

CONTENTS

<i>List of Symbols</i>	xv
1 Structure of Crystalline Solids and the “Defect State”	1
1.1 Overview	1
1.2 Principal Crystal Structures of Interest	2
1.3 Small-Strain Elasticity in Crystals	4
1.3.1 Hooke’s Law	4
1.3.2 Orthorhombic Crystals	9
1.3.3 Hexagonal Crystals	9
1.3.4 Cubic Crystals	10
1.3.5 Isotropic Materials	10
1.3.6 Temperature and Strain Dependence of Elastic Response	11
1.4 Inelastic Deformation and the Role of Crystal Defects	13
1.5 Vacancies and Interstitials	14
1.6 Line Properties of Dislocations	17
1.6.1 Topology and Stress Fields of Dislocations	17
1.6.2 Line Energies of Dislocations	20
1.7 Planar Faults	22
References	25
Appendix: Dislocation Stress Fields in a Finite Cylinder	26
2 Kinematics and Kinetics of Crystal Plasticity	27
2.1 Overview	27
2.2 Kinematics of Inelastic Deformation	27
2.2.1 Plasticity Resulting from Shear Transformations	27
2.2.2 Plasticity Resulting from Dislocation Glide	29
2.2.3 Lattice Rotations Accompanying Slip	31
2.3 Flexure and Motion of Dislocations under Stress	33
2.3.1 Interaction of a Dislocation Line with an External Stress	33
2.3.2 Interaction Energies of Dislocations with Stresses External to Them	35
2.3.3 Interaction of a Dislocation with Free Surfaces and Inhomogeneities	36
2.3.4 Line Tension of a Dislocation	37

CONTENTS

2.3.5	Uniformly Moving Dislocations and The Dislocation Mass	39
2.3.6	The Basic Differential Equation for a Moving Dislocation Line	40
2.3.7	The Multiplication of Dislocation Line Length	41
2.4	The Mechanical Threshold of Deformation	44
2.5	Elements of Thermally Activated Deformation	45
2.5.1	General Principles	45
2.5.2	Principal Activation Parameters for Crystal Plasticity	49
2.6	Selection of Slip Systems in Specific Crystal Structures	52
2.7	Dislocations in Close-packed Structures	54
2.7.1	Dissociation of Perfect Dislocations in FCC	54
2.7.2	The Thompson Tetrahedron and Other Partial Dislocations	57
2.7.3	The Burgers Vector/Material Displacement Rule	59
2.7.4	Dislocation Reactions and Sessile Locks	60
2.8	Plastic Deformation by Shear Transformations	62
2.8.1	Types of Transformation	62
2.8.2	Deformation Twinning	62
2.8.3	Stress-induced Martensitic Transformations	64
2.8.4	Kinking	66
	References	68
3	Overview of Strengthening Mechanisms	70
3.1	Introduction	70
3.2	The Continuum Plasticity Approach to Strengthening Compared with the Dislocation Mechanics Approach	70
3.3	The Lattice Resistance	73
3.4	Solid-solution Strengthening	73
3.5	Precipitation Strengthening	74
3.6	Strengthening by Strain Hardening	76
3.7	Phenomena Associated with Strengthening mechanisms	77
	References	77
4	The Lattice Resistance	78
4.1	Overview	78
4.2	Model of a Dislocation in a Discrete Lattice	78
4.2.1	The Peierls–Nabarro Model of an Edge Dislocation—Updated	78
4.2.2	The Stress to Move the Dislocation	81
4.3	Inception of Plastic Deformation	85
4.3.1	HCP and FCC Metals	85
4.3.2	BCC Metals	87

4.4	Structure of the Cores of Screw Dislocations in BCC Metals	89
4.5	Temperature and Strain Rate Dependence of the Lattice Resistance in BCC Metals	94
4.5.1	The Nature of Thermal Assistance over a Lattice Energy Barrier	94
4.5.2	Lattice Potentials	98
4.5.3	Shapes and Energies of Geometrical Kinks	99
4.5.4	Double-kink Energy in <i>Regime I</i>	101
4.5.5	Double-kink Energy in <i>Regime II</i>	102
4.6	The Plastic Strain Rate in BCC Metals	104
4.6.1	The Preexponential Factor and the Net Shear Rate	104
4.6.2	Temperature and Strain Rate Dependence of the Plastic Resistance	106
4.6.3	Comparison of Theory with Experiments on BCC Transition Metals	108
4.7	The Lattice Resistance of Silicon	114
4.7.1	Dislocations in Silicon	114
4.7.2	Dislocation Mobility in Silicon	118
4.7.3	Models of the Dislocation Core Structure in Silicon	119
4.7.4	Model of Dislocation Motion	123
4.7.5	Comparison of Models with Experiments	128
4.8	The Phonon Drag	132
	References	133
5	Solid-solution Strengthening	136
5.1	Overview	136
5.2	Forms of Interaction of Solute Atoms with Dislocations in FCC Metals	136
5.2.1	Overview	136
5.2.2	The Size Misfit Interaction	137
5.2.3	The Modulus Misfit Interaction	139
5.2.4	Combined Size and Modulus Misfit Interactions	141
5.3	Forms of Sampling of the Solute Field by a Dislocation in an FCC Metal	145
5.4	The Solid-solution Resistance of FCC Alloys	149
5.4.1	The Athermal Resistance	149
5.4.2	Thermally Assisted Advance of a Dislocation in a Field of Solute Atoms in an FCC Metal	151
5.5	Comparison of Solid-solution-strengthening Models for FCC Metals with Experiments	153
5.5.1	Overview of Experimental Information	153
5.5.2	Peak Solute Interaction Forces	155

