Titanium Powder Metallurgy

Science, Technology and Applications

EDITED BY
MA QIAN
FRANCIS H. FROES

BH

Titanium Powder Metallurgy

Science, Technology and Applications

Ma Qian

RMIT University, School of Aerospace, Mechanical and Manufacturing Engineering, Centre for Additive Manufacture, Melbourne, Victoria, Australia

Francis H. (Sam) Froes

Consultant to the Titanium Industry, Tacoma, WA, USA

ELSEVIER

AMSTERDAM • BOSTON • HEIDELBERG • LONDON
NEW YORK • OXFORD • PARIS • SAN DIEGO
SAN FRANCISCO • SINGAPORE • SYDNEY • TOKYO
Butterworth-Heinemann is an imprint of Elsevier

Butterworth-Heinemann is an imprint of Elsevier
225 Wyman Street, Waltham, MA 02451, USA
The Boulevard, Langford Lane, Kidlington, Oxford OX5 1GB, UK

Notices

Knowledge and best practice in this field are constantly changing. As new research and experience broaden our understanding, changes in research methods, professional practices, or medical treatment may become necessary.

Practitioners and researchers must always rely on their own experience and knowledge in evaluating and using any information, methods, compounds, or experiments described herein. In using such information or methods they should be mindful of their own safety and the safety of others, including parties for whom they have a professional responsibility.

To the fullest extent of the law, neither the Publisher nor the authors, contributors, or editors, assume any liability for any injury and/or damage to persons or property as a matter of products liability, negligence or otherwise, or from any use or operation of any methods, products, instructions, or ideas contained in the material herein.

Library of Congress Cataloging-in-Publication Data

Qian, Ma, author.
Titanium powder metallurgy / by Ma Qian, Francis H. Froes. – First edition.
pages cm
Includes bibliographical references and index.
ISBN 978-0-12-800054-0
1. Powder metallurgy. 2. Titanium alloys. I. Froes, F. H., author. II. Title.
TN697.T5Q27 2015
669'.7322–dc23

2014034817

British Library Cataloguing-in-Publication Data
A catalogue record for this book is available from the British Library

For information on all Butterworth-Heinemann publications visit our website at http://store.elsevier.com/

This book has been manufactured using Print On Demand technology. Each copy is produced to order and is limited to black ink. The online version of this book will show color figures where appropriate.

ISBN: 978-0-12-800054-0

List of contributors

Stanley Abkowitz Dynamet Technology, Inc. (now RTI Advanced Powder Materials a unit of RTI International)

Susan Abkowitz Dynamet Technology, Inc. (now RTI Advanced Powder Materials a unit of RTI International)

Kamal Akhtar Director of Technology and Quality, Cristal Metals Inc., Lockport, IL, USA

Kerem Araci Process Development Engineer, Technology and Quality, Cristal Metals Inc., Lockport, IL, USA

Daniel P. Barbis AMETEK Specialty Metal Powders

Christopher C. Berndt Industrial Research Institute Swinburne, Faculty of Science, Engineering and Technology, Swinburne University of Technology, Hawthorn, Australia; Department of Materials Science and Engineering, Stony Brook University, NY, USA

R.R. Boyer Retired Boeing Technical Fellow, Seattle, WA, USA

G.M.D. Cantin CSIRO Process Science and Engineering, Clayton South MDC, Victoria, Australia

Joseph A. Capone AMETEK Specialty Metal Powders

Richard R. Chromik Department of Mining and Materials Engineering, McGill University, Montréal, Québec, Canada

L.P. Clark Retired Boeing, Phoenix, AZ, USA

Melchiorre Conti Metalysis Limited, Wath-upon-Dearne, Rotherham, United Kingdom

James Deane Metalysis Limited, Wath-upon-Dearne, Rotherham, United Kingdom

Greg Doughty Metalysis Limited, Wath-upon-Dearne, Rotherham, United Kingdom

B. Dutta DM3D Technology, Auburn Hills, MI, USA

Z. Zak Fang Department of Metallurgical Engineering, University of Utah, Salt Lake City, UT, USA

Thomas Ebel Helmholtz-Zentrum Geesthacht, Zentrum für Material- und Küstenforschung GmbH, Geesthacht, Germany

