

CONTENTS

Preface

v

Chapter 1 Microstructure and Mechanical Properties of Titanium Alloys

G. Lütjering, Technical University Hamburg-Harburg, Hamburg, Germany,

J. C. Williams, General Electric Aircraft Engines, Cincinnati, OH, USA, and

A. Gysler, Technical University Hamburg-Harburg, Hamburg, Germany

1. Introduction	1
1.1 Crystal structure	1
1.2 Deformation modes	
1.2.1 Slip modes	2
1.2.2 Deformation twinning	5
1.3 Phase diagrams	
1.4 Phase transformations	
1.4.1 Martensitic transformations	6
1.4.2 Nucleation and diffusional growth	
1.5 Alloy classification	7
1.6 Basic hardening mechanisms	
1.6.1 Hardening of the α phase	
1.6.2 Hardening of the β phase	11
1.7 Basic physical and chemical properties	12
1.7.1 Diffusion	
1.7.2 Oxidation	13
1.7.3 Corrosion behavior	
2. Thermomechanical processing and microstructure	14
2.1 CP titanium	14
2.2 Alpha + Beta alloys	
2.2.1 Bi-modal microstructures	17
2.2.2 Fully lamellar microstructures	21
2.3 Beta alloys	
2.3.1 Beta annealed microstructures	
2.3.2 Bi-modal microstructures	22
2.3.3 Necklace microstructures	
3. Basic correlation between microstructures and mechanical properties	25
3.1 Alpha + Beta alloys	
3.1.1 Fully lamellar microstructures	26
3.1.2 Bi-modal microstructures	29
3.1.3 Bi-lamellar microstructures	
3.2 Beta alloys	37
4. Properties and applications	
4.1 Alpha titanium alloys	44
4.2 Alpha + Beta titanium alloys for high temperature use	48

4.3 High strength Alpha + Beta titanium alloys	50
4.4 Beta titanium alloys.....	58
4.5 Titanium based intermetallic compounds.....	62
4.5.1 Alpha-2 and orthorhombic alloys (~25 at % Al)	63
4.5.2 Gamma alloys (~50 at % Al)	64
5. Titanium production and inspection	70
References	73
Problems	75

Chapter 2 Interfacial Structures and Mechanical Properties of Titanium Aluminides

M. H. Yoo, Metals and Ceramics Division, Oak Ridge National Laboratory, Oak Ridge,
TN 37831-6115, USA, and

M. Yamaguchi, Department of Materials Science and Engineering, Kyoto University, Kyoto
606-8501, Japan

1. Introduction	79
2. Phase stability, bulk and defect properties	
2.1 Crystal structures and parameters	79
2.2 Elastic properties	83
2.3 Defect structures and properties	
2.3.1 Point defects and diffusivity.....	85
2.3.2 Dislocations and planar faults.....	87
3. Deformation of single-phase titanium aluminides	
3.1 γ -TiAl	90
3.1.1 Ordinary slip	91
3.1.2 Superlattice slip	95
3.1.3 Deformation twinning	98
3.2 α_2 -Ti ₃ Al	
3.2.1 Prismatic and basal slip	100
3.2.2 Nonbasal slip and twinning	102
4. Interfacial structures and energies	
4.1 γ/α_2 interfaces in γ/α_2 two-phase titanium aluminides alloys	105
4.1.1 Structures.....	106
4.1.2 Energies and chemistry	111
4.2 γ/α_2 interfaces in two-phase titanium aluminide alloys.....	115
5. Mechanical properties of PST crystals	
5.1 Yield and flow behavior	
5.1.1 Yield stress and tensile ductility	
5.1.2 Easy and hard types of deformation.....	116
5.1.3 Deformation microstructures and operative deformation modes.....	118
5.1.4 Macroscopic deformation compatibility at interfaces.....	121
5.1.5 Comparison between two hard orientations of $\phi = 0^\circ$ and $\phi = 90^\circ$	122
5.1.6 Coherency strains and stresses in lamellar structure	
5.2 Fracture behavior	123

6. Summary	128
7. Acknowledgments	
8. References	129
Problems	137

Chapter 3 Iron Aluminides

N. S. Stoloff, Materials Science and Engineering Department, Rensselaer Polytechnic Institute, Troy, NY 12180-3590, USA, and

