

# Contents

---

---

<b>Preface</b> . . . . .	<b>ix</b>
<b>About the Editor</b> . . . . .	<b>xi</b>
<b>Chapter 1</b>	
<b>History and Extractive Metallurgy</b> . . . . .	<b>1</b>
Historical Background . . . . .	1
The Early Titanium Industry and More Recent Developments . . . . .	2
Ores and Their Occurrences . . . . .	9
The Metal Titanium . . . . .	9
General Properties and Alloying Behavior . . . . .	15
Mechanical Properties . . . . .	16
Special Chemical and Physical Properties . . . . .	17
Economics . . . . .	17
Process Challenges . . . . .	18
Extractive Metallurgy . . . . .	19
Summary . . . . .	27
<b>Chapter 2</b>	
<b>Introduction to Solidification and Phase Diagrams</b> . . . . .	<b>31</b>
Atoms . . . . .	31
Solidification of Metals . . . . .	32
Alloying . . . . .	35
Phase Diagrams . . . . .	37
Summary . . . . .	47
Glossary . . . . .	48
<b>Chapter 3</b>	
<b>Principles of Alloying Titanium</b> . . . . .	<b>51</b>
Atomic Structure of Titanium . . . . .	51
Alloying Elements . . . . .	56
Titanium Alloys . . . . .	66
Terminal Alloy Formulation . . . . .	71
Intermetallic compounds $Ti_3Al$ and $TiAl$ . . . . .	71
Summary . . . . .	72

<b>Chapter 4</b>	
<b>Principles of Beta Transformation and Heat Treatment of Titanium Alloys . . . . .</b>	<b>75</b>
Beta Transformation . . . . .	75
Metastable Phases and Metastable Phase Diagrams . . . . .	77
Transformation Kinetics . . . . .	84
Heat Treatment . . . . .	86
Summary . . . . .	93
<b>Chapter 5</b>	
<b>Deformation and Recrystallization of Titanium and Its Alloys . . . . .</b>	<b>95</b>
Deformation . . . . .	95
Development of Texture in Titanium . . . . .	98
Texture Strengthening . . . . .	99
Strain Hardening . . . . .	102
Strain Effects . . . . .	104
Superplasticity . . . . .	104
Internal Changes . . . . .	105
Annealing . . . . .	106
Neocrystallization . . . . .	108
Gamma Titanium Aluminide . . . . .	110
Summary . . . . .	110
<b>Chapter 6</b>	
<b>Mechanical Properties and Testing of Titanium Alloys . . . . .</b>	<b>113</b>
Effect of Alpha Morphology on Titanium Alloy Behavior . . . . .	113
Hardness . . . . .	116
Tensile Strength . . . . .	116
Ductility . . . . .	118
Creep and Stress Rupture . . . . .	119
Fatigue Strength . . . . .	121
Toughness . . . . .	125
Fatigue Crack Growth Rate . . . . .	129
High-Temperature Near-Alpha Alloys . . . . .	130
Alpha-Beta Alloys . . . . .	131
Beta Alloys . . . . .	133
Titanium Aluminides . . . . .	133
Metal-Matrix Composites . . . . .	136
Shape Memory Alloys . . . . .	138
Summary . . . . .	139
<b>Chapter 7</b>	
<b>Metallography of Titanium and Its Alloys . . . . .</b>	<b>141</b>
Review of Physical Metallurgy—Alpha and Beta . . . . .	141
Terminology Used to Describe Titanium Alloys Structures . . . . .	143
Metastable Phases . . . . .	146
Related Terms . . . . .	149
Ordered Intermetallic Compounds . . . . .	151
Effect of Fabrication and Thermal Treatment on Microstructure . . . . .	152

Metallographic Specimen Preparation . . . . .	154
Summary . . . . .	154
Glossary . . . . .	155
Appendix—Metallographic Preparation . . . . .	157
<b>Chapter 8</b>	
<b>Melting, Casting, and Powder Metallurgy . . . . .</b>	<b>161</b>
Melting . . . . .	161
Casting . . . . .	168
Titanium Powder Metallurgy . . . . .	176
Safety . . . . .	200
Future Developments in Titanium Powder Metallurgy . . . . .	202
Summary . . . . .	203
Glossary of Acronyms . . . . .	203
<b>Chapter 9</b>	
<b>Primary Working . . . . .</b>	<b>207</b>
Crystal Structure . . . . .	207
Forging . . . . .	208
Ingot Breakdown . . . . .	208
Forged Billets and Bars . . . . .	210
Rolling . . . . .	211
Radial Precision Forging Machines . . . . .	212
Rolled Rod and Bar . . . . .	212
Plate, Sheet, Coil, and Foil Rolling . . . . .	214
Extrusion . . . . .	216
Wire and Tube Processing . . . . .	219
Summary . . . . .	221
<b>Chapter 10</b>	
<b>Secondary Working of Bar and Billet . . . . .</b>	<b>225</b>
Physical Metallurgy . . . . .	225
Forging . . . . .	226
Classes of Forgings . . . . .	228
Extrusion . . . . .	231
Microstructure and Mechanical Properties . . . . .	234
Surface Effects of Heating . . . . .	239
Modeling . . . . .	240
Summary . . . . .	240
Glossary . . . . .	241
<b>Chapter 11</b>	
<b>Forming of Titanium Plate, Sheet, Strip, and Tubing . . . . .</b>	<b>243</b>
Forming Considerations . . . . .	243
Preparation for Forming . . . . .	245
Heating Methods . . . . .	246
Forming Lubricants . . . . .	247
Tooling Materials . . . . .	247
Forming Processes . . . . .	247
Summary . . . . .	262

<b>Chapter 12</b>	
<b>Joining Titanium and Its Alloys</b>	<b>265</b>
Welding	265
Welding Procedures	269
Brazing	283
Soldering	285
Adhesive Bonding	286
Mechanical Fastening	287
Summary	290
<b>Chapter 13</b>	
<b>Machining and Chemical Shaping of Titanium</b>	<b>293</b>
Machinability	293
General Machining Requirements	295
Scrap Prevention	299
Hazards and Safety Considerations	300
Milling Titanium	300
Turning, Facing, and Boring	305
Drilling Titanium	313
Surface Grinding	318
Broaching	319
Tapping	319
Recent Advances in Machining	320
Flame Cutting	322
Chemical Machining	323
Electrochemical Machining	327
Summary	328
<b>Chapter 14</b>	
<b>Corrosion</b>	<b>331</b>
Corrosion Behavior of Titanium	331
Forms of Corrosion	335
Alloying for Corrosion Prevention	345
Chemical and Related Applications	347
Summary	350
<b>Chapter 15</b>	
<b>Applications of Titanium</b>	<b>353</b>
Early Applications	353
Material Availability	353
Aerospace Applications	354
Sheet Metal Applications	362
Industrial Applications	363
Engineering Properties	363
Medical Applications	370
Consumer Applications	372
Armor Applications	373
Automotive Applications	374

Building Applications . . . . .	375
Power Utility Applications . . . . .	375
Marine Applications . . . . .	378
Miscellaneous Applications. . . . .	378
Summary . . . . .	379
<b>Index. . . . .</b>	<b>381</b>