

Contents

Preface xi

- 1 The structure and bonding of atoms 1**
- 1.1 The realm of materials science 1
 - 1.2 The free atom 2
 - 1.2.1 The four electron quantum numbers 2
 - 1.2.2 Nomenclature for electronic states 3
 - 1.3 The Periodic Table 4
 - 1.4 Interatomic bonding in materials 7
 - 1.5 Bonding and energy levels 9
- 2 Atomic arrangements in materials 11**
- 2.1 The concept of ordering 11
 - 2.2 Crystal lattices and structures 12
 - 2.3 Crystal directions and planes 14
 - 2.4 Stereographic projection 16
 - 2.5 Selected crystal structures 19
 - 2.5.1 Pure metals 19
 - 2.5.2 Diamond and graphite 21
 - 2.5.3 Coordination in ionic crystals 22
 - 2.5.4 AB-type compounds 24
 - 2.5.5 Silica 24
 - 2.5.6 Alumina 26
 - 2.5.7 Complex oxides 27
 - 2.5.8 Silicates 28
 - 2.6 Inorganic glasses 31
 - 2.6.1 Network structures in glasses 31
 - 2.6.2 Classification of constituent oxides 32
 - 2.7 Polymeric structures 33
 - 2.7.1 Thermoplastics 33
 - 2.7.2 Elastomers 36
 - 2.7.3 Thermosets 37
 - 2.7.4 Crystallinity in polymers 39
- 3 Structural phases; their formation and transitions 43**
- 3.1 Crystallization from the melt 43
 - 3.1.1 Freezing of a pure metal 43
 - 3.1.2 Plane-front and dendritic solidification at a cooled surface 44
 - 3.1.3 Forms of cast structure 45
 - 3.1.4 Gas porosity and segregation 46

- 3.1.5 Directional solidification 47
- 3.1.6 Production of metallic single crystals for research 48
- 3.2 Principles of applications of phase diagrams 49**

 - 3.2.1 The concept of a phase 49
 - 3.2.2 The Phase Rule 49
 - 3.2.3 Stability of phases 51
 - 3.2.4 Two-phase equilibria 54
 - 3.2.5 Three-phase equilibria and reactions 57
 - 3.2.6 Intermediate phases 60
 - 3.2.7 Limitations of phase diagrams 61
 - 3.2.8 Some key phase diagrams 62
 - 3.2.9 Ternary phase diagrams 67

- 3.3 Principles of alloy theory 75**

 - 3.3.1 Primary substitutional solid solutions 75
 - 3.3.2 Interstitial solid solutions 78
 - 3.3.3 Types of intermediate phase 79
 - 3.3.4 Order-disorder phenomena 82

- 3.4 The mechanism of phase changes 83**

 - 3.4.1 Kinetic considerations 83
 - 3.4.2 Homogeneous nucleation 84
 - 3.4.3 Heterogeneous nucleation 85
 - 3.4.4 Nucleation in solids 85

- 4 Defects in solids 87**

 - 4.1 Types of imperfection 87
 - 4.2 Point defects 87
 - 4.2.1 Point defects in metals 87
 - 4.2.2 Point defects in non-metallic crystals 89
 - 4.2.3 Irradiation of solids 91
 - 4.2.4 Point defect concentration and annealing 92
 - 4.3 Line defects 93
 - 4.3.1 Concept of a dislocation 93
 - 4.3.2 Edge and screw dislocations 94
 - 4.3.3 The Burgers vector 94
 - 4.3.4 Mechanisms of slip and climb 95
 - 4.3.5 Strain energy associated with dislocations 98
 - 4.3.6 Dislocations in ionic structures 100

