

## Index

### **a**

- acoustic softening 244, 252–255
- additive friction stir deposition 7, 10, 135, 380, 381
  - AA2024 tracer distribution after 147–148
- additional zones 137
- feed-rod plunge stage 138
- heat generation mechanisms 142–143
- heating and cooling mechanisms 142
- industrial applications
  - large-scale metal additive manufacturing 209–211
  - recycling and upcycling 214–220
  - selective area cladding 211–214
  - structural repair 220–224
  - underwater deposition 224–227
- macroscopic process overview 136–139
- material flow and deformation 146–149
- microstructure evolution 154–155
  - dynamic 155–162
- microstructures 153–177
- peak temperature and material dependence 143–146
- processing stages of 138
- thermomechanical processing
  - evolution 139–142
- thermomechanical processing history 135
  - tool 136
  - tool-plunge stage 138
- additive friction stir deposits 181, 184
  - aluminum-based alloys 189–197
    - 2xxx series 192–193
    - 5xxx series 190–192
    - 6xxx series 193–194
    - 7xxx series 195–197
  - cast Al alloys 197
  - copper-based alloys 198
  - high entropy alloys 199–200
  - magnesium-based alloys 184–189
    - AZ31 187–189
    - WE43 184–187
  - metal matrix composites 200
  - nickel-based alloys 197–198
  - steel alloys 199
  - structural repair 200
  - thermomechanical processing 183
  - titanium-based alloys 198–199
- additive manufacturing (AM) 361, 365, 369
  - advantage 361, 362
  - binder jetting 369–371
  - building and consolidation stages 12–14
  - vs. formative manufacturing 362
  - sintering 369
  - vs. subtractive manufacturing 361
- adhesive-free interfacial bonding strength
  - characterization 79
- adhesive-free test methods 79, 92

- adhesive strength, cold sprayed deposits
    - adhesive strength test methods 77–80
    - effect of pre/post-treatment on 80–83
    - effect of process parameters on 80
  - adiabatic plastic deformation heating
    - model 235
  - adiabatic shear instability 23, 36–40, 42
  - age hardenable alloys 189
  - Al<sub>2</sub>Cu intermetallics 58
  - alloying 8, 156, 182, 197, 226, 366, 368
  - Al 2219 mechanical properties 192
  - Al 5083 mechanical properties 190
  - Al upcycling 216–217
  - anisotropic crack propagation behavior
    - 91
  - Apollonian packing 321
  - artificial intelligence
    - approach 379, 382, 383
    - for quality control and process
      - prediction 381–383
  - asperity deformation 15, 243–247, 254
  - AZ31 magnesium-based alloys 187–189
- b**
- Bayesian learning 383
  - binder jetting (BJT) process 9, 12, 314, 339, 340, 369–371, 373, 380
    - advantages 340
    - drawback 341
    - feedstock materials 342–343
    - feedstock morphology and size
      - distribution 343–344
    - future developments 350
    - magnetic properties of 373, 374
    - non-spherical particle usage 351
    - printing phase of 341
      - binder selection 344–345
      - particulate feedstock 341–344
      - powder spreading and binder
        - deposition system configurations 345–346
    - thermal treatment
      - curing 346–347
      - debinding/binder burnout 347–348
      - hot isostatic pressing 350
      - infiltration 349
      - sintering 348–349
  - binder saturation 346
  - Body Center Cubic (BCC) refractory
    - metals 112
    - niobium 114
    - tantalum 112–113
  - bonded conventional magnetic
    - manufacturing process 365, 367
  - bulk transport 306
- c**
- carbon nanotube (CNT) reinforced MMC
    - 119
  - cast Al alloys 197, 218
  - catalytic debinding process 315
  - ceramic-reinforced MMCs 166, 173
  - chemical debinding 315
  - cladding reinforcement 211
  - Coble creep 306
  - CoCrFeMnNi HEA coatings 121
  - coefficient of thermal expansion (CTE)
    - 282, 284, 285
  - cohesive strength, cold sprayed deposits
    - anisotropy in 90–91
    - under fatigue loading 86, 90
    - under static loading 84–85
    - test methods 84
  - cold gas dynamic manufacturing (CGDM)
    - 121
  - cold spray 6, 104, 380, 381
    - with accumulative roll bonding (ARB)
      - 121
    - Al and Al alloys 108–109
    - BCC refractory metals 112–114
      - niobium 114
      - tantalum 112–113
    - bonding mechanisms in 32–42
    - Cu coatings 104–107
      - for nuclear fuel storage 104–107
    - Cu-Ga based alloys 107
    - Cu-In-Ga based alloys 107
    - Cu-Sn alloys 107
    - Cu-W composites 107–108
  - deposits 75