C. T. Liu, Metals and Ceramics Division, Oak Ridge National Laboratory, Oak Ridge, TN 37831-6115, USA

1. Introduction	139
2. The Fe-Al phase diagram	139
3. Applications and development potential	141
4. Processing	142
Part 1: Fe ₃ Al Alloys	144
5. Dislocations and antiphase boundaries	
6. Mechanical properties	
6.1 Yielding	144
6.2 Tensile strength and ductility	
6.3 Impact properties	
6.4 Fracture toughness	146
6.5 Creep and stress rupture	148
6.6 Superplasticity	149
7. Environmental resistance	
7.1 Environmental embrittlement	151
7.2 Aqueous corrosion and stress corrosion	153
7.3 Oxidation and hot corrosion	154
8. Alloy development	155
9. Welding	
Part 2: Fe-Al Alloys	156
10. Dislocations and antiphase boundaries	
11. Mechanical properties	
11.1 Vacancy hardening and yield behavior anomaly	156
11.2 Tensile strength and ductility	159
11.3 Impact properties	
11.4 Creep and stress rupture	160
12. Embrittlement phenomena	
12.1 Environmental embrittlement	163
12.2 Grain-boundary weakness in FeAl alloys	165
12.3 Vacancy hardening and embrittlement	167

13. Alloy development	168
14. Oxidation and hot corrosion	169
15. Welding	170
16. Concluding remarks	
17. Acknowledgments	
18. References	171
Problems	177

Chapter 4 Iron and Steels

Chi-Mei Hsiao (Xiao, Jimei), Department of Material Physics, University of Science and Technology of Beijing, Beijing, China, and

Tong-Yi Zhang, Department of Mechanical Engineering, Hong Kong University of Science and Technology, Kowloon, Hong Kong, China

I. Introduction.....	179
1. Methodology of Materialogy	
1.1 One definition of materials	
1.2 Two models regarding materials matters	
1.2.1 Macro-control.....	179
1.2.2 Micro-control	
1.3 One symbol, $P_{\#}$, used for material properties	
1.3.1 Definition.....	180
1.3.2 Classification	
1.3.3 Analysis methods.....	181
1.4 One equation to describe microstructure	182
1.5 Five ways to treat environment	183
1.6 Three principles of natural processing	184
1.7 Eight energy methods of analysis	185
2. Steels	
2.1 Characteristics	186
2.2 Classification	187
II. Structures at various levels	189
1. Pure iron	
1.1 Electronic structure	
1.2 Crystal structure	189
2. Phases and phase diagrams	
2.1 Introduction	
2.1.1 Geometrical factor – atomic diameter	192
2.1.2 Chemical factor – electronegativity	
2.1.3 Electronic factor – relative valency	
2.2 Interstitial solid solution and the Fe-C phase diagram.....	193
2.3 Substitutional solid solutions and alloy steels	195

2.4 Carbides and nitrides	196
2.5 Ternary and more complicated ferrous alloys	
3. Grain boundary segregation	197
4. Phase transformation and heat treatment	
4.1 Pearlite and normalizing	198
4.2 Martensite and quenching	200
4.3 Bainite	201
4.4 Transformation diagram and hardenability	202
4.5 Tempering of martensite	203
4.6 Spheroidizing and annealing	205
5. Deformation and Recrystallization	
5.1 Deformation	
5.1.1 Iron and ferritic steel	206
5.1.2 Austenitic steels	
5.2 Recovery and recrystallization	
5.2.1 Recovery	207
5.2.2 Recrystallization	
5.2.3 Kinetics of recrystallization	210
III. Strength, Ductility and Strengthening.....	216
1. Introduction	216
2. Composition – solid solution hardening	219
3. Strengthening by heat treatment	
3.1 Grain refinement	
3.2 Second-phase hardening and precipitation hardening	
3.2.1 Undeformable particles	220
3.2.2 Deformable particles	
3.2.3 Massive second-phase particles or aggregates	222
3.3 Effect of transformation temperature	223
4. Work hardening	
5. Ductility and formability	
5.1 Structural factors affecting ductility.....	224
5.2 Formability	
5.2.1 Cold forming processes	225
5.2.2 Important mechanical parameters	226
5.2.3 Hot ductility	228
IV. Toughness and Toughening	230
1. Logic analysis	
1.1 Smooth specimen under tension	230
1.2 Notched specimen under impact	
1.3 Pre-cracked specimen under tension or bending	
1.3.1 Critical stress intensity factor	231
1.3.2 Critical energy release rate	
1.3.3 Displacement or strain	232