4.4	Planar defects	100	5.5	Observation of defects	161
4.4.1	Grain boundaries	100	5.5.1	Etch pitting	161
4.4.2	Twin boundaries	102	5.5.2	Dislocation decoration	161
4.4.3	Extended dislocations in close-packed crystals	103	5.5.3	Dislocation strain contrast in TEM	161
4.5	Volume defects	108	5.5.4	Contrast from crystals	163
4.5.1	Void formation and annealing	108	5.5.5	Imaging of dislocations	164
4.5.2	Irradiation and voiding	108	5.5.6	Imaging of stacking faults	164
4.5.3	Voiding and fracture	108	5.5.7	Application of dynamical theory	165
4.6	Defect behaviour in some real materials	109	5.5.8	Weak-beam microscopy	167
4.6.1	Dislocation vector diagrams and the Thompson tetrahedron	109	5.6	Specialized bombardment techniques	
4.6.2	Dislocations and stacking faults in fcc structures	110	168		
4.6.3	Dislocations and stacking faults in cph structures	113	5.6.1	Neutron diffraction	168
4.6.4	Dislocations and stacking faults in bcc structures	115	5.6.2	Synchrotron radiation studies	169
4.6.5	Dislocations and stacking faults in ordered structures	118	5.6.3	Secondary ion mass spectrometry (SIMS)	170
4.6.6	Dislocations and stacking faults in ceramics	119	5.7	Thermal analysis	171
4.6.7	Defects in crystalline polymers	120	5.7.1	General capabilities of thermal analysis	171
4.6.8	Defects in glasses	121	5.7.2	Thermogravimetric analysis	171
4.7	Stability of defects	122	5.7.3	Differential thermal analysis	172
4.7.1	Dislocation loops	122	5.7.4	Differential scanning calorimetry	173
4.7.2	Voids	124	6	<i>The physical properties of materials</i>	175
4.7.3	Nuclear irradiation effects	124	6.1	Introduction	175
5	<i>The characterization of materials</i>	130	6.2	Density	175
5.1	Tools of characterization	130	6.3	Thermal properties	175
5.2	Light microscopy	131	6.3.1	Thermal expansion	175
5.2.1	Basic principles	131	6.3.2	Specific heat capacity	177
5.2.2	Selected microscopical techniques	133	6.3.3	The specific heat curve and transformations	177
5.3	X-ray diffraction analysis	138	6.3.4	Free energy of transformation	179
5.3.1	Production and absorption of X-rays	138	6.4	Diffusion	180
5.3.2	Diffraction of X-rays by crystals	139	6.4.1	Diffusion laws	180
5.3.3	X-ray diffraction methods	140	6.4.2	Mechanisms of diffusion	181
5.3.4	Typical interpretative procedures for diffraction patterns	144	6.4.3	Factors affecting diffusion	183
5.4	Analytical electron microscopy	148	6.5	Anelasticity and internal friction	183
5.4.1	Interaction of an electron beam with a solid	148	6.6	Ordering in alloys	185
5.4.2	The transmission electron microscope (TEM)	149	6.6.1	Long-range and short-range order	185
5.4.3	The scanning electron microscope	150	6.6.2	Detection of ordering	186
5.4.4	Theoretical aspects of TEM	152	6.6.3	Influence of ordering upon properties	187
5.4.5	Chemical microanalysis	156	6.7	Electrical properties	188
5.4.6	Electron energy loss spectroscopy (EELS)	159	6.7.1	Electrical conductivity	188
5.4.7	Auger electron spectroscopy (AES)	161	6.7.2	Semiconductors	191
			6.7.3	Superconductivity	193
			6.7.4	Oxide superconductors	195
			6.8	Magnetic properties	196
			6.8.1	Magnetic susceptibility	196
			6.8.2	Diamagnetism and paramagnetism	197
			6.8.3	Ferromagnetism	198
			6.8.4	Magnetic alloys	199
			6.8.5	Anti-ferromagnetism and ferrimagnetism	200