- HCP metals
    - magnesium 116
    - titanium 114–116
  - high entropy alloy coatings 120–121
  - hypothetical collision angle vs. collision velocity scenarios 32
  - jetting 39
  - MCrAlY multicomponent alloy
    - coatings 120
  - metal matrix composites 117–119
  - metal mixes 117
  - multi-materials 121–122
  - Ni and Ni alloys 110–111
  - perspective and challenges 122–124
  - process 10, 11, 21
  - pure copper 104, 107
  - ratio 40
  - stainless steels 111–112
  - system setup 101, 102
  - cold spray additive manufacturing (CSAM) 77, 103, 113
    - advantages 103
    - disadvantages 103
  - cold sprayed Al-Cu coating 51
  - cold sprayed deposits 77
    - adhesive strength
      - effect of pre/post-treatment on 80–83
      - effect of process parameters on 80
      - test methods 77–80
    - cohesive strength 83–91
      - anisotropy in 90–91
      - under fatigue loading 86–90
      - under static loading 84–85
      - test methods 84
  - cold sprayed materials
    - applications 102
    - defect structures 50–61
      - dislocations 52–55
      - grain structure 55–56
      - porosity 60–61
      - precipitate structure 56–59
      - vacancies 51–52
    - microstructure 49
  - collar-pin pull-off test 78, 79
  - computer numerical control (CNC)
    - system 6, 11, 233, 259, 273, 279, 283, 286, 287, 297
    - milling 279
  - consolidation, sintering process 309
  - contact mechanics 244, 247
  - continuous dynamic recrystallization (CDRX) 157–159, 219, 225
  - Convolutional Multiple Whole Profile (CMWP) technique 53
  - coordination number 299–300
  - copper-based alloys 198
  - core loss 368, 369
  - critical bonding velocity 34, 38, 40, 42
  - critical materials 363, 364, 366, 372
  - critical velocity 22, 33, 38, 42, 76, 110, 114, 117, 123
  - CuNi antibacterial applications 106
  - Curie temperature ( $T_c$ ) 363, 371
  - curing 77, 92, 299, 340, 342, 344–347, 370, 371, 373
  - Cu-TiO<sub>2</sub> antibacterial coating 105
  - cyclic strain ratcheting 253–254
- d**
- data-driven approach 379, 382, 383
  - debinding steps 313
  - debinding types 315
  - debinding/binder burnout 347–348
  - Deep Reinforcement Learning (DRL)
    - framework 382
  - deformation-based additive manufacturing 381
  - deformation-based additive process 11, 379, 381
  - deformation-based metal additive manufacturing 9–11
  - deformation-dominated material transport 170
  - deformation history of material voxel 379, 380
  - densification process 301, 307, 348, 349, 369
  - depowdering step 347

