Contents

List of contributors xv
Preface xxi
About the editors xxiii

Section 1 Titanium alloy properties, fabrication approaches and alloy design for biomedical use 1

1.1 Titanium for medical and dental applications—An introduction 3
F.H. (Sam) Froes
1.1.1 Background 3
1.1.2 Body implants 5
1.1.3 Dental implants 10
1.1.4 Titanium surgical instruments 11
1.1.5 Titanium in wheel chairs, etc. 13
1.1.6 Specifications for titanium in medical and dental applications 13
1.1.7 Other titanium-based materials 13
1.1.8 Post script 19
1.1.9 This book 19
References 20

1.2 Titanium background, alloying behavior and advanced fabrication techniques—An overview 23
F.H. (Sam) Froes, M. Qian
1.2.1 Titanium alloys and their importance 23
1.2.2 Metallurgy of the titanium system 26
1.2.3 Advanced fabrication techniques for titanium components 27
1.2.4 Conclusions 35
Acknowledgments 35
References 35

1.3 The molecular orbital approach and its application to biomedical titanium alloy design 39
M. Morinaga
1.3.1 Introduction 39
1.3.2 Theory of alloy design 39

1.3.3 Molecular orbital calculation and alloying parameters of titanium alloys 45
1.3.4 Correlation of alloying parameters with alloy properties 48
1.3.5 Alloy design of titanium alloys 55
1.3.6 Conclusion 62
Acknowledgments 62
References 62

1.4 Titanium and titanium alloys: Materials, review of processes for orthopedics and a focus on a proprietary approach to producing cannulated bars for screws and nails for trauma 65
F. Ory, J.L. Fraysse
1.4.1 General processes for titanium alloys: From ore to bar material 65
1.4.2 Families of titanium and titanium alloys for orthopedics 66
1.4.3 Proprietary approach to producing cannulated bars for screws and nails for trauma 75
1.4.4 Summary 91
References 91

Section 2 Surface biofunctionalization of titanium and titanium alloys for biomedical applications 93

2.1 Transition of surface modification of titanium for medical and dental use 95
T. Hanawa
2.1.1 Clinical demands and purpose of surface modification 95
2.1.2 Surface of titanium 100
2.1.3 Surface modification techniques 104
2.1.4 Transient of surface modification 109
2.1.5 Application to regenerative medicine 110
2.1.6 Future of surface modification 110
References 111

2.2 Modern techniques of surface geometry modification for the implants based on titanium and its alloys used for improvement of the biomedical characteristics 115
E.G. Zemtsova, A.Y. Arbenin, R.Z. Valiev, V.M. Smirnov
2.2.1 Introduction 115
2.2.2 Classical methods of the surface geometry modification of titanium implants 122
2.2.3 Prospective methods of geometry implant surface changes to create a two-level hierarchy of topography 134

2.2.4 The practical application of the coating with a two-level hierarchy of the surface relief in implantology 139
2.2.5 Conclusion 139
Acknowledgments 140
References 140

2.3 Nanobioceramic thin films: Surface modifications and cellular responses on titanium implants 147
A.H. Choi, S. Akyol, A. Bendavid, B. Ben-Nissan
2.3.1 Introduction 147
2.3.2 Adhesion of thin films and coatings 149
2.3.3 Anodic oxidation (anodizing) of titanium surfaces 151
2.3.4 Surface coatings on titanium 153
2.3.5 Stresses in thin films and coatings 157
2.3.6 Stress and adhesion measurement techniques 158
2.3.7 Cellular responses and biological activities 164
2.3.8 Concluding remarks 167
References 168

2.4 Ti-Nb-Zr system and its surface biofunctionalization for biomedical applications 175
M. Dinu, S. Franchi, V. Pruna, C.M. Cotrut, V. Secchi, M. Santi, I. Titorencu, C. Battocchio, G. Iucci, A. Vladescu
2.4.1 Introduction 175
2.4.2 Classification of titanium alloys 176
2.4.3 Fabrication of titanium alloys 177
2.4.4 Titanium alloy types used in medicine 178
2.4.5 Elastic modulus of Ti-Nb-Zr system 180
2.4.6 Corrosion resistance of the Ti-Nb-Zr system 181
2.4.7 In vitro biological properties of the Ti-Nb-Zr system 182
2.4.8 Methods for improving the bioactivity of the Ti-Nb-Zr system 187
Acknowledgments 192
References 192

Section 3 Additive manufacturing of titanium and titanium alloys for implant applications 201

3.1 Design of titanium implants for additive manufacturing 203
M. Leary
3.1.1 Introduction 203
3.1.2 Additive manufacture 204
3.1.3 Manufacturability 206
3.1.4 Cellular structures and lattice design 211

3.1.5 Data management 212
3.1.6 Geometry conformance 215
3.1.7 Topology optimization 216
3.1.8 Just-in-time implant philosophy 217
Acknowledgments 218
References 218

