

Contents

List of symbols and abbreviations xvii

Useful approximate conversions from f.p.s. to S.I. units xxii

Part I. BASIC METHODS

CHAPTER 1 THE NATURE AND PURPOSE OF METALWORKING THEORY 1

- 1.1 Introduction 1
- 1.2 Yielding, and the simplification of stress combinations 2
- 1.3 Mohr's circles and the yield criterion 4
- 1.4 Simple estimation of working load from yield stress 5
- 1.5 Stress-evaluation to allow for friction 6
- 1.6 Slip-line field theory, allowing for redundant work 7
- 1.7 Load-bounding technique 8
- 1.8 The situation in 1965 9
- 1.9 Developments since 1965 10

CHAPTER 2 STRESS-STRAIN CURVES 13

- 2.1 The tensile test 13
 - 2.1.1 A typical load-extension curve and stress-strain curve 13
 - 2.1.2 The stress-strain curve for annealed mild steel 15
 - 2.1.3 The plastic region of the stress-strain curve 15
 - 2.1.4 Special characteristics and results of tensile testing 16
- 2.2 True stress and natural strain 18
 - 2.2.1 True stress 18
 - 2.2.2 Natural strain 18
 - 2.2.3 Relationships between nominal and natural strain 19
- 2.3 True stress-strain curves 20
 - 2.3.1 Tension 20
 - 2.3.2 Compression 21
- 2.4 Simplified forms of stress-strain curve 21
 - 2.4.1 A simple method of determining a flow-stress curve 23
- 2.5 Selection of stress-strain curves for cold- and hot-working 23
- 2.6 Compression tests for yield-stress determination 24
 - 2.6.1 Axially-symmetrical compression 24
 - 2.6.2 Plane-strain compression (Ford test) 25
- 2.7 Torsion test 27
- 2.8 Yield-stress determination at high strain rates 28
 - 2.8.1 Plane-strain compression 28
 - 2.8.2 Twisted-bar test 28
 - 2.8.3 Machining as a high-strain-rate property test 29
- 2.9 Hardness test 30
 - Examples 30

CHAPTER 3 PRINCIPAL STRESSES AND YIELDING 35

- 3.1 Introduction 35

3.2	Principle stresses in two dimensions	35
3.3	Maximum shearing stresses	38
3.4	Principal stresses in three dimensions	39
3.5	Mohr's Circle representation of stress states	39
3.5.1	Two-dimensional stress,	40
3.5.2	Two-dimensional stress, referred to principal axes	42
3.5.3	Three-dimensional stress	43
3.6	Yield criteria	45
3.6.1	Tresca maximum shear-stress criterion	46
3.6.2	Von Mises maximum shear-strain-energy criterion	46
3.6.3	Relationship between tensile yield-stress Y and shear yield-stress k	47
3.6.4	Yield under plane-strain conditions	48
	Examples	48
CHAPTER 4	DETERMINATION OF WORKING LOADS BY CONSIDERATION OF WORK, AND OF STRESS DISTRIBUTION	52
4.1	Introduction	52
4.2	Load required to produce yielding in homogeneous deformation	52
4.3	Work formula for homogeneous deformation	55
4.3.1	Work formula for wire drawing	56
4.3.2	Example of application: maximum possible reduction of area per pass	57
4.3.3	Extrusion of a bar	57
4.3.4	Forging and rolling	58
4.4	Allowance for frictional constraint by local stress-evaluation	58
4.4.1	Drawing of wide, non-hardening, strip through wedge-shaped dies	58
4.4.2	Example of application: maximum reduction of area per pass, allowing for friction	61
4.5	Comparison of work formula and stress evaluation, for drawing	62
4.6	Allowance for work-hardening, in stress evaluations	62
4.7	Validity of stress-evaluation approach	63
	Examples	64
CHAPTER 5	DETERMINATION OF WORKING LOADS BY CONSIDERATION OF METAL FLOW	69
5.1	Introduction	69
5.2	Deformation in simple compression	70
5.3	Stress evaluation using slip-lines	71
5.4	Determination of hydrostatic pressure from slip-line rotation. The Hencky equations	73
5.5	Stresses and slip-lines at boundaries of the plastic body	75
5.5.1	Free surface	75
5.5.2	Frictionless interface	77
5.5.3	Interface with Coulomb friction	77
5.5.4	Perfectly rough interface	77
5.6	Application of the slip-line field to a static system. Plane-strain indentation with flat, frictionless platens	78
5.6.1	Strip thickness equal to platen breadth, $h = b$	79
5.6.2	Platen breadth an integral multiple of strip thickness ($b/h = 2, 3, 4, \text{etc.}$)	79
5.6.3	$b > h$ but b/h not integral	79