Sami M. El-Soudani Associate Technical Fellow, The Boeing Company, Huntington Beach, CA, USA

Harvey Fisher Dynamet Technology, Inc. (now RTI Advanced Powder Materials a unit of RTI International)

V. Friederici Fraunhofer-Institut für Fertigungstechnik und Angewandte Materialforschung IFAM, Bremen, Germany

Francis H. (Sam) Froes Consultant to the Titanium Industry, Tacoma, WA, USA

Jo Ann Gan Industrial Research Institute Swinburne, Faculty of Science, Engineering and Technology, Swinburne University of Technology, Hawthorn, Australia; Research Services, La Trobe University, Melbourne, Australia

Robert M. Gasior AMETEK Specialty Metal Powders

Randall M. German Professor, Mechanical Engineering, San Diego State University, San Diego, CA, USA

M.A. Gibson CSIRO Process Science and Engineering, Clayton South MDC, Victoria, Australia

Dina Goldbaum Department of Mining and Materials Engineering, McGill University, Montréal, Québec, Canada

Lucy Grainger Metalysis Limited, Wath-upon-Dearne, Rotherham, United Kingdom

T. Hartwig Fraunhofer-Institut für Fertigungstechnik und Angewandte Materialforschung IFAM, Bremen, Germany

M. Ashraf Imam Materials Science and Technology Division, Naval Research Laboratory, Washington DC, USA

P. Imgrund Fraunhofer-Institut für Fertigungstechnik und Angewandte Materialforschung IFAM, Bremen, Germany

Eric Irissou National Research Council Canada, Boucherville, Québec, Canada

Orest Ivasishin Institute for Metal Physics, Kiev, Ukraine

Mingtu Jia Waikato Centre for Advanced Materials, School of Engineering, The University of Waikato, Hamilton, New Zealand

Katsuyoshi Kondoh Osaka University, Joining and Welding Research Institute (JWRI), Ibaragi, Osaka, Japan

Jean-Gabriel Legoux National Research Council Canada, Boucherville, Québec, Canada

Bin Liu State Key Lab of Powder Metallurgy, Central South University, Changsha, P.R. China

Yong Liu State Key Lab of Powder Metallurgy, Central South University, Changsha, P.R. China

Shudong D. Luo The University of Queensland, School of Mechanical and Mining Engineering, Brisbane, Australia

Damien Mangabhai Quality Superintendent, Technology and Quality, Cristal Metals Inc., Ottawa, IL, USA

Ian Mellor Metalysis Limited, Wath-upon-Dearne, Rotherham, United Kingdom

Vladimir Moxson ADMA Products, Inc., Hudson, OH, USA

James D. Paramore Department of Metallurgical Engineering, University of Utah, Salt Lake City, UT, USA

Ma Qian RMIT University, School of Aerospace, Mechanical and Manufacturing Engineering, Centre for Additive Manufacture, Melbourne, Victoria, Australia

Kartik Rao Metalysis Limited, Wath-upon-Dearne, Rotherham, United Kingdom

V. Samarov President, LNT PM Inc. (Laboratory of New Technologies)

Teddi S. Schaeffer AMETEK Specialty Metal Powders

D. Seliverstov President, LNT PM Inc. (Laboratory of New Technologies)

Pei Sun Department of Metallurgical Engineering, University of Utah, Salt Lake City, UT, USA

H.P. Tang State Key Laboratory of Porous Metal Materials, Northwest Institute for Nonferrous Metal Research, Xi'an, China