6.9	Dielectric materials	201	7.5.2	Nucleation and growth of twins	232
6.9.1	Polarization	201	7.5.3	Effect of impurities on twinning	233
6.9.2	Capacitors and insulators	202	7.5.4	Effect of prestrain on twinning	233
6.9.3	Piezoelectric materials	202	7.5.5	Dislocation mechanism of twinning	233
6.9.4	Pyroelectric and ferroelectric materials	203	7.5.6	Twinning and fracture	234
6.10	Optical properties	203	7.6	Strengthening and hardening mechanisms	234
6.10.1	Reflection, absorption and transmission effects	203	7.6.1	Point defect hardening	234
6.10.2	Optical fibres	204	7.6.2	Work-hardening	236
6.10.3	Lasers	204	7.6.3	Development of preferred orientation	243
6.10.4	Ceramic 'windows'	205	7.7	Macroscopic plasticity	246
6.10.5	Electro-optic ceramics	205	7.7.1	Tresca and von Mises criteria	246
7	Mechanical behaviour of materials	206	7.7.2	Effective stress and strain	247
7.1	Mechanical testing procedures	206	7.8	Annealing	247
7.1.1	Introduction	206	7.8.1	General effects of annealing	247
7.1.2	The tensile test	206	7.8.2	Recovery	248
7.1.3	Indentation hardness testing	208	7.8.3	Recrystallization	249
7.1.4	Impact testing	208	7.8.4	Grain growth	253
7.1.5	Creep testing	209	7.8.5	Annealing twins	254
7.1.6	Fatigue testing	209	7.8.6	Recrystallization textures	255
7.1.7	Testing of ceramics	209	7.9	Metallic creep	256
7.2	Elastic deformation	210	7.9.1	Transient and steady-state creep	256
7.2.1	Elastic deformation of metals	210	7.9.2	Grain boundary contribution to creep	257
7.2.2	Elastic deformation of ceramics	212	7.9.3	Tertiary creep and fracture	260
7.3	Plastic deformation	212	7.9.4	Creep-resistant alloy design	260
7.3.1	Slip and twinning	212	7.10	Deformation mechanism maps	263
7.3.2	Resolved shear stress	213	7.11	Metallic fatigue	263
7.3.3	Relation of slip to crystal structure	213	7.11.1	Nature of fatigue failure	263
7.3.4	Law of critical resolved shear stress	214	7.11.2	Engineering aspects of fatigue	264
7.3.5	Multiple slip	215	7.11.3	Structural changes accompanying fatigue	266
7.3.6	Relation between work-hardening and slip	216	7.11.4	Crack formation and fatigue failure	268
7.4	Dislocation behaviour during plastic deformation	216	7.11.5	Fatigue at elevated temperatures	270
7.4.1	Dislocation mobility	216	8	Strengthening and toughening	271
7.4.2	Variation of yield stress with temperature and strain rate	217	8.1	Introduction	271
7.4.3	Dislocation source operation	219	8.2	Strengthening of non-ferrous alloys by heat-treatment	271
7.4.4	Discontinuous yielding	220	8.2.1	Precipitation-hardening of Al-Cu alloys	271
7.4.5	Yield points and crystal structure	222	8.2.2	Precipitation-hardening of Al-Ag alloys	275
7.4.6	Discontinuous yielding in ordered alloys	223	8.2.3	Mechanisms of precipitation- hardening	277
7.4.7	Solute-dislocation interaction	223	8.2.4	Vacancies and precipitation	281
7.4.8	Dislocation locking and temperature	226	8.2.5	Duplex ageing	284
7.4.9	Inhomogeneity interaction	226	8.2.6	Particle-coarsening	284
7.4.10	Kinetics of strain-ageing	227	8.2.7	Spinodal decomposition	286
7.4.11	Influence of grain boundaries on plasticity	228			
7.4.12	Superplasticity	229			
7.5	Mechanical twinning	231			
7.5.1	Crystallography of twinning	231			