- 5.6.4 Strip thickness greater than platen breadth ($1 < \frac{h}{b} < 10$) 80
- 5.6.5 Single-punch indentation, $h/b \approx \infty$:
 - (a) Construction of the slip-line field 80
 - (b) Stress determination from the slip-line field 81
- 5.6.6 The Brinell hardness test 82
- 5.7 Significance of velocity in slip-line field evaluations 83
 - 5.7.1 Derivation of Geiringer's velocity equations 83
- 5.8 Application of the slip-line field to steady-state motion: 50% inverted extrusion in plane strain, with unlubricated 180° die 84
 - 5.8.1 Construction of the slip-line field 84
 - 5.8.2 Verification of conformity to velocity boundary-conditions 86
 - 5.8.3 Stress-determination from the slip-line field 88
 - 5.8.4 Slip-line fields for axi-symmetric deformation 89
 - 5.8.5 Inclusion of strain-hardening in slip-line field theory 90
 - 5.8.6 The influence of strain-rate and temperature 92
- 5.9 Velocity diagrams or hodographs 93
- 5.10 Upper-bound and lower-bound techniques of load estimation 94
 - 5.10.1 Lower bound 94
 - 5.10.2 Upper bound 94
 - 5.10.3 Upper-bound theorem in plane strain 95
 - 5.10.4 Application of upper-bound theory to plane-strain indentation 96
 - 5.10.5 Application of upper bounds to axial symmetry 98
 - 5.10.6 The plastic hinge 99
- Examples 100

Part II. EXAMINATION OF PROCESSES

CHAPTER 6 DRAWING OF ROUND BARS AND FLAT STRIP 105

- 6.1 Introduction 105
- 6.2 Elementary assessment of drawing force: homogeneous-deformation contribution 107
- 6.3 Determination of plane-strain drawing load from local stress-evaluation 108
 - 6.3.1 Drawing of wide, flat, strip with wedge-shaped dies (B constant, S constant) 108
 - 6.3.2 Drawing of strain-hardening strip with wedge-shaped dies:
 - (a) No strain-hardening, $S = \text{constant}$. (b) Linear strain-hardening.
 - (c) Exponential strain-hardening.
 - (d) General strain-hardening characteristic 109
 - 6.3.3 Drawing of strain-hardening strip with cylindrical dies 111
- 6.3 Determination of drawing load for cylindrical rod, from local stress-evaluation 114
 - 6.4.1 Cylindrical-rod drawing, with a conical die (α, μ, Y constant) 114
 - 6.4.2 Frictionless drawing of cylindrical rod (Y constant) 116
 - 6.4.3 Allowance for strain-hardening in rod drawing 116
 - 6.4.4 Maximum reduction of area per pass, in rod drawing 117
- 6.5 Slip-line field solution for plane-strain frictionless drawing, with wedge-shaped dies (α constant) 117
 - 6.5.1 Simple slip-line field solution for frictionless strip-drawing, $r = 2 \sin \alpha / (1 + 2 \sin \alpha)$ 118
 - 6.5.2 The slip-line field for reductions less than $2 \sin \alpha / (1 + 2 \sin \alpha)$. Construction for extending slip-line fields from radial fans 123
 - 6.5.3 Construction of the hodograph [$r < 2 \sin \alpha / (1 + 2 \sin \alpha)$] 125