David S. van Vuuren The CSIR, PO Box 395, Pretoria, South Africa

Dion Vaughan Metalysis Limited, Wath-upon-Dearne, Rotherham, United Kingdom

Phuong Vo National Research Council Canada, Boucherville, Québec, Canada

Graham P. Walker AMETEK Specialty Metal Powders

J. Wang State Key Laboratory of Porous Metal Materials, Northwest Institute for Nonferrous Metal Research, Xi'an, China

David Whittaker DW Associates 231, Coalway Road, Merryhill Wolverhampton, United Kingdom

J.C. Williams Professor Emeritus, The Ohio State University, Columbus, OH, USA

James C. Withers Materials & Electrochemical Research (MER) Corporation, Tucson, AZ, USA

Wilson Wong Department of Mining and Materials Engineering, McGill University, Montréal, Québec, Canada

X. Wu ARC Centre for Design in Light Metals, Monash University, Melbourne, Australia

Ming Yan RMIT University, School of Aerospace, Mechanical and Manufacturing Engineering, Centre for Additive Manufacture, Melbourne, Victoria, Australia

Ya F. Yang RMIT University, School of Aerospace, Mechanical and Manufacturing Engineering, Centre for Additive Manufacturing, Melbourne, Victoria, Australia

C.F. Yolton CTO, Summit Materials LLC, McDonald, PA, USA

Stephen Yue Department of Mining and Materials Engineering, McGill University, Montréal, Québec, Canada

Deliang Zhang State Key Laboratory of Metal Matrix Composites, School of Materials Science and Engineering, Shanghai Jiao Tong University, Shanghai, China

About the editors

Dr. Ma Qian is Professor and Deputy Director of the Centre for Additive Manufacturing of RMIT University (Royal Melbourne Institute of Technology), Australia. He received his BSc (1984), MSc (1987), and PhD (1991) all from the University of Science and Technology Beijing. He then worked as a postdoctoral research fellow and lecturer with Tsinghua University Beijing from 1991 to 1994. Before joining RMIT University in 2013, he was a Reader in Materials Engineering (2008–2013) and leader of the Powder Metallurgy Group at the University of Queensland, Australia. Prior to that, he worked as a researcher or academic with several other institutions in Japan, Singapore, Australia, and the United Kingdom. He has more than 200 peer-reviewed publications, with about half focused on titanium powder metallurgy (PM) and additive manufacturing of titanium alloys. Recent publications include understanding the effect of oxygen on the ductility of as-sintered Ti-6Al-4V (*Acta Mater.* 68 (2014) 196–206), Additive manufacturing of strong and ductile Ti-6Al-4V (*Acta Mater.* 85 (2015) 74–84) and understanding the impacts of trace carbon on the microstructure of as-sintered biomedical Ti-15Mo (*Acta Biomater.* 10 (2014) 1014–1023). He initiated the Titanium PM conference in 2011, cosponsored by Materials Australia, the Minerals, Metals & Materials Society (TMS), Japan Society of Powder and Powder Metallurgy (JSPM), Titanium Industry Development Association (TiDA), and the PM Branch of China Society for Metals (CSM). He was leader organizer for the TMS Symposium Novel Synthesis and Consolidation of Powder Materials (2013 and 2015). Currently he serves as a board member of the Asian Powder Metallurgy Association (APMA) and an editorial/review/advisory board member of a number of journals including *Metallurgical and Materials Transactions A*, *JOM*, *Powder Metallurgy*, *International Journal of Powder Metallurgy*, *Korean Journal of Powder Metallurgy*, *Acta Metallurgica Sinica (English Letters)*, and *Powder Metallurgy Technology*. He is also advisory editor to Elsevier on powder materials science and engineering.

