aligocation, 177
aluminum alloys, 300-302
aluminum-killed steels, 295
anisotropy
  crystallographic basis, 207-208, 215-216
  effect on forming limits, 248
  effect on limiting drawing ratio, 223-224
  effect on wrinkling, 258
  strain ratio (R-value), 209
  yield criteria, 209-215
Arrhenius, Svante A., 72
Arrhenius equation, 66
Backofen, W.A., 164, 166, 180, 253
bake hardening, 295, 296, 301-302
Barlat's criteria, 215
barrelling, 38, 191
Bauschinger, Johann, 267
Bauschinger effect, 261
bending, 195-203
  shapes and tubes, 202-203
  sheet, 195-201
  springback, 198-200
boundary conditions, 13-14
brass, 302-303
Bridgman, Percy W., 193
Bridgman correction, 37
bulge test, 38-39, 284-285
bulging in drawing, 144-146
centerline cracking, 175
chevron cracks, 174
coining, 101
compression
  average pressure, 92
  slab analysis, 92
  test, 38
copper, 302-303
cracking. See also fracture
  in rolling, 99, 182
cup drawing, 220-230
  analysis, 220-222
  earing, 228-234
  effect of R-value, 223-224
  effect of tooling, 227
  limiting drawing ratio, 220-222
  wrinkling, 220
dead metal zone, 38
definition of delta, 163
deforination mechanism maps, 69
deforination-zone geometry, 163-180
density changes, 171
deviatoric stress, 18
die angle effect, 80
die design, 262-264
distortion, 137
draw beads, 255
drawing. See also extrusion
  deep (see cup drawing)
  plain strain, 85-87
deltar parameter, 163
inhomogeneity, 166
slip-line field, 142-146

Index
### INDEX

- **upper-bound analysis**, 121
- **wire and rod**
  - delta parameter, 163
- **energy balance**, 77
- **inhomogeneity**, 166
- **maximum reduction**, 79
- **upper bound analysis**, 121
- **dual-phase steels**, 296
- **ductility**
  - definition, 31
  - effect on formability, 182
  - relation to microstructure, 182
- **Duncan friction test**, 285
- **earing**, 228
- **efficiency**
  - definition, 78
  - effect on maximum reduction, 79
- **elasticity**, 10
- **elastic-plastic transition**, 32
- **Erichsen test**, 279
- **extrusion**
  - pipe formation, 147
  - plane-strain
    - slip-line fields, 135–138
    - upper-bounds, 112
  - work balance, 77
- **flanging**, 259
- **flow rules**
  - anisotropic, 210, 213
  - isotropic, 23
- **forging. See compression**
- **formability**
  - bending, 201, 203
  - bulk forming, 182–193
  - bulk tests, 191
  - sheet forming tests, 279–285
- **forming limit diagrams**, 237–253
  - calculation, 244–247
  - changing strain paths, 251
  - experimental, 242
  - stress-based, 134, 253
  - thickness effect, 247–250
  - use, 249
- **forming limits**
  - bending of shapes, 203
  - bending of sheet, 201
  - compression, 191
- **fracture. See also tearing**
  - edge cracking in rolling, 100, 182
  - edge cracking in sheet forming, 259
  - effect of hydrostatic stress, 187
  - effect of inclusions, 182
- **friction. See also lubricants**
  - constant shear stress, 91, 146
  - dry, 102
  - experimental findings, 103
  - mixed conditions, 90
  - sand-pile analogy, 93
  - sticking, 90
  - tests, 105, 285
- **frictional work, effect of deformation-zone geometry**, 164
- **friction hill**
  - in compression, 88
  - in rolling, 94
- **Fukui test**, 279
- **galvanized steels**, 298
- **Gurson’s analysis**, 190
- **Hall, Charles M.**, 306
- **Hérout, Paul-Louis**, 306
- **Hill, Rodney**, 216
- **Hill’s anisotropic analysis**, 209–212
- **hodograph**
  - slip-line field, 134
  - upper-bound, 110
- **hole expansion**, 283
- **Holomon, J. Herbert**, 40, 66–69
- **hot working**, 69, 192
- **HSLA steels**, 295
- **hydraulic bulge test**, 284
- **hydrodynamic lubrication**, 103
- **hydroforming**
  - bent sections, 276
  - square cross sections, 274
  - tubes, 272
  - hydrostatic pressure, 187
- **ideal work**, 76
- **inclusions**, 182–187
- **indentation**
  - slip-line field, 138–141
  - upper-bounds, 116
- **inhomogeneity**
  - effect of, 44, 58–61, 248
  - factor, 166
  - sheet metals, 305
  - instability, 43–48
  - biaxial tension, 45
  - effect of inhomogeneities, 44
  - significance, 48
  - tensile, 43
  - thin-wall sphere, 47
  - internal damage, 171
INDEX