- 6.5.4 Stress-determination from the slip-line field
[$r < 2 \sin \alpha / (1 + 2 \sin \alpha)$] 126
- 6.5.5 Redundant-work factor in terms of geometrical parameters 129
- 6.6 Determination of plane-strain drawing stress, allowing for friction, redundant work and strain-hardening 130
 - 6.6.1 Slip-line field solution including friction 130
 - 6.6.2 Allowance for strain-hardening, zero friction 132
 - 6.6.3 Allowance for friction, redundant work, and strain-hardening simultaneously 133
- 6.7 Determination of drawing stress for round bar, allowing for friction, redundant work and strain-hardening 134
- 6.8 Bulge formation 136
- 6.9 Optimum die angles 137
- 6.10 Tandem drawing 138
- 6.11 Streamlines, and the deformation in drawn strip and rod 139
 - 6.11.1 Metal-flow streamlines in plain-strain drawing 139
 - 6.11.2 Metal-flow streamlines in round-bar drawing 139
 - 6.11.3 Ductility of drawn wire 139
- 6.12 Lubrication in practical wire drawing 140
 - 6.12.1 Steel wire 140
 - 6.12.2 Aluminium wire 142
 - 6.12.3 Copper and copper alloys 142
 - 6.12.4 Other alloys 142
- 6.13 Recent developments in wire manufacture 143
 - 6.13.1 Theoretical contributions 143
 - 6.13.2 Improvements in conventional processes 143
 - 6.13.3 Newer processes 144
- Examples 145

CHAPTER 7 TUBE MAKING AND DEEP DRAWING 151

- 7.1 Introduction 151
- 7.2 Determination by stress-evaluation of the load for close-pass drawing of thin-walled tube 152
 - 7.2.1 Close-pass plug-drawing with a conical die 153
 - 7.2.2 Close-pass mandrel-drawing with a conical die 155
 - 7.2.3 Plug-drawing with circular-profile dies 156
 - 7.2.4 Maximum reductions of area in tube-drawing (plug-drawing, mandrel-drawing) 156
- 7.3 Tandem drawing of tubes on a mandrel 157
- 7.4 Tube sinking 158
- 7.5 Redundant work in tube-drawing 159
- 7.6 Deep drawing and pressing 160
- 7.7 Tube production by rolling and extrusion 160
 - 7.7.1 Pilgering and cold reducing 160
 - 7.7.2 Roll and plug profiles 162
 - 7.7.3 Tube extrusion 162
- 7.8 Lubrication in practical tube making 162
 - 7.8.1 Steel tube drawing 163
 - 7.8.2 Other alloys 164
- 7.9 Lubrication in deep-drawing and pressing 164
 - 7.9.1 Sheet steel forming 165
 - 7.9.2 Copper alloys 166
 - 7.9.3 Other alloys 166

- 7.10 Recent developments in tube manufacture 166
 - 7.10.1 Theoretical contributions 166
 - 7.10.2 Improvements in conventional processes 167
 - 7.10.3 Newer processes 167
- Examples 168

CHAPTER 8 EXTRUSION 174

- 8.1 Introduction 174
- 8.2 Stress-evaluation for extrusion of round bar and flat strip 176
 - 8.2.1 Round-bar extrusion through a conical die 176
 - 8.2.2 Allowance for container friction 177
 - 8.2.3 Flat strip extruded through dies of constant angle 179
 - 8.2.4 Flat strip extruded through cylindrical dies 179
 - 8.2.5 Limitations of stress evaluation for extrusion 179
- 8.3 Slip-line field solutions for strip extrusion through tapered dies 180
 - 8.3.1 Frictionless extrusion, $r = \frac{2 \sin \alpha}{1 + 2 \sin \alpha}$ 180
 - 8.3.2 Frictionless extrusion, $r < \frac{2 \sin \alpha}{1 + 2 \sin \alpha}$ 181
 - 8.3.3 Frictionless extrusion, $r > \frac{2 \sin \alpha}{1 + 2 \sin \alpha}$ 181
 - 8.3.4 Extrusion with friction at the die and the container 182
- 8.4 Slip-line fields for extrusion through square dies 184
- 8.5 Extrusion through unsymmetrical and multi-hole dies 184
- 8.6 Metal-flow streamlines deduced from upper-bound solutions 185
- 8.7 Upper-bound solutions for plane-strain extrusion 188
 - 8.7.1 Upper-bound solution for strip-extrusion through tapered dies: frictionless extrusion 189
 - 8.7.2 Upper-bound solution for strip extrusion through tapered dies: sticking friction at the die 190
 - 8.7.3 Upper-bound solutions for strip extrusion through square dies 190
 - 8.7.4 Metal-flow streamlines deduced from upper-bound solutions 190
 - 8.7.5 Temperature distribution deduced from upper-bound solutions 192
 - 8.7.6 Upper-bound solutions for complex extrusion problems 192
- 8.8 Axially-symmetrical extrusion 193
 - 8.8.1 Application of upper-bound technique to axial symmetry 193
 - 8.8.2 Semi-empirical method based on plane-strain slip-line field solutions 194
 - 8.8.3 Die profiles 194
- 8.9 Special forms of extrusion 195
 - 8.9.1 Bridge dies 195
 - 8.9.2 Impact extrusion 195
- 8.10 Lubrication in practical hot extrusion 196
 - 8.10.1 Hot extrusion of steels 197
 - 8.10.2 Copper alloys 198
 - 8.10.3 Aluminium alloys 198
 - 8.10.4 Other alloys 198
- 8.11 Lubrication in practical cold extrusion 199
 - 8.11.1 Cold extrusion of steels 199
 - 8.11.2 Copper alloys 199
 - 8.11.3 Aluminium alloys 199
 - 8.11.4 Other alloys 200
- 8.12 Recent developments in extrusion 200
 - 8.12.1 Theoretical contributions 200