CONTENTS

5.5.3	Dependence of Flow Stress on Solute Concentration	156
5.5.4	Comparison of Temperature Dependence of CRSS between Experiments and Theoretical Models	157
5.5.5	Summary of Solid-solution Strengthening of FCC Alloys	159
5.5.6	The “Stress Equivalence” of the Solid-solution Resistance of FCC Alloys	159
5.5.7	The Plateau Resistance	163
5.6	Solid-solution Strengthening of BCC Metals by Substitutional Solute Atoms	163
5.6.1	Overview of Phenomena	163
5.6.2	Experimental Manifestations of BCC Solid-solution Alloy Systems	165
5.7	Interactions of Solute Atoms with Screw Dislocations in BCC Metals	166
5.7.1	Overview of Model of Interaction of Solute Atoms with Screw Dislocation Cores	166
5.7.2	Interaction of Solute Atoms with Screw Dislocation Cores	168
5.7.3	Binding Potential of Solutes to Screw Dislocation Cores	170
5.8	The Shear Resistance	172
5.8.1	The Athermal Resistance at the Plateau	172
5.8.2	Resistance Governed by Kink Mobility	173
5.8.3	Double-kink-nucleation-controlled Resistance	177
5.8.4	Combination of Resistances	180
5.8.5	The Strain Rate Dependence of the Flow Stress in the Plateau Range	181
5.9	Comparison of Model Results with Experiments	184
5.9.1	The Athermal Resistance at the Plateau	184
5.9.2	Kink-mobility-controlled Plastic Resistance	185
5.9.3	Double-kink-nucleation-controlled Resistance	187
5.9.4	Strain Rate Dependence of the Flow Stress in the Plateau Region, and Activation Volumes	189
	References	191
6	Precipitation Strengthening	193
6.1	Overview	193
6.2	Formation of Second Phases in the Form of Precipitate Particles, Heterogeneous Domains, or other Lattice Defect Clusters	194
6.2.1	Discrete Precipitates	194

CONTENTS

xiii

6.2.2	Spinodal-decomposition Domains	198
6.2.3	Defect Clusters and Nanovoids	199
6.3	Sampling of Precipitates by Dislocations	200
6.3.1	Precipitate Shapes and Sizes	200
6.3.2	Two Forms of Interaction of Precipitates with Dislocations	201
6.3.3	Statistics of Sampling Random Point Obstacles in a Plane	202
6.3.4	Sampling Point Obstacles of Different Kinds	207
6.3.5	Sampling Obstacles of Finite Width	208
6.3.6	Precipitate Growth, Peak Aging, and Overaging	212
6.3.7	Thermally Assisted Motion of Dislocations through a Field of Penetrable Obstacles	213
6.4	Specific Mechanisms of Precipitation Strengthening	219
6.4.1	Overview	219
6.4.2	Chemical Strengthening, or Resistance to Interface Step Production in Shearing	220
6.4.3	Stacking-fault Strengthening	223
6.4.4	Atomic-order Strengthening	235
6.4.5	Size Misfit Strengthening (Coherency Strengthening)	247
6.4.6	Modulus Misfit Strengthening	256
6.4.7	The Orowan Resistance and Dispersion Strengthening	264
6.4.8	Strengthening by Spinodal-decomposition Microstructures	267
6.4.9	Precipitate-like Obstacles	271
	References	279
7	Strain Hardening	283
7.1	Overview	283
7.2	Features of Deformation	284
7.2.1	Active Slip Systems in FCC Metals	284
7.2.2	Stress–Strain Curves	286
7.2.3	Slip Distributions	292
7.2.4	Dislocation Microstructures	294
7.3	Strain-hardening Models	306
7.3.1	Overview	306
7.3.2	Dislocation Intersections	307
7.3.3	Stage I Strain Hardening	312
7.3.4	Stage II Strain Hardening	317
7.3.5	Ingredients of Stage III Hardening	320
7.3.6	Components of Strain Hardening in Stage III	325

7.3.7	Recovery Processes in Stage III	330
7.3.8	Total Strain-hardening Rate in Stage III	334
7.3.9	Strain Hardening in Stage IV	336
7.3.10	Stage V Deformation with No Strain Hardening	340
7.4	Strain Hardening in Other Crystal Structures	340
	References	340
8	Deformation Instabilities, Polycrystals, Flow in Metals with Nanostructure, Superposition of Strengthening Mechanisms, and Transition to Continuum Plasticity	344
8.1	Overview	344
8.2	Yield Phenomena	345
8.3	Balance between the Interplane and the Intraplane Resistances and the Mobile Dislocation Density	349
8.4	The Portevin–Le Chatelier Effect and Jerky Flow	351
8.5	Dynamic Overshoot at Low Temperatures	355
8.6	Plastic Deformation in Polycrystals	358
8.6.1	Plastic Resistance of Polycrystals	358
8.6.2	Evolution of Deformation Textures	360
8.7	Plastic Deformation in the Presence of Heterogeneities	364
8.7.1	Geometrically Necessary Dislocations	364
8.7.2	Rise in Flow Stress and Enhanced Strain-hardening-rate Effects of Geometrically Necessary Dislocations	364
8.8	Grain Boundary Strengthening	370
8.9	Plasticity in Metals with Nanoscale Microstructure	376
8.10	Superposition of Deformation Resistances	382
8.11	The Bauschinger Effect	386
8.12	Phenomenological Continuum Plasticity	388
8.12.1	Conditions of Plastic Flow in the Mathematical Theory of Plasticity	388
8.12.2	Transition from Dislocation Mechanics to Continuum Mechanics	389
	References	391
	<i>Author Index</i>	394
	<i>Subject Index</i>	399