interstitial-free steels, 295
ironing, 231
isotropic elasticity, 10

Keeler, S. P., 253
Keeler–Goodwin diagram, 241
limiting drawing ratio, 220–222
limiting dome height, 281
lubricants, 102
Lüders bands, 289–294

magnesium, 303–305
Marciniak, Zdzislaw, 49
martensitic steels, 297
Mohr, Otto, 14
Mohr's circles for strains, 10
Mohr's circles for stresses, 5

necking
behavior during, 36
localized and diffuse, 237–239
in tension test, 31, 35
normality principle, 25

Olsen test, 279
orange peel, 290
OSU test, 282

pipe, 147
plastic potential, 23
plastic work, 21
porosity, 171
post-uniform elongation, 282
power-law hardening, 34
principal strain, 10
principal stress, 4

redrawing, 230
redundant work
parameter, 164
upperbound, 179
residual stress
bending, 197
bulk forming, 175
cup drawing, 233
ridging (roping), 290
ring friction test, 105
rolling, 93–102
average pressure, 94
cambering, 99
defects, 99
delta parameter, 163
friction hill, 94
minimum thickness, 97

roll bending, 99
roll flattening, 95
roll forming, 270
Rumford, Count, 72
R-value. See anisotropy, strain ratio

Saint Venant, Barré de, 14
Saint Venant's principle, 13
sand-pile analogy, 93
Sendzheimer mill, 97
shearing, 276
sheet metal properties, 289–305
slab analysis, 85–93
axisymmetric compression, 92
flat rolling, 93–95
plane-strain compression, 85–87, 88–92
wire and rod drawing, 128–149

slip-line fields, 128–150
extrusion, 135–138
hodograph, 134–135
indentation, 138–141
spheroidization, 185
spinning, 271
springing, 198–200, 260
stamping, 255
steel sheet, 290–299
coated, 298
dual phase, 296
HSLA, 295
low-carbon, 295
martensitic, 297
stainless, 299
TRIP, 296
sticking friction, 90

strain
definition, 7
distribution, 257
effective, 22, 26
energy, 11
Mohr's circle equations, 10
principle, 10
tensor, 10
transformation equations, 10
ture vs. nominal, 7
strain aging, 290–293
strain-hardening exponent, 34
effect on cup drawing, 224–227
effect on forming limits, 247
effect on sheet formability, 247
typical values, 289
stainless steels, 299
strain-rate dependence, 52–55
strain-rate exponent, 52
combined strain and strain-rate effects, 62
INDEX

- effect on flow stress, 52–55
- effect of temperature on, 53
  - typical values, 289
- strain ratio, 207
- strain signatures, 261
- strength coefficient, 34
- stress
  - definition, 1
  - deviatoric, 18
  - effective, 22
  - equilibrium equations, 15
  - invariants, 4
  - Mohr’s circle equations, 5
  - principal, 4
  - temperature dependence, 65–69
  - tensor, 1
  - transformation equations, 2–4
  - true vs. nominal, 30
  - stress-corrosion cracking, 233, 303
  - stretcher strains, 290
  - surface appearance, 290
  - surface treatment, 298
  - swaging, 81

- tailor-welded blanks, 261
- tearing, 265
- temperature
  - dependence of flow stress, 65–69
  - rise during deformation, 71

- Zener–Hollomon parameter, 67
- tension test, 30–32
  - ductility, 31
  - tensile strength, 31
- titanium, 305
- Tresca, 18–28, 86, 92
- tooling, 227, 305
- torsion, 40
- TRIP steels, 296

- uniformity, 305
- upper bound analysis, 110–123

- work balance, 76–80
- work hardening, power law, 34
- wrinkling
  - in cup drawing, 220
  - forming limits, 258
  - in stampings, 258
- yield criteria
  - anisotropic, 209–215
  - isotropic, 17–21

- yield strength, 31
- yield locus, 19

- Zener–Hollomon parameter, 67
- zinc, 298, 305