- 8.12.2 Conventional and newer processes 201
- Examples 201

CHAPTER 9 ROLLING OF FLAT SLABS AND STRIP 208

- 9.1 Introduction 208
 - 9.1.1 Hot rolling 208
 - 9.1.2 Cold rolling 208
- 9.2 Elementary assessment of roll load 210
 - 9.2.1 Homogeneous deformation 210
 - 9.2.2 Work evaluation 211
- 9.3 Roll-pressure determination from local stress-evaluation 212
 - 9.3.1 Derivation and general solution of the differential equation 212
 - 9.3.2 Rolling with no external tensions 216
 - 9.3.3 Rolling with front and back tension 217
- 9.4 Assumptions and applicability of the stress-evaluation method 217
 - 9.4.1 Discussion of the assumptions: (i) Plane-strain conditions
(ii) Homogeneous deformation, (iii) Constant coefficient of friction, (iv) Constant radius of curvature of the rolls
(v) Neutral point within the arc of contact, (vi) Negligible elastic deformation of the strip, (vii) Low rate of strain-hardening, (viii) Low applied tensions 217–220
 - 9.4.2 Applicability of the stress-evaluation equations 220
- 9.5 Evaluation of load, torque and mill power for cold rolling 221
 - 9.5.1 Roll load 221
 - 9.5.2 Roll torque 222
 - 9.5.3 Mill power 223
- 9.6 Stress-evaluation for rolling with high friction 223
 - 9.6.1 Pressure-distribution measurements 223
 - 9.6.2 Stress-evaluation with partial sticking-friction 225
- 9.7 The influences of elastic deformation in cold rolling 226
 - 9.7.1 Minimum thickness in rolling 226
 - 9.7.2 Bending of the rolls: camber 227
 - 9.7.3 Bending of the rolls: backup rolls 229
 - 9.7.4 Elastic distortion of the mill 229
 - 9.7.5 Gauge control 231
 - 9.7.6 Elastic deformation of the strip. Temper rolling 232
- 9.8 Other methods of roll-load determination 233
 - A. Cold rolling 233
 - 9.8.1 Cook and Parker method 233
 - 9.8.2 Bland and Ford graphical solution 233
 - 9.8.3 Ekelund's equation 234
 - 9.8.4 C. E. Davies' method 234
 - B. Hot rolling 234
 - 9.8.5 Ekelund's equation 234
 - 9.8.6 Sims' method 235
 - 9.8.7 Alexander's slip-line field 236
- 9.9 Special rolling mills 237
 - 9.9.1 The Sendzimir cluster mill 237
 - 9.9.2 The planetary mill 238
 - 9.9.3 The Saxl pendulum mill 240
 - 9.9.4 Continuous rotary-casting and rolling lines 240
- 9.10 Lubrication in practical hot rolling 241
 - 9.10.1 Hot rolling of steels and other alloys 241

- 9.11 Lubrication in practical cold rolling 242
 - 9.11.1 Cold rolling of steels 242
 - 9.11.2 Aluminium 243
 - 9.11.3 Other alloys 243
- 9.12 Recent developments in rolling 243
 - 9.12.1 Theoretical contributions 243
 - 9.12.2 Conventional and newer processes 244
 - Examples 244

