 264
 - XRD, 248
- solute atoms
 - aging process, 343
 - as alloying elements, 396
 - coarsening, 345, 349
 - equilibrium phase, 344
 - as impurities, 396
 - interstitial solid solutions, 20–21, 313
 - point defects, 396
 - precipitation hardening aluminum alloys, 352
 - solid-solution hardening, 21
 - substitutional solid solutions, 20–21
- solute drag, 165–166, 333
- solution heat treating, 289, 342, 352, 353, 356, 359
- space lattices, 371

space model (ternary systems)
 isopleth plots, 194
 isothermal plots, 193
 liquidus plots, 193
 overview, 191–193
 single-phase boundary line, 194–195
 zero-phase fraction line, 194–196
 specific heat, 45–46
 spheroidal graphite cast iron, 98, 99
 spinodal decomposition, 181–185, 187, 350
 spinodal transformation structures
 microstructure, 185–188
 overview, 181–182
 spinal decomposition, theory of, 182–185
 stable equilibrium state, 44
 stacking fault energy (SFE), 425
 stacking faults, 423–425
 fcc structure, 423
 stacking fault energy, 425
 stainless steels
 austenitic stainless steel, 293
 Fe-Cr-Ni system, 229
 peritectic reactions, 131
 precipitation hardening, 339
 state (use of term), 15
 steels. *See also* individual steels
 alloying elements, 24
 CALPHAD, 269
 cementite, 146, 159–160
 ferrite-pearlite steels, 163–164
 hypereutectoid, 160
 martensite in (*see* martensite-in steels)
 martensitic transformation, 33
 pearlitic, 157–158
 Stirling's approximation, 55, 60
 strain hardening, 409
 subcrystals, 411
 subgrains, 411
 substitutional defects, 396
 substitutional solid solutions, 20, 24–25
 superalloys (definition), 358
 superlattice (definition), 174
 superlattice dislocations, 181
 surface or planar defects
 grain boundaries, 410–414
 overview, 409–410
 phase boundaries, 417–420
 polycrystalline metals, 414–417
 stacking faults, 423–425
 twinning, 420–423
 volume defects, 425

T

Taylor factor, 403
 temperature hysteresis of allotropic phase transformation, 38

temperature scale, 4
 temperature-composition (T-X-Y) diagram, 200
 tempering
 as-quenched martensite, 310
 austempering, 327
 bainitic steels, 334
 martensite-in steels, 316–320
 nonequilibrium cooling–TTT diagrams, 307
 terminal solid solutions
 cellular or discontinuous precipitation, 112–114
 general or continuous precipitation, 110, 111
 overview, 108–110
 Widmanstätten morphology, 111–112
 ternary four-phase equilibrium ($L + \alpha + \beta \rightarrow \gamma$), 224–227
 ternary four-phase equilibrium ($L + \alpha \rightarrow \beta + \gamma$), 218–223
 ternary isomorphous systems
 equilibrium freezing (solid-solution alloys), 206–207
 isothermal sections, 200–201
 liquidus plots, 201–202
 overview, 200
 phase rule, application of, 203–206
 solidus plots, 202
 tie triangles, 208–210
 vertical sections (isopleths), 202–203
 ternary phase diagrams
 alloy, equilibrium freezing of, 212–214
 eutectic system with three-phase equilibrium, 210–214
 example: Fe-Cr-Ni system, 227–229
 Gibbs triangle, 196–198
 overview, 191
 peritectic system with three-phase equilibrium, 214–216
 space model (*see* space model (ternary systems))
 ternary four-phase equilibrium, 217–218
 ternary four-phase equilibrium ($L + \alpha + \beta \rightarrow \gamma$), 224–227
 ternary four-phase equilibrium ($L + \alpha \rightarrow \beta + \gamma$), 218–223
 ternary isomorphous systems (*see* ternary isomorphous systems)
 ternary three-phase phase diagrams, 207–210
 tie lines, 198–199
 ternary three-phase phase diagrams, 207–210
 tervariant, 205
 tetrakaidecahedron, 413
 theorem of Le Châtelier, 6–8
 thermal analysis (TA), 244, 249–250
 thermal supercooling, 430–432, 433
 thermal vibrations, 394
 Thermo-Calc, 267, 268