2. System analysis	233
2.1 Stress, strain and energy – black box method.....	235
2.2 Extrinsic and intrinsic factors – environment and structure	
2.2.1 Extrinsic factors	236
2.2.2 Intrinsic factors.....	239
2.3 Energy and process	
2.3.1 Fracture criteria	
2.3.2 Fracture processing.....	240
2.3.3 Fractography	
2.4 Toughness and brittleness	
3. Summary.....	241
V. Environmental Cracking.....	243
1. Methodology	
1.1 Logic analysis	
1.2 System analysis	243
2. Mechanisms	
2.1 HIC in metals	
2.1.1 Enrichment of hydrogen.....	245
2.1.2 Strain field of hydrogen atom in α -Fe and HIC under Mode II or Mode III loading	247
2.1.3 Hydrogen induced phase transformation	248
2.1.4 Experimental evidence of energy analysis.....	249
2.1.5 Chemical reaction with hydrogen gas at high temperature and high pressure	251
2.1.6 Hydrogen diffusion through the surface and in the bulk of α -Fe.....	252
2.2 SCC of metallic materials	
2.2.1 Electrochemical consideration and SCC systems.....	253
2.2.2 Local environment	255
2.3 HIC and SCC of intermetallic compounds	257
3. Measures for prevention	
3.1 HIC	258
3.2 Anodic dissolution type of SCC.....	259
VI. Structural Steels.....	261
1. Low carbon mild steels	
1.1 General	
1.2 Property and microstructure	261
1.3 Processing.....	262
2. High strength low-alloy (HSLA) steels	
2.1 General.....	262
2.2 Property and microstructure	263
2.3 Processing.....	266

3. Medium-high carbon ferrite-pearlite steels	
3.1 General	
3.2 Property and microstructure	267
3.3 Processing	270
4. Medium carbon quenched and high temperature tempered steels	
4.1 General	
4.2 Property, microstructure and processing	271
5. Ultra-high strength (UHS) steels	
5.1 General	280
5.2 Property, microstructure and processing	281
5.2.1 Modification of conventional steels	282
5.2.2 Developing new steels	283
5.2.3 Other strengthening processing	284
6. Low carbon bainite steels	
6.1 General	
6.2 Property and microstructure	285
6.3 Processing	286
7. Other structural steels	
7.1 Low temperature steels	287
7.2 Spring steels	288
VII. Special Alloy Steels	290
1. Stainless steels	
1.1 Corrosion	290
1.2 Steels – property, microstructure and processing	293
1.3 Intergranular corrosion	297
2. High temperature steels	
2.1 Property and microstructures	298
2.2 Steels	304
3. Wear resistant steels	
3.1 Friction and wear	
3.1.1 Concept	
3.1.2 Fundamental processes	305
3.2 Property – wearability	
3.3 Steels with high wear resistance	307
3.4 Tool steels	308
3.5 High speed steels	
3.5.1 Hot hardness	311
3.5.2 Steels	312
4. Steels with other special physical properties	
4.1 Magnetic and electrical properties	314
4.2 Acoustic and mechanical properties	
4.3 Thermal and chemical properties	315

VIII. Design against Fracture	317
1. General methodology for material design	
1.1 From failure analysis to material design	317
1.2 Structural design	318
2. Design of high creep strength steels	
2.1 Introduction and objectives	319
2.2 Results and use of the nomograph	320
3. Design of steels against intergranular fracture	
3.1 Objective	
3.2 Modeling	
3.2.1 Equilibrium grain boundary segregation	321
3.2.2 Effect of impurities on intergranular fracture	323
4. Design of steels against environmental cracking	325
IX. Concluding Remarks	325
Acknowledgments	
References	326
Problems	332