- diamond-reinforced metal matrix (DMMC) coatings 118
  - diffusional bonding process 246–247
  - diffusion-based recrystallization, of cold sprayed materials 55, 62
  - dihedral angle 300–301, 303
  - discontinuous dynamic recrystallization 159–160, 199
  - dislocation glide 155–157, 162
  - dislocation mobility 155–157, 159, 164, 166
  - dislocation structure 52–55, 67, 155, 160, 189, 248
    - in cold sprayed materials 52–55, 67
  - dissimilar material joining with UAM
    - Al 6061-ceramic welding 262, 266
    - Ni-steel weld 263–266
  - dissimilar materials impact 23, 40–41
  - double cantilever beam (DCB) test 77, 78
  - double-notch shear test 267, 268
  - dynamic discontinuous recrystallization (DDR<sub>X</sub>) 160
  - dynamic microstructure evolution, in multiple phase materials 162
    - secondary phase evolution
      - after deformation 168
      - at high temperatures 166–167
      - at low temperatures 164–166
      - mapping to processing space 168–170
    - thermal evolution during additive friction stir deposition 162–164
  - dynamic microstructure evolution, in single phase materials 155
    - continuous dynamic recrystallization 157–159
    - discontinuous dynamic recrystallization 159–160
    - dislocation mobility 155–157
    - dynamic recovery 157
    - heterogeneous deposits 161–162
    - metadynamic recrystallization 161–162
    - stacking fault energy 155–157
    - static and post-dynamic recrystallization 160–161
- e**
- e-beam melting (EBM) 3–5, 7, 12
  - eddy current loss 368, 373
  - electrification 11, 15, 282–285
  - electron backscatter diffraction (EBSD) 58, 59, 62, 64, 65, 160, 174, 175, 195, 214, 225, 259–263, 275
  - embedded electronics 11, 15, 282, 288–292
  - energy product ((BH)<sub>max</sub>) 363, 373
  - evaporation/condensation 307
  - explosive welding 25, 30
    - arrangement 25
    - geometry 25
    - limiting conditions for 24–30
    - plate impacts and 23–30
- f**
- fatigue
    - AA7075 deposits 196
    - AA6061-T651 feedstock 194
    - Al 5083 alloys 191
    - AZ31 magnesium-based alloys 187–189
    - Ni-based alloys 198
    - performance
      - of cold spray coatings 86–88
      - of cold spray repaired specimens/components 88–90
      - of CSAM parts 90
      - WE43 magnesium based alloys 186
  - feedstock powders, heat treatment of 66–67
  - Fe-Si soft magnets 371
  - FFF technique 326
  - finite element (FE)
    - model 268
    - modeling, of shear test 270–273
  - fluid mechanics approach 147
  - formative manufacturing 361, 362

frictional heating 15, 135, 136, 140, 142, 148, 235, 236, 238, 243, 244, 247, 254  
 friction coefficient 107, 140, 238, 240  
 friction stir additive manufacturing (FSAM) 141, 186, 187, 199  
 friction stir consolidation 215  
 friction stir extrusion 215  
 fused deposition modeling (FDM) 6, 12  
 fused filament fabrication (FFF) technique 6, 313, 325–327  
 fusion-based additive manufacturing 3, 4, 7, 210, 221, 247, 254, 283, 382  
 fusion-based cladding routes 211

## g

gas atomized powder particle microstructure 50  
 gas diffusion 307  
 geometric dynamic recrystallization (GDRX) 158, 159  
 grain boundary diffusion 306, 309  
 grain boundary solute segregation, in cold sprayed materials 64  
 grain boundary strengthening 183, 184, 190, 267, 275  
 grain growth, in cold sprayed materials 64  
 grain orientation spread (GOS) maps 62  
 grain structure, in cold sprayed materials 55–56, 62, 67  
 green density 297–299, 301, 309, 341, 343, 344

## h

Hall–Petch equation 183  
 hard ferrites 372  
 hard magnets 362, 363, 366, 372, 374  
 hardness  
   for AA7075 deposits 195  
   Al 5083 alloys 191  
   AZ31 magnesium-based alloys 188–189  
   Cu-based alloys 198  
   Ti-based alloys 198–199

WE43 magnesium-based alloys 185–186  
 hardness analysis of UAM 266–267  
 heat-affected zone (HAZ) 138, 182  
 Hertzian contact theory 237  
 hexagonal close-packed (HCP) metals  
   magnesium 116  
   titanium 114–116  
 high entropy alloy (HEA) 21, 56, 120–121, 199–200, 342  
   coatings 120  
 hot isostatic pressing (HIP) 6, 11, 66, 85, 107, 209, 260, 262, 275, 342, 350  
 hysteresis loss 368