thermodynamic modeling
 dilute solution models, 265
 ideal solution model, 265
 non-ideal solutions, 265–266
 overview, 264
 regular solution model, 265
 sublattice model, 265–266
 subregular solution model, 265
thermodynamically stable state, 30
thermodynamics
 activity, 62–63
 binary solutions, 51–56
 chemical potential, 56–58
 Gibbs free energy, 43–51
 laws (*see* thermodynamics, laws of)
 overview, 41
 real solutions, 64–72
 regular solutions, 58–62
thermodynamics, laws of
 first law, 42
 overview, 41–42
 second law, 42–43
 third law, 43
Thomson, William (Lord Kelvin), 42
TiAl-base alloys, 269
tie lines, 198–199
tie triangles, 208–210
time-temperature cooling curves, 76
time-temperature-transformation (TTT)
 diagram
 eutectoid structures, 156
 nonequilibrium cooling, 303–308
tin cry, 421
titanium alloys
 CALPHAD, 269
 computer simulation, 277–282
 industrial applications, 271, 272–282
tool steels, 26, 284
topologically close-packed (tcp) phases, 271,
 276–277, 286–287
transgranular, 414
transition phases, 350–351
transmission electron microscopy (TEM)
 antiphase boundaries, 175
 nonferrous martensite, 322
 phase diagram determination, 246
 precipitation sequences, 352
 spinodal structures, 185–186
true equilibrium, 11
twin boundaries, 422–423
twinning, 420–423
 annealing twins, 421
 mechanical twinning, 420, 421
 twin boundaries, 422–423
 twins, 420–421
twins, 420–421
two-dimensional (2-D), 194
two-way shape memory, 324

U

ultrasonic agitation, 33
unary systems
 introduction, 2
 solid solutions, 15–19
underaging, 343
undercooling
 constitutional supercooling, 432–433
 coupled zone of eutectics, 108
 dendritic growth, 430–431
 irregular eutectic growth, 106
 liquid-solid phase transformations, 30–33
 martensitic transformation, 309
 monotectics, 139–140
 nucleation-controlled peritectic structures,
 123–124
 pearlite, 306
 peritectic reactions, 122, 125
 precipitation sequences, 350
 regular eutectic growth, 104
 solidification interfaces, 430
 solid-state reactions, 144
 spinodal transformation, 183
 thermal supercooling, 430–432, 433
 TTT diagram, 156
 Widmanstätten structures, 111
univariant equilibrium, 19, 217, 220
upper bainite, 328–330, 331
uranium-silicon alloys, 166–169
U.S. Bureau of Standards, 292

V

vacancies
 climb, 406
 formation of, 407
 grain boundaries, 412
 Guinier-Preston zones, 355–356
 liquid metals, 429–430
 nucleation of precipitates, 348
 point defects, 394–395
vacancy diffusion, 395, 408
vacuum degassing, 442
valence, of a metal, 25–26
valence electrons, 366–369, 402
van der Waals bonding, 370
vertical sections (isopleths), 202–203
volume defects, 394, 425
volume free energy, 32, 347
von Helmholtz, Hermann, 42
von Mayer, Julius, 42

W

wavelength dispersive spectrometers (WDS),
 246, 254

- welding, 164, 291, 296
- white cast iron, 101
- Widmanstätten morphology, 111–112
- Widmanstätten plates, 159
- work hardening, 408–409
- wrought precipitation-strengthened nickel-base superalloys, 359–360
- wrought products
 - porosity, 440
 - segregation, 440
 - solidification process, 429

X

- X-ray diffraction (XRD), 244, 245, 246–248, 249, 391–393, 429–430

Z

- zero-phase fraction (ZPF) line, 194–196