Dr. Francis H. (Sam) Froes has been involved in the Titanium field with emphasis on powder metallurgy (PM) for more than 40 years. After receiving a BSc (Liverpool University) and an MSc and PhD (from Sheffield University) he was employed by a primary titanium producer, Crucible Steel Company, where he was leader of the titanium group and led a major effort on PM titanium under US Air Force (USAF) funding. He then spent time at the USAF Materials Lab, where he was supervisor of the Light Metals group (which included titanium) and again involved an emphasis on PM. While at the USAF Laboratory, he coorganized a landmark TMS-sponsored Conference on Titanium PM (1980) and presented the keynote speech at the first International Titanium Association Conference in 1984. This was followed by 17 years at the University of Idaho, where he was a director and department head of the

Materials Science and Engineering Department, again leading a number of programs on titanium PM. During this tenure, he was the Chairman of the World Titanium Conference held in San Diego in 1992. He has more than 800 publications, in excess of 60 patents, and has edited almost 30 books – the majority on various aspects of titanium. Recent publications include a comprehensive review of titanium PM and an article on titanium additive manufacturing. Since the early 1980s, he has taught the ASM International course on "Titanium and Its Alloys." He has organized more than 10 symposia on various aspects of Titanium Science and Technology, including in recent years cosponsored four TMS Symposia on Cost Effective Titanium (which included a large number of papers on titanium PM). He is a Fellow of ASM and a member of the Russian Academy of Science, and he was awarded the Service to Powder Metallurgy by the Metal Powder Association.

Preface

The first known research effort of titanium powder metallurgy (PM) was made by Dr Kroll (W. Kroll, Verformbare Legierungen des Titans, *Z Metallkunde,* 29 (1937) 189–192). In the work published, Dr Kroll compacted and sintered 14 different binary titanium alloys (Mo, W, Ni, Fe, Co, Be, Si, Mn, Cr, Cu, Al, Zr, V, and Ta with one addition for each element in the range of 2–9 wt%) in argon soon after he was able to produce about 0.5 kg batches of sponge fines in 1937. Thanks to the persistent development of the Kroll process since 1937 (Dr Kroll switched to the magnesium approach from the calcium in late 1937), titanium as a metal of industrial stature was established in 1948 in the United States, marked by world's first high-quality sponge production by DuPont (3 metric tons of >99% pure sponge in 1948) and the 1st Titanium Symposium in Washington, DC, held also in 1948. Although more than seven decades have passed, the high cost of titanium components still limits its usage compared to the lower-cost structural material options such as steel and aluminum alloys. A major proportion of this high cost is associated with the machining of wrought products to final configurations, suggesting that fabrication of near-net shaped titanium products could lead to dramatically increased use. In that regard, PM techniques remain to be an attractive solution to the production of cost-effective near-net shaped titanium components. In addition, it offers the potential for rapid turnaround prototype parts, manufacture of complex parts without having to make dies or molds, and a method for repairing mismachined parts or worn parts. Another important advantage is that Powder Metallurgy (PM) offers the potential of producing alloys that could not be produced via ingot metallurgy due to segregation problems.

The purpose of this book is to review the developments of titanium PM technologies to date. The subjects covered include titanium powder production methods, including both well-established and developing potential lower-cost approaches, and various near-net-shape-forming PM techniques, including the blended elemental approach, the prealloyed plus hot isostatic pressing method, additive manufacturing, metal injection molding, and spray forming. The last two chapters discuss the current and future markets for Ti PM and the editors' perspectives on the future of Ti PM. In total, the field has been covered in a comprehensive manner and we hope that this effort could help in bringing titanium components made from powder into widespread use in the future.