## i

impact bonding  
   fundamentals of 23–31  
   laser 30–31  
 impact melting, limiting case of 33–36  
 Inconel 625 197  
   nickel superalloy 111  
 infiltration 108, 299, 339, 341–344, 347, 349, 350, 371, 373, 374  
*in situ* laser heating, of cold sprayed materials 63  
 interdiffusion 15, 111, 216, 241, 246, 247, 249–251, 254  
 Iosipescu test 268

## j

jetting criteria 27  
 Johnson–Cook constitutive law 244

## k

kernel average misorientation (KAM) map 160, 175, 225

## l

large-scale metal additive manufacturing 15, 209–211, 227  
 laser ablation 81  
 laser-assisted cold spray (LACS) 63, 65  
 laser-based surface treatments 81

- laser engineered net shaping (LENS)
    - 3–5, 7, 221
  - laser-heated cold spray (LHCS) 63
  - laser impact bonding 23, 30–31
  - laser impact welding (LIW) 30–32
  - laser shock adhesion test (LASAT) 78,
    - 79, 81, 82
  - lattice/volume diffusion 306
  - layer-by-layer approach 3, 5, 249, 339
  - liquid-phase bonding 247
  - liquid phase sintering 108, 298, 299, 309,
    - 342, 380
  - liquid-state bonding 7–9
  - low-angle grain boundary (LAGB) 157,
    - 158
  - low-pressure cold sprayed-produced
    - CuSn5-Al<sub>2</sub>O<sub>3</sub> coatings 107
- m**
- machine core soft magnet manufacturing
    - process, drawback of 368
  - macroporosity 319, 320, 332, 334
  - magnetic coercivity 362
  - magnetic field strength 362
  - magnetic flux density 362
  - magnetic hysteresis 362, 363
    - curves 363
  - magnetic intensity 362
  - magnetic materials 15, 361–375
    - classification 362
  - magnetic permeability 363
  - magnetic pulse welding (MPW) 26
  - Maron–Pierce description 322, 323
  - mass transport mechanisms 306
    - evaporation/condensation 307
    - gas diffusion 307
    - grain boundary diffusion 306
    - lattice/volume diffusion 306
    - surface diffusion 307
    - viscous flow 306
  - material extrusion additive
    - manufacturing (MEAM) 6,
      - 313–335
    - benefits 316
    - drawbacks 316
  - extrusion control 327–331
  - feedstock attributes 325–327
  - parts and feedstock behavior, hierarchy
    - of 316–325
  - toolpath strength and quality
    - 331–335
  - material extrusion process 4, 6, 12, 15,
    - 146, 313–335, 380, 381
  - MCrAlY multicomponent alloy coatings
    - 120
  - metal additive manufacturing 3
    - history 4–7
    - method 4, 209, 361–375, 379
  - metal injection molding (MIM) 6, 313,
    - 316, 323, 325, 335, 340
  - metallurgical bonding 7, 9, 22, 61, 62,
    - 76, 80, 81, 83, 85, 92, 135, 215, 235,
      - 241, 243, 249, 369
  - metal matrix composites (MMCs) 15,
    - 116–118, 162, 166, 168, 171–173,
      - 200, 254, 255, 286
  - metal recycling 209, 214, 216, 227
  - microporosity 60, 61, 319, 320
  - microstructural evolution 170, 247
    - in additive friction stir deposition
      - 175–177
    - contemporary approaches 175–176
    - novel approaches 177
  - material transport
    - densification 173–174
    - homogenization of mixtures
      - 172–173
    - mechanisms 170–171
    - spatial variance in
      - thermomechanical conditions
        - 174–175
  - multilayered 1060Al/Al-Al<sub>2</sub>O<sub>3</sub> composites
    - 121
- n**
- Nabarro–Herring creep 306
  - NdFeB magnets 372
  - neck growth 301, 302, 307, 308
  - Ni-based superalloy 111
  - nickel-based alloys 197–198