CHAPTER 10 FORGING, PUNCHING AND PIERCING 251

- 10.1 Introduction 251
- 10.2 Determination of plane-strain compression load from local stress evaluation 251
 - 10.2.1 Low-friction conditions. Thin strip 251
 - 10.2.2 High-friction conditions. Thin strip 253
 - 10.2.3 Inclined platens. Thin strip 256
- 10.3 Determination by stress-evaluation of the load for forging a flat circular disc 257
- 10.4 Slip-line field solutions for plane-strain compression between parallel, frictionless platens 259
- 10.5 Slip-line fields for plane-strain compression between parallel platens, with sticking friction 260
 - 10.5.1 Construction of the slip-line field ($b/h = 3-6$) 260
 - 10.5.2 Construction of the hodograph 260
 - 10.5.3 Stress-determination from the slip-line field ($b/h = 3-6$) 262
 - 10.5.4 General solution for sticking friction with parallel platens ($b > h$) 263
- 10.6 Compression with intermediate friction values 264
- 10.7 Slip-line field solutions for plane-strain indentation or punching 264
 - 10.7.1 Indentation with a flat punch ($h > b$) 264
 - 10.7.2 Deep penetration by a flat punch 265
 - 10.7.3 Wedge-indentation of a semi-infinite block 265
 - 10.7.4 Wedge-indentation of a finite strip 266
- 10.8 Piercing 267
- 10.9 Upper-bound solutions for compression with smooth platens 268
- 10.10 A semi-empirical method for force calculations in extrusion-forging 269
- 10.11 Application of theoretical analysis to automatic forging 270
- 10.12 Extrusion-forging 270
 - 10.12.1 Slip-line field solution for plane strain 270
 - 10.12.2 The construction of a composite slip-line field 272
 - 10.12.3 Extension to axial symmetry 272
 - 10.12.4 Inclusion of strain-hardening and friction variations 274
 - 10.12.5 Upper-bound solutions using rigid-triangle velocity fields in plane strain 274
 - 10.12.6 Upper-bound solutions using deforming elements in axial symmetry 275
 - 10.12.7 Stress analysis in unit deformation zone 277
 - 10.12.8 Comparison of methods of analysis 278
- 10.13 Lubrication in practical hot forging 279
 - 10.13.1 Hot forging of steels 279
 - 10.13.2 Copper alloys 279
 - 10.13.3 Aluminium alloys 279
 - 10.13.4 Other alloys 280

10.14	Lubrication in practical cold forging	280
10.15	Recent developments in forging	280
10.15.1	Theoretical contributions	280
10.15.2	Improvements in conventional processes	281
10.15.3	Newer processes	281
	Examples	282
CHAPTER 11	FRICITION AND LUBRICATION IN METALWORKING	287
11.1	Influences of friction in metalworking processes	287
11.1.1	Increases in forces attributable to friction	287
11.1.2	Inhomogeneity of deformation produced by friction	288
11.1.3	Metal transfer	290
11.1.4	Beneficial effects of friction	291
11.2	Measurement of coefficient of friction	292
11.2.1	Direct measurement of friction in metalworking	293
11.2.2	Coefficients obtained from correlation with theory	293
11.2.3	Measurements depending upon shape change	294
11.2.4	Friction measurement in rolling	294
11.3	The elements of friction theory	295
11.4	Elementary principles of lubrication	297
11.4.1	Hydrodynamic and thick-film lubrication	298
11.4.2	Boundary and extreme-pressure lubricants	298
11.4.3	Solid lubricants	299
11.4.4	Melting solids	300
11.5	Examples of lubricants used in industrial metalworking	300
11.5.1	Lubricants for rolling	301
11.5.2	Cold drawing	301
11.5.3	Forging	301
11.5.4	Extrusion	301
11.5.5	Cutting, drilling and other machining operations	301
11.6	An assessment of simulative testing for lubricant evaluation	302
11.6.1	Rolling	302
11.6.2	Extrusion	303
11.6.3	Forging	303
11.6.4	Wire drawing	305
11.6.5	Tube drawing and wall ironing	305
11.6.6	Sheet pressing and deep drawing	306
CHAPTER 12	METALLURGICAL FACTORS IN METALWORKING	308
12.1	Introduction	308
12.2	Hot, cold and warm working	309
12.2.1	Recrystallisation	310
12.2.2	Hot-working characteristics	311
12.2.3	Elements of dislocation theory	313
12.2.4	Cold working	316
12.2.5	Warm working	317
12.2.6	Superplastic alloys	317
12.2.7	Workability	318
12.3	Defects in metalworking	319
12.3.1	Defects characteristic of individual processes	319
12.3.2	Residual stresses	322
12.3.3	Measurement of residual stresses	325