Ma Qian
RMIT University, School of Aerospace, Mechanical and Manufacturing Engineering, Centre for Additive Manufacture, Melbourne, Victoria, Australia

Francis H. (Sam) Froes
Consultant to the Titanium Industry, Tacoma, WA, USA

Contents

List of contributors xiii
About the editors xvii
Preface xix

1 A historical perspective of titanium powder metallurgy 1
Francis H. (Sam) Froes
1.1 Introduction 1
1.2 The early years (late 1940s to early 1950s) 2
1.3 The 1980 TMS Conference 2
1.4 Developments 1980–present 5
1.5 Developments in the PA/HIP technology 6
1.6 The BE method 8
1.7 Metal injection molding 13
1.8 Additive manufacturing 13
1.9 Other developments 16
1.10 Research-based processes 16
1.11 The 2011 conference on titanium PM 17
1.12 Thoughts for the future 18

2 Conventional titanium powder production 21
C.F. Yolton, Francis H. (Sam) Froes
2.1 Introduction 21
2.2 Prealloyed spherical powder (conventional titanium powder production) 21
2.3 Gas atomization 22
2.4 Plasma rotating electrode process 24
2.5 Electrode induction–melting gas atomization 26
2.6 Plasma atomization 28
2.7 Induction plasma spheroidization 28
2.8 Conclusions 31

3 Production of titanium powder by an electrolytic method and compaction of the powder 33
James C. Withers
3.1 Introduction 33
3.2 New and advanced processing 35
3.3 Electrolytic production of titanium powder 37
3.4 Titanium alloy powder 38
3.5 Compaction of electrolytically produced titanium powder 41

4 Titanium powder production via the Metalysis process **51**
Ian Mellor, Lucy Grainger, Kartik Rao, James Deane, Melchiorre Conti, Greg Doughty, Dion Vaughan
4.1 Introduction 51
4.2 FFC® process overview 52
4.3 Preforms: evolution to elimination 54
4.4 Titanium alloys via the FFC® process 56
4.5 Metalysis titanium powder characterization 58
4.6 Additive manufacturing (AM) 60
4.7 Hot isostatic pressing 62
4.8 Spark plasma sintering (SPS) and hot rolling 64
4.9 Summary 65

5 Direct titanium powder production by metallothermic processes **69**
David S. van Vuuren
5.1 Introduction 69
5.2 Precursors 69
5.3 Reducing agents 73
5.4 Reactor type 77
5.5 Separation principle 81
5.6 Recent developments 82
5.7 Concluding remarks 89

6 Research-based titanium powder metallurgy processes **95**
Francis H. (Sam) Froes
6.1 Introduction 95
6.2 Rapid solidification, mechanical alloying, and vapor deposition 95
6.3 Thermohydrogen processing (THP) 95
6.4 Porous structures 97

7 Titanium powders from the hydride–dehydride process **101**
Daniel P. Barbis, Robert M. Gasior, Graham P. Walker, Joseph A. Capone, Teddi S. Schaeffer
7.1 Introduction 101
7.2 HDH titanium feedstock 101
7.3 The HDH process 102
7.4 The hydriding process 103
7.5 The dehydriding process 107
7.6 Dehydride recovery 107
7.7 Magnetic separation and acid washing 108
7.8 Interstitial contents 108
7.9 Screening and screen specifications 110
7.10 Laser specifications 111
7.11 Powder morphologies 112
7.12 Spherical powders 114
7.13 Summary 115

8 Low-cost titanium hydride powder metallurgy 117
Orest Ivasishin, Vladimir Moxson
8.1 Introduction 117
8.2 Titanium hydride: physical and mechanical properties and phase transformations upon heating 119
8.3 Surface contamination of titanium hydride powder 124
8.4 PM processing of CP Ti 128
8.5 BEPM processing of titanium alloys 130
8.6 Production of hydrogenated titanium powder 138
8.7 Scaling up titanium hydride powder metallurgy 141

9 Production of titanium by the Armstrong Process® 149
Kerem Araci, Damien Mangabhai, Kamal Akhtar
9.1 Process overview 149
9.2 Powder characteristics 149
9.3 Compaction 154
9.4 Densification 158
9.5 Spheroidization 160

10 Hydrogen sintering of titanium and its alloys 163
James D. Paramore, Z. Zak Fang, Pei Sun
10.1 Introduction 163
10.2 Background and history 164
10.3 HSPT process description 170
10.4 Typical results 172
10.5 Cost and energy savings 176
10.6 Conclusions 177