- Ni-steel weld 263, 265  
 non-age hardenable alloys 189  
 nozzle clogging 108, 123
- O**
- oxide breakdown process 241, 243
- P**
- particle adhesion 76  
 particle bonding  
   role of jetting and impact pressure  
     32–33  
 particle impact velocity 32, 76, 113, 123  
 particle size 23, 36, 42, 49, 83, 118, 297,  
   298, 303, 308, 321, 369  
 particle temperature 41–42, 76  
 Peclet number 240, 241  
 permanent magnets (PMs) 362–366,  
   372, 374  
   applications, in electric motors  
     372–374  
 physics-based simulations 382  
 plate impacts and explosive welding  
   23–30  
 porosimetry 324  
 porosity in cold sprayed microstructures  
   60–61  
 portable adhesion test (PAT) 77, 78  
 powder injection molding (PIM) 297  
 powder metallurgy (PM) 9, 14, 49, 297,  
   308, 320, 331, 339, 341  
 precipitate evolution 184, 187  
 precipitate structure of cold sprayed  
   materials 56, 59  
 precipitation strengthened alloys 201  
   active cooling/heating 202  
   anisotropy 201–202  
   graphite lubricant 202  
   multi-material/defined feedstock  
     202  
   post-deposition heat treatment 202  
   process parameters effect on  
     mechanical properties 202  
   tool wear 203  
 precipitation strengthening 183, 184,  
   189, 192–195  
 precipitation, in cold sprayed materials  
   65–66  
 printable material library 381  
 process-structure-property relationship  
   135, 181, 202  
 progressive lattice rotation (PGL) 158,  
   159  
 progressive subgrain misorientation  
   (PRisM) model 55  
 pulsed laser ablation (PLA) 81, 326  
 push pin testing method 235, 267
- Q**
- quality control methods 321
- R**
- Rankine–Hugoniot relations 23  
 rapid solidification process 51  
 rare earth (RE) magnets 364  
 recurrent neural network (RNN) 382  
 recycling, of AA5083 chips 216  
 relative density, of powder compact  
   299  
 remanence 362, 363, 371, 373  
 resin coated isotropic NdFeB powder, BJT  
   printing and curing of 370  
 rod-style extruder 330
- S**
- saturation magnetization 363, 372–374  
 selective area cladding 11, 209, 211–214,  
   227  
 SensePipe 291–292  
 severe plastic deformation (SPD) process  
   155, 182, 183  
   AA7075 195  
   AZ31 189  
 shear test 267, 268  
   application to UAM samples 273–275  
   custom method design 268  
   finite element modeling 270–273  
   validation 268–270  
 Shockley partial dislocations 56

- shock loading and unloading 24
  - shrinkage 8, 12, 159, 301–304, 306–308, 310, 321, 335, 348, 349, 370, 380, 382
  - similar material joining with UAM 260–266
  - sintering 298, 348, 349, 369
    - of BJT silicon steel soft magnet 370
    - process 297
    - simulation 308–309
    - stages 307–308
  - sintering-based additive manufacturing methods 381
  - sintering-based metal additive manufacturing 11–12, 15, 361–375
  - sintering-based solid-state additive manufacturing 9
  - sintering stress 302, 309
    - driving force 303–304
    - interfacial activity/thermodynamics 304–306
    - two particle model 302–303
  - sinter setters/fixtures 352
  - slip systems 114, 116, 155–157, 170
  - SmartPlate 290, 291
  - soft magnetic materials 368, 369, 371
  - soft magnets (SM) 362, 363, 368–372, 375
  - Solidica commercialized innovative system health monitoring applications 281
  - solid-phase hybrid additive manufacturing method 234
  - solid solution strengthening 107, 182, 184, 189, 190, 197, 198
    - WE43 184–187
  - solid-state additive manufacturing 3
    - methods 13–14
    - techniques 380
  - solid-state bonding 7–9, 22, 23, 36, 41, 42
    - driving forces for 22
  - solid-state metal additive manufacturing 3, 4, 6, 9–12, 14, 15, 21, 49, 379, 380, 382, 383
    - future research directions 379
  - solid-state metallic bonding 8, 22
  - sonotrode contact stress 237–238, 251
  - stacking fault energy 155–157, 225, 253
  - static DRX 157, 159, 160, 162, 164, 166
  - steel alloys 199
  - strain hardening 37, 183, 190, 192, 215, 220, 244, 254
  - strengthening mechanisms 182
    - in 2xxx (Al–Cu) series aluminum alloys 192–193
    - in 6xxx (Al–Mg–Si) series aluminum alloys 193–194
    - of Al 5083 190
  - stress-strain response of metals 36
  - structural repair process 220, 224
  - subtractive manufacturing 361, 364
  - surface diffusion 9, 306, 307, 309, 348
  - surface energy 156, 300–302, 304, 307, 348, 369
  - surface oxide and hydroxide effects 42
  - surface restoration
    - and grey cast iron components enhancement 111
    - using cold spray aluminum-based materials 109
  - surface tension 300, 308, 326
  - surface transport 306
- t**
- Taylor–Quinney constant 143
  - temperature-induced debind process 315
  - tensile adhesion test (TAT) 77, 78
  - tensile strength
    - for AA7075 deposits 195
    - Al 5083 alloys 191
    - AZ31 magnesium-based alloys 188, 189
    - high entropy alloys 200
    - Ni-based alloys 197–198
    - steel alloys 199