3.2 Anatomics 3D-printed titanium implants from head to heel 225
R.G. Thompson
3.2.1 Anatomics—Company overview 225
3.2.2 3D-printed titanium implants—Selected case studies 226
3.2.3 Conclusion 235
References 236

3.3 Ti-6Al-4V orthopedic implants made by selective electron beam melting 239
H.P. Tang, P. Zhao, C.S. Xiang, N. Liu, L. Jia
3.3.1 Introduction 239
3.3.2 Feedstock material and the SEBM manufacturing process 240
3.3.3 Microstructural characteristics and mechanical properties of SEBM-fabricated Ti-6Al-4V 241
3.3.4 Case study 1: SEBM-fabricated ELI Ti-6Al-4V ankle implants 243
3.3.5 Case study 2: SEBM-fabricated ELI Ti-6Al-4V cervical vertebral fusion cages 243
3.3.6 Case study 3: SEBM-fabricated ELI Ti-6Al-4V sacral vertebral fusion cages 244
3.3.7 Other Ti-6Al-4V bone implants manufactured by Xi'an Sailong Metal Materials Co. Ltd. 246
3.3.8 Conclusion and outlook 248
Acknowledgments 248
References 248

3.4 3D-printed titanium alloys for orthopedic applications 251
A. Kumar, R.D.K. Misra
3.4.1 Introduction 251
3.4.2 Metallic biomaterials 252
3.4.3 Titanium alloys 253
3.4.4 Toxicological effect of titanium alloys 254
3.4.5 3D printing of titanium alloy scaffolds 255
3.4.6 Biocompatibility of titanium alloys 256
3.4.7 Vascularization of 3D scaffolds with designed porous architecture 262
3.4.8 Antibacterial effect of titanium alloys 264
3.4.9 Conclusions 265
References 267

3.5 Ti-6Al-4V lattice structures fabricated by electron beam melting for biomedical applications 277
S. Zhao, W.T. Hou, Q.S. Xu, S.J. Li, Y.L. Hao, R. Yang
3.5.1 Introduction 277
3.5.2 Design of Ti-6Al-4V cellular structures 278
3.5.3 Fabrication of Ti-6Al-4V cellular structures 278
3.5.4 Surface characteristics and microstructure of Ti-6Al-4V cellular structures 280
3.5.5 Mechanical properties of Ti-6Al-4V cellular structures 280
3.5.6 Biocompatibility of Ti-6Al-4V cellular structures 291
3.5.7 Conclusion and future research trends 295
Acknowledgments 297
References 297

3.6 Additive manufacturing of cp-Ti, Ti-6Al-4V and Ti2448 303
T.B. Sercombe, L.-C. Zhang, S. Li, Y. Hao
3.6.1 Introduction 303
3.6.2 Additive manufacturing 306
3.6.3 Additive manufacturing of Ti2448 310
3.6.4 Biocompatibility of AM porous Ti 319
3.6.5 Summary 320
References 321
Further reading 324

3.7 Additive manufacturing of titanium and titanium alloys for biomedical applications 325
J.D. Avila, S. Bose, A. Bandyopadhyay
3.7.1 Introduction 325
3.7.2 Additive manufacturing processes 327
3.7.3 Challenges and future trends 338
Acknowledgments 339
References 340

Section 4 Titanium for implant applications 345

4.1 Titanium spinal-fixation implants 347
M. Niinomi
4.1.1 Introduction 347
4.1.2 Requirements for spinal-fixation rods 348
4.1.3 Advantages of Ti alloys with low rigidity for spinal-fixation implants 350
4.1.4 Improvement of the strength of low rigidity Ti alloys while keeping low rigidity 351

4.1.5 Ti alloys with changeable Young's moduli for spinal-fixation implants **359**
4.1.6 Applications in cage and wire for spinal-fixation implants **361**
4.1.7 Summary **366**
References **367**

4.2 Biocompatible beta-Ti alloys with enhanced strength due to increased oxygen content **371**
J. Stráský, M. Janeček, P. Harcuba, D. Preisler, M. Landa
4.2.1 Introduction **371**
4.2.2 Effect of oxygen content on phase stability and elastic modulus in biomedical β-Ti alloys **375**
4.2.3 Effect of oxygen on strength **380**
4.2.4 The case study: The Ti-Nb-Zr-ta-O alloy for load-bearing implant manufacturing **384**
4.2.5 The applicability of biomedical β-Ti alloys with increased oxygen content in orthopedics **386**
Acknowledgments **387**
References **388**

4.3 Nanostructured commercially pure titanium for development of miniaturized biomedical implants **393**
R.Z. Valiev, I. Sabirov, E.G. Zemtsova, E.V. Parfenov, L. Dluhoš, T.C. Lowe
4.3.1 Introduction **393**
4.3.2 Material and methods **394**
4.3.3 Design of miniaturized implants **395**
4.3.4 Nano-Ti studies and implant characterization **396**
4.3.5 Surface modification of nano Ti implants **403**
4.3.6 Conclusions **411**
Acknowledgments **412**
References **412**