11 Warm compaction of titanium and titanium alloy powders 183
Mingtu Jia, Deliang Zhang
11.1 Introduction 183
11.2 Warm compaction process 185
11.3 Compaction pressure 187
11.4 Compaction temperature 188
11.5 Particle shape effects on Ti powder warm compaction 192
11.6 Mechanical properties of sintered titanium and titanium alloy powder compacts produced by warm compaction 195
11.7 Applications 198

12 Pressureless sintering of titanium and titanium alloys: sintering densification and solute homogenization 201
Ma Qian, Ya F. Yang, Shudong D. Luo, H.P. Tang
12.1 Introduction 201
12.2 Stability of the surface titanium oxide film 202
12.3 Sintering of CP-Ti 204

12.4 Sintering of Ti-10V-2Fe-3Al 205
12.5 Sintering of Ti-6Al-4V 213
12.6 Enhanced densification with sintering aids 214
12.7 Conclusion remarks 216

13 Spark plasma sintering and hot pressing of titanium and titanium alloys 219
Ya F. Yang, Ma Qian
13.1 Introduction 219
13.2 HP of CP-Ti and Ti-6Al-4V 219
13.3 SPS of CP-Ti 223
13.4 SPS of Ti-6Al-4V from EMA powder mixtures and PA powder 227
13.5 Comparison of SPS and HP 233
13.6 Conclusion remarks 233

14 Microwave sintering of titanium and titanium alloys 237
Shudong D. Luo, Ma Qian, M. Ashraf Imam
14.1 Introduction 237
14.2 Heating of metal powders by microwaves 238
14.3 Heating of Ti powder by microwaves 238
14.4 Sintering densification 240
14.5 Mechanical properties 242
14.6 Microwave heating and sintering of titanium hydride powder 245
14.7 Summary 248

15 Scavenging of oxygen and chlorine from powder metallurgy (PM) titanium and titanium alloys 253
Ming Yan, H.P. Tang, Ma Qian
15.1 Introduction 253
15.2 The effect of oxygen on ductility of Ti materials 255
15.3 Scavenging of oxygen from PM Ti and Ti alloys 256
15.4 Impact of chlorine on PM Ti materials 265
15.5 Scavenging of chlorine from PM Ti and Ti alloys 265
15.6 Scavenging of oxygen in additively manufactured Ti alloys and reaction kinetics 270
15.7 Concluding remarks 270

16 Titanium metal matrix composites by powder metallurgy (PM) routes 277
Katsuyoshi Kondoh
16.1 Introduction 277
16.2 Materials design and processing of TMCs 278
16.3 Carbon fiber–reinforced TMCs 286
16.4 Atomic-scale reinforced TMCs with solute light elements 287

17 Titanium alloy components manufacture from blended elemental powder and the qualification process **299**
Stanley Abkowitz, Susan Abkowitz, Harvey Fisher
17.1 Introduction 299
17.2 The CHIP PM process 300
17.3 Titanium metal matrix composites 303
17.4 Commercial products 306
17.5 The Boeing qualification process 309
17.6 Industry specification for PM titanium alloys 310
17.7 The shape-making capability 311
17.8 Conclusions 312

18 Fabrication of near-net-shape cost-effective titanium components by use of prealloyed powders and hot isostatic pressing **313**
V. Samarov, D. Seliverstov, Francis H. (Sam) Froes
18.1 Introduction 313
18.2 The ceramic mold process 313
18.3 The metal can process 313
18.4 Problems and solutions 322
18.5 Analysis and conclusions 334

19 Metal injection molding of titanium **337**
Thomas Ebel, V. Friederici, P. Imgrund, T. Hartwig
19.1 The MIM process and market 337
19.2 Titanium MIM 339
19.3 Powders and powder handling 340
19.4 Binder systems 342
19.5 Debinding and sintering 343
19.6 Properties of specific alloys processed by MIM 344
19.7 Perspectives 356