Ti-based alloys 199  
 WE43 magnesium-based alloys 185, 186  
 thermal conductivity for MEAM feedstocks 325  
 thermal history of material voxel 380  
 thermal management 11, 15, 284–288, 381  
 thermally treated cold sprayed materials  
 microstructural evolution of 61–67  
 feedstock powders, heat treatment of 66–67  
 precipitation 65–66  
 recovery, recrystallization and grain growth 62–65  
 thermomechanically affected zone (TMAZ) 137  
 3D printing 6, 279, 283, 287, 288, 290, 292, 309–310, 352, 361, 380  
 Ti-6Al-4V recycling 216  
 titanium-based alloys 198–199  
 tool protrusions 136, 140, 147, 161, 170  
 torsional shear tests 267  
 Tresca friction model 143  
 triple lug shear test 80  
 tubular coating tensile test (TCT-Test) 84

## u

ultrasonic additive manufacturing (UAM) 6, 11, 233, 381  
 acoustic softening 251–253  
 additive and subtractive stages of 233  
 advantage 282  
 bonding mechanisms in 254  
 coefficient of friction 238–239  
 cyclic strain ratcheting 253–254  
 dissimilar metal consolidation 247  
 dissimilar metal junction growth 248–249  
 interdiffusion 249–251  
 mechanical and thermal modeling 247–248  
 early years 279–281  
 electrification 282–285

embedded electronics 288–292  
 feedstock bonding mechanisms 241  
 asperity deformation 243–246  
 diffusional bonding process 246–247  
 liquid-phase bonding 247  
 oxide breakdown 241–243  
 future applications 292  
 heat generation during welding 235–237  
 of net-shaped components 234  
 process parameters 234–235  
 sonotrode contact stress 237–238  
 temperature profile 239–241  
 hardness analysis of 266–267  
 mechanical characterization of 267–268  
 push pin testing method 267  
 shear tests 267–275  
 Z-tensile test 267  
 microstructure analysis of 259–260  
 dissimilar material joining 262–266  
 similar material joining 260–262  
 modern applications 282  
 solid-state nature of 259  
 thermal management 286–288  
 ultrasonic consolidation 6, 11, 15, 234, 238, 243–246, 250–251, 255, 259, 279–280  
 ultrasonic inspection 177  
 underwater additive friction stir deposition 224–227  
 upcycling 216  
 capability, of additive friction stir deposition 218  
 effect 220

## v

vacuum sintering 298, 310, 366  
 viscous flow 306  
 von Mises yield criteria 147  
 voxel-by-voxel approach 3

**W**

WE43 magnesium-based alloys 184–187

wetting angle 300–301

Williamson–Hall equation 53

wire arc additive manufacturing (WAAM)  
3–7, 221

**Y**

Young–Laplace equation 302, 303, 306

**Z**

Zener–Hollomon parameter 147

Z-tensile tests 267

