8.3	Strengthening of steels by heat-treatment 287	9.6.3	Titanium aluminides 329
8.3.1	Time-temperature-transformation diagrams 287	9.6.4	Other intermetallic compounds 330
8.3.2	Austenite-pearlite transformation 288	9.7	Aluminium alloys 331
8.3.3	Austenite-martensite transformation 291	9.7.1	Designation of aluminium alloys 331
8.3.4	Austenite-bainite transformation 295	9.7.2	Applications of aluminium alloys 331
8.3.5	Tempering of martensite 295	9.7.3	Aluminium-lithium alloys 332
8.3.6	Thermo-mechanical treatments 297	9.7.4	Processing developments 333
8.4	Fracture and toughness 298	10	Ceramics and glasses 335
8.4.1	Griffith micro-crack criterion 298	10.1	Classification of ceramics 335
8.4.2	Fracture toughness 299	10.2	General properties of ceramics 336
8.4.3	Cleavage and the ductile-brittle transition 301	10.3	Production of ceramic powders 337
8.4.4	Factors affecting brittleness of steels 303	10.4	Selected engineering ceramics 338
8.4.5	Hydrogen embrittlement of steels 304	10.4.1	Alumina 338
8.4.6	Intergranular fracture 305	10.4.2	From silicon nitride to sialons 341
8.4.7	Ductile failure 306	10.4.3	Zirconia 345
8.4.8	Rupture 307	10.4.4	Glass-ceramics 347
8.4.9	Voiding and fracture at elevated temperatures 307	10.4.5	Silicon carbide 350
8.4.10	Fracture mechanism maps 309	10.4.6	Carbon 353
8.4.11	Crack growth under fatigue conditions 309	10.5	Aspects of glass technology 361
9	Modern alloy developments 311	10.5.1	Viscous deformation of glass 361
9.1	Introduction 311	10.5.2	Some special glasses 363
9.2	Commercial steels 311	10.5.3	Toughened and laminated glasses 363
9.2.1	Plain carbon steels 311	10.6	The time-dependency of strength in ceramics and glasses 364
9.2.2	Alloy steels 312	11	Plastics and composites 368
9.2.3	Maraging steels 313	11.1	Utilization of polymeric materials 368
9.2.4	High-strength low-alloy (HSLA) steels 313	11.1.1	Introduction 368
9.2.5	Dual-phase (DP) steels 314	11.1.2	Mechanical aspects of T_g 368
9.2.6	Mechanically alloyed (MA) steels 316	11.1.3	The role of additives 369
9.2.7	Designation of steels 317	11.1.4	Some applications of important plastics 370
9.3	Cast irons 318	11.1.5	Management of waste plastics 371
9.4	Superalloys 320	11.2	Behaviour of plastics during processing 372
9.4.1	Basic alloying features 320	11.2.1	Cold-drawing and crazing 372
9.4.2	Nickel-based superalloy development 321	11.2.2	Processing methods for thermoplastics 373
9.4.3	Dispersion-hardened superalloys 322	11.2.3	Production of thermosets 375
9.5	Titanium alloys 323	11.2.4	Viscous aspects of melt behaviour 375
9.5.1	Basic alloying and heat-treatment features 323	11.2.5	Elastic aspects of melt behaviour 377
9.5.2	Commercial titanium alloys 325	11.2.6	Flow defects 378
9.5.3	Processing of titanium alloys 326	11.3	Fibre-reinforced composite materials 379
9.6	Structural intermetallic compounds 327	11.3.1	Introduction to basic structural principles 379
9.6.1	General properties of intermetallic compounds 327	11.3.2	Types of fibre-reinforced composite 384
9.6.2	Nickel aluminides 327	12	Corrosion and surface engineering 395
		12.1	The engineering importance of surfaces 395

12.2 Metallic corrosion	395	12.3.4 Surface modification with high-energy beams	411
12.2.1 Oxidation at high temperatures	395		
12.2.2 Aqueous corrosion	401	Appendices	414
12.3 Surface engineering	407	1 SI units	414
12.3.1 The coating and modification of surfaces	407	2 Conversion factors, constants and physical data	416
12.3.2 Surface coating by vapour deposition	407		
12.3.3 Surface coating by particle bombardment	410	Figure references	418
		Index	421