4.4 Mechanical performance and cell response of pure titanium with ultrafine-grained structure produced by severe plastic deformation **419**
Y. Estrin, R. Lapovok, A.E. Medvedev, C. Kasper, E. Ivanova, T.C. Lowe
4.4.1 Introduction **419**
4.4.2 Manufacturing of ultrafine-grained and nanostructured commercially pure Ti by SPD **420**
4.4.3 Mechanical performance of SPD-modified CP Ti with a focus on fatigue strength **424**
4.4.4 Enhancement of cell adhesion and proliferation on surfaces of SPD-processed CP titanium **426**

4.4.5 Effect of surface treatment by the commonly used SLA technique on the mechanical and biological properties of CP titanium 437
4.4.6 Recommendations for Ti implant manufacturers 445
4.4.7 Conclusions 448
Acknowledgments 448
References 449

4.5 Microstructure and lattice defects in ultrafine grained biomedical α+β and metastable β Ti alloys 455
J. Stráský, M. Janeček, I. Semenova, J. Čížek, K. Bartha, P. Harcuba, V. Polyakova, S. Gatina
4.5.1 Introduction 455
4.5.2 Strain accumulation, grain refinement, and Hall-Petch strengthening 456
4.5.3 Dislocations and vacations/point defects in biomedical Ti alloys prepared by severe plastic deformation 462
4.5.4 Mechanical properties of UFG biomedical Ti alloys 466
4.5.5 Microstructural stability and phase transformations in UFG biomedical Ti alloys 468
4.5.6 Applicability of UFG Ti and Ti alloys as orthopedic implants 471
Acknowledgments 472
References 472

4.6 Aluminum- and vanadium-free titanium alloys for application in medical engineering 477
C. Siemers, M. Bäker, F. Brunke, D. Wolter, H. Sibum
4.6.1 Introduction and state of the art 477
4.6.2 Simulation and experimental procedures 479
4.6.3 Choice of alloying elements and alloy compositions 481
4.6.4 Interaction between the alloying elements and titanium 483
4.6.5 Results of the experimental investigations and discussion 484
4.6.6 Conclusions and future work 489
Acknowledgments 490
References 490
Further reading 492

Section 5 Titanium implants for dental applications 493

5.1 Why titanium in dental applications? 495
H.S. Baumgarten
5.1.1 Introduction 495
5.1.2 Titanium in dental implants 495
5.1.3 Titanium in restorative dentistry 497

5.1.4 Titanium in oral and maxillofacial surgery 499
5.1.5 Titanium in orthodontics 501
5.1.6 Titanium in endodontics 502
5.1.7 Conclusion 503
References 503

5.2 The role of titanium in implant dentistry 505
P. Gubbi, T. Wojtisek
5.2.1 Historical background of dental implants 505
5.2.2 Influence of characteristics of dental implant surface on its osseointegration 519
Acknowledgments 526
References 526

5.3 Titanium MIM for manufacturing of medical implants and devices 531
T. Ebel
5.3.1 The technology of metal injection molding 531
5.3.2 Challenges of titanium MIM 536
5.3.3 Current success and research of titanium MIM 539
5.3.4 Case studies of medical components made by titanium MIM 546
5.3.5 Summary and outlook 548
References 549

Section 6 Nitinol and Ni-free superelastic titanium alloys in medical and dental applications 553

6.1 The metallurgy of Nitinol as it pertains to medical devices 555
T. Duerig
6.1.1 The metallurgy of Nitinol 555
6.1.2 Mechanical properties and their value to medical devices 563
6.1.3 Direction forward 568
References 569

6.2 The effect of Nitinol on medical device innovation 571
D.B. Spenciner, J.J. Scutti
6.2.1 Introduction 571
6.2.2 Methods 572
6.2.3 Results 574
6.2.4 Discussion 580
References 581

6.3 Advanced TiNi shape memory alloy stents fabricated by a powder metallurgy route 583
K. Kondoh, J. Umeda, R. Soba, Y. Tanabe
6.3.1 Introduction 583
6.3.2 Preparation of TiNi SMAs by the powder metallurgy process 585

6.3.3 Microstructures and mechanical properties of PM TiNi SMAs 586
6.3.4 Fundamental properties of PM TiNi SMA stents 588
6.3.5 Conclusion and outlook 589
Acknowledgments 590
References 590

6.4 Ni-free superelastic titanium alloys for medical and dental applications 591
A. Ramezannejad, W. Xu, M. Qian
6.4.1 Introduction 591
6.4.2 Metallurgical aspects of superelasticity 592
6.4.3 Stress-induced transformation 592
6.4.4 Alloy design (superelasticity) and the origin of superelasticity in NiTi 594
6.4.5 Potential health hazards of Ni-Ti alloys 596
6.4.6 Recent Ni-free superelastic alloys 596
6.4.7 Role of alloying elements (Ni-free) 599
6.4.8 Strain accommodation 602
6.4.9 Crystallographic texture 604
6.4.10 Current applications 607
6.4.11 Concluding remarks 608
Acknowledgments 608
References 608

Index 613