- 12.4 In-process heat treatment 327
 - 12.4.1 Annealing 327
 - 12.4.2 Heat-treatable precipitation-hardening alloys 329
 - 12.4.3 Thermo-mechanical treatments 330
- 12.5 Post heat-treatment 332
 - 12.5.1 Stress relieving 332
 - 12.5.2 Improvement of properties 333
 - 12.5.3 Recrystallisation after metalworking 334
- 12.6 Tool materials 334
 - 12.6.1 Solid tools 334
 - 12.6.2 Coated tools 337
- 12.7 The properties and forming of polymers 338
 - 12.7.1 The nature of simple polymers 338
 - 12.7.2 Analysis of the mechanical properties of polymers 340
 - 12.7.3 The forming of polymers 343

CHAPTER 13 NUMERICAL METHODS IN METALWORKING THEORY 347

- 13.1 Introduction 347
- 13.2 Stress-strain relationships for elastic-plastic solids 348
 - 13.2.1 Elastic deformation 348
 - 13.2.2 Plastic deformation 349
 - 13.2.3 Combined elastic and plastic deformation 350
 - 13.2.4 Generalised stress and strain 351
- 13.3 Visioplasticity 352
 - 13.3.1 Technique 352
 - 13.3.2 Determination of stresses: (a) Plane strain, (b) Axial symmetry 353
 - 13.3.3 Solution of the stress equations:
 - (a) Graphical method, (b) Flow function solution 355
 - 13.3.4 Evaluation of distortion in extrusion 358
 - 13.3.5 Assessment of visioplasticity 359
- 13.4 Use of a digital computer to draw slip-line fields 359
 - 13.4.1 Computer drawing of the slip-line field for plane-strain compression 359
 - 13.4.2 Drawing the hodograph 362
 - 13.4.3 Slip-line fields for all possible friction coefficients, applied to compression with width/height ratio 2:1 363
 - 13.4.4 Application to non-steady conditions. Progressive deformation in forging with sticking friction 365
 - 13.4.5 Construction of a slip-line field from a distorted grid. Experimental technique 366
- 13.5 Upper-bound solutions 369
 - 13.5.1 Subdivision of a deforming unit by two shear lines (Type I) 370
 - 13.5.2 Subdivision of a deforming unit by four shear lines (Type II) 371
 - 13.5.3 Application to simple forging 371
 - 13.5.4 Subdivision into multiple unit zones for simple forging 372
 - 13.5.5 Application to more complex conditions 373
 - 13.5.6 Application of upper-bound solutions to axial symmetry 373
 - 13.5.7 Unit zone upper-bound solutions for axial symmetry 374
 - 13.5.8 Curved-element upper-bound solutions 374
- 13.6 Finite-element analysis for elastic-plastic deformation 375
 - 13.6.1 Fundamentals of finite-element elastic analysis 376
 - 13.6.2 Expressions for the displacements of the nodes of one triangular element 376
 - 13.6.3 Evaluation of the local strain from the displacement 378

13.6.4	Evaluation of the local stress from the strain	380
13.6.5	Displacement under force. The stiffness matrix for an element	381
13.6.6	The stiffness matrix for the whole system	382
13.6.7	Method of solution of an elastic problem	382
13.6.8	Finite-element analysis in plastic deformation	382
13.7	Applications of variational calculus	387
13.7.1	The general method of weighted residuals	387
13.7.2	Weighted-residuals method in plasticity	388
13.7.3	Application of weighted residuals to axisymmetric extrusion	390
13.7.4	A matrix functional method	391
13.8	Numerical computation of stress-analysis solutions	393
13.9	Assessment of the current state of metalworking theory	394
	Index	398