20 Powder-processing linkages to properties for complex titanium shapes by injection molding **361**
Randall M. German
20.1 Introduction 361
20.2 Powders for Ti-MIM 362
20.3 Key Ti-MIM success factors 364
20.4 Optimized Ti-MIM processing 367
20.5 Components design factors 372
20.6 Summary 373

21 Titanium sheet fabrication from powder **383**
G.M.D. Cantin, M.A. Gibson
21.1 Introduction 383
21.2 Direct powder rolling and consolidation 384
21.3 Summary 399

22 Cold-spray processing of titanium and titanium alloys **405**
Phuong Vo, Dina Goldbaum, Wilson Wong, Eric Irissou, Jean-Gabriel Legoux, Richard R. Chromik, Stephen Yue
22.1 Introduction 405
22.2 Process description 407
22.3 Cold-spray principles 408
22.4 Properties of deposited material 410
22.5 Process–microstructure–property relationships 414
22.6 Applications 417
22.7 Status and future 419

23 Thermal spray forming of titanium and its alloys **425**
Jo Ann Gan, Christopher C. Berndt
23.1 Introduction to thermal spray 425
23.2 Titanium and titanium alloy feedstock characteristics 426
23.3 Deposition of titanium and titanium alloy coatings 428
23.4 Microstructure of titanium coatings 437
23.5 Potential applications 439
23.6 Summary 440

24 The additive manufacturing (AM) of titanium alloys **447**
B. Dutta, Francis H. (Sam) Froes
24.1 Introduction 447
24.2 Technology overview 449
24.3 Titanium AM applications 453
24.4 Microstructure and mechanical properties 458
24.5 Economics of AM 460
24.6 Research and development 463
24.7 Summary 465

25 Powder-based titanium alloys: properties and selection **469**
Sami M. El-Soudani
25.1 Mechanical properties of PM titanium alloys 469
25.2 Selection of powder processes and materials 492

26 A realistic approach for qualification of PM applications in the aerospace industry **497**
R.R. Boyer, J.C. Williams, X. Wu, L.P. Clark
26.1 Introduction 497
26.2 A brief history of Ti powder metallurgy in the United States 498
26.3 Assessment of the current status of Ti PM and its potential 505
26.4 Qualification requirements 506

26.5 Other development areas 510
26.6 Additive manufacturing (AM) 510
26.7 Summary 512

27 Powder metallurgy titanium aluminide alloys 515
Bin Liu, Yong Liu
27.1 Introduction 515
27.2 Preparation of PA TiAl powder 515
27.3 Consolidation of TiAl powder 519
27.4 Hot deformation of PM TiAl-based alloys 521
27.5 Properties of PM TiAl-based alloys 526
27.6 Summary 528

28 Porous titanium structures and applications 533
H.P. Tang, J. Wang, Ma Qian
28.1 Introduction 533
28.2 Porous titanium structures 535
28.3 Properties of porous titanium 539
28.4 Commercial applications 544
28.5 Concluding remarks 550

29 Microstructural characterization of as-sintered titanium and titanium alloys 555
Ming Yan
29.1 Introduction 555
29.2 Microstructural features of PM Ti and Ti alloys 555
29.3 Common phases in PM Ti and Ti alloys 556
29.4 Analytical techniques for microstructural characterization of PM Ti and Ti alloys 566
29.5 Concluding remarks 574

30 Future prospects for titanium powder metallurgy markets 579
David Whittaker, Francis H. (Sam) Froes
30.1 Introduction 579
30.2 Current markets for titanium 580
30.3 New product opportunities in established market sectors 582
30.4 Health care 588
30.5 Jewelry 591
30.6 Other sectors 593
30.7 Prospects for developing applications in new market sectors – automotive and general engineering 594
30.8 Concluding discussion 597