Chapter 5 Synthesis and Soft Magnetic Properties of Fe-Based Bulk Amorphous Alloys

Akihisa Inoue, Akira Takeuchi and Tao Zhang, Institute for Materials Research, Tohoku University, Sendai 980-77, Japan

1. History of Fe-based amorphous alloys	335
2. Glass-forming ability and its dominant factors	336
3. Formation and mechanical properties of bulk amorphous alloys	339
4. Viscous flow of bulk amorphous alloys in the supercooled liquid region	341
5. Formation of Fe-(Al,Ga)-(P,C,B,Si) bulk amorphous alloys and their soft magnetic properties	342
6. Formation of Fe-based thick amorphous ribbons by melt spinning and their soft magnetic properties	346
7. Formation of Fe-(Co,Ni)-Zr-B bulk amorphous alloys and their soft magnetic properties	347
8. Formation of Co-based amorphous alloys with a wide supercooled liquid region and their soft magnetic properties	349
9. Formation of bulk amorphous Nd-Fe-Al alloys and their magnetic properties	351
10. Conclusions	
References	356

Chapter 6 Nanocrystalline Materials

C. C. Koch, Department of Materials Science and Engineering, North Carolina State University, Raleigh, NC 27695-7907, and

C. Suryanarayana, Department of Metallurgical and Materials Engineering, Colorado School of Mines, Golden, CO 80401-1887

1. Introduction/historical	360
2. Classification	360
3. Preparation	
3.1 From the vapor phase.....	362
3.1.1 Inert gas condensation	363
3.1.2 Sputtering	
3.1.3 Electron beam vapor deposition	
3.1.4 Plasma processing	
3.1.5 Chemical vapor condensation	364
3.2 From the liquid phase	
3.2.1 Rapid solidification	
3.2.2 Electrodeposition	
3.2.3 Chemical reactions	
3.3 From the solid state	
3.3.1 Mechanical attrition	365
3.3.2 Devitrification	
3.3.3 Spark erosion	366
3.3.4 Sliding wear	
4. Structure	367
4.1 Microstructure – grain size and measurement techniques	368
4.2 Atomic structure of the crystal lattice	
4.3 Atomic structure of the grain boundaries	369
4.4 Triple junctions and higher-order grain junctions	370
5. Stability	
5.1 Grain growth in nanocrystalline materials	371
5.2 Grain growth at ambient temperature	372
5.3 Examples of grain growth inhibition	
5.4 Isothermal grain growth kinetics	373
6. Particulate consolidation while maintaining a nano-scale microstructure	
6.1 Electro-discharge compaction	
6.2 Plasma activated sintering	375
6.3 Shock consolidation	
6.4 Hot isostatic pressing	376
6.5 Ceracon processing	
6.6 Sinter forging	
7. Properties of nanoscale materials	
7.1 Diffusion and sinterability	377

7.2 Physical properties	
7.2.1 Thermal expansion	
7.2.2 Specific heat	379
7.3 Mechanical properties	
7.3.1 Elastic properties	
7.3.2 Hardness and strength	380
7.3.3 Ductility and toughness	382
7.3.4 Superplastic behavior	384
7.3.5 Deformation mechanisms in nanoscale materials	385
7.4 Electrical properties	
7.4.1 Electrical resistivity	386
7.4.2 Giant magnetoresistance	
7.5 Magnetic properties	
7.5.1 Fundamental properties	387
7.5.2 Soft magnetic materials	388
7.5.3 Hard magnetic materials	
7.5.4 Other ferromagnetic nanocrystalline materials	389
7.6 Optical and semiconducting properties – quantum confinement	
7.7 Chemical properties	
7.7.1 Corrosion behavior	390
7.7.2 Catalytic properties	391
8. Applications of nanocrystalline materials – present and potential	
8.1 Structural applications	
8.1.1 Cutting tools	
8.1.2 Nanocomposites	392
8.1.3 Superplastic materials	
8.1.4 Coatings	
8.2 Magnetic applications	394
8.3 Catalysts and hydrogen storage materials	
8.4 Functional nanostructures – electronic applications	
9. Summary	395
References	396
Problems	403
Subject Index	405
Author Index	423