

# Contents

<b>Introduction to Additive Manufacturing in Biomedical Applications</b> . . . . .	<b>1</b>	Thermally Fused Powder-Bed Fusion Processes . . . . .	59
Developments and Trends in Additively Manufactured Medical Devices . . . . .	3	Polymer Powder 3D Printing Processes Using Fusing Agents and Energy . . . . .	61
<i>Shervin Foroughi, Mahdi Derayatifar, Mohsen Habibi, and Muthukumar Packirisamy, Concordia University (Canada)</i>		Process Parameters and Modeling . . . . .	62
Anesthesiology . . . . .	3	Powder-Handling System . . . . .	62
Ear and Nose . . . . .	4	Powder Characterization . . . . .	63
General Hospital . . . . .	5	Flowability . . . . .	63
Ophthalmic . . . . .	6	Polymer Part Characteristics . . . . .	66
Plastic Surgery . . . . .	7	Types of Polymers in Powder-Bed Fusion . . . . .	67
Radiology . . . . .	8	Powder Recycling . . . . .	68
Cardiovascular . . . . .	9	Prospects of Powder-Bed Fusion in Additive Manufacturing . . . . .	69
Orthopedic . . . . .	10	Biomedical Application of Polyether Ether Ketone . . . . .	69
Dental . . . . .	10	<b>Ceramic Additive Manufacturing Processes in Biomedical Applications</b> . . . . .	<b>75</b>
Neurology . . . . .	12	Binder Jet Additive Manufacturing of Biomaterials . . . . .	77
Gynecology and Obstetrics . . . . .	13	<i>Susmita Bose, Yongdeok Jo, Ujjayan Majumdar, and Amit Bandyopadhyay, Washington State University</i>	
Physical Medicine . . . . .	14	Additive Manufacturing Technologies . . . . .	77
Urology . . . . .	14	Binder Jet Printing Process . . . . .	77
Toxicology . . . . .	15	Biomaterials for Binder Jet Printing . . . . .	80
Pathology . . . . .	16	Biological Applications of Binder Jet Printing . . . . .	85
Material Aspects of Additively Manufactured Medical Devices . . . . .	22	Current Challenges and Future Directions . . . . .	87
<i>Wei Long Ng, Nanyang Technological University</i>		Selective Laser Sintering of Hydroxyapatite-Based Materials for Tissue Engineering . . . . .	92
<i>Chee Kai Chua, Singapore University of Technology and Design</i>		<i>Christos Softas, University of Birmingham</i>	
Different Additive Manufacturing Techniques . . . . .	23	Selective Laser Sintering . . . . .	92
Material Considerations . . . . .	26	Selective Laser Sintering of Hydroxyapatite Analysis . . . . .	98
<b>Polymer Additive Manufacturing Processes in Biomedical Applications</b> . . . . .	<b>37</b>	Production of Dicalcium Phosphate with Controlled Morphology and Reactivity . . . . .	106
Vat Polymerization . . . . .	39	<i>Masamoto Tafu and Takeshi Toshima, National Institute of Technology, Toyama College</i>	
<i>Caroline A. Murphy, Cesar R. Alcalá-Orozco, Alessia Longoni, Tim B. F. Woodfield, and Khoon S. Lim University of Otago</i>		Morphology Control by Precipitation . . . . .	106
Overview of Vat Polymerization Techniques . . . . .	39	Enhanced Reactivity by Hybridization of Nano-Apatite . . . . .	107
Vat Polymerization Printer Set Up . . . . .	40	<b>Metal Additive Manufacturing Processes in Biomedical Applications</b> . . . . .	<b>113</b>
Photo-Cross-Linking . . . . .	41	Powder-Bed Fusion . . . . .	115
Considerations Using Vat Polymerization . . . . .	41	<i>Leon Pope, Darpan Shidid, and Kate Fox, Royal Melbourne Institute of Technology University</i>	
Biomedical Applications of Vat Polymerization . . . . .	42	Powder-Bed Fusion for Biomedical Applications . . . . .	115
Medical Applications of Vat Polymerization . . . . .	48	Powder-Bed Fusion Processes and Parameters . . . . .	116
<i>Hideyuki Kanematsu, National Institute of Technology (KOSEN), Suzuka College</i>		Biomedical Applications of Powder-Bed Fusion . . . . .	118
<i>Dana M. Barry, Clarkson University and The State University of New York at Canton</i>		Directed-Energy Deposition . . . . .	130
<i>Rafiqul Noorani, Loyola Marymount University</i>		<i>Mohan Sai Kiran Kumar Yadav Nartu, Shashank Sharma, Srinivas Aditya Mantri, Sameehan S. Joshi, Mangesh V. Pantawane, Sangram Mazumder, Narendra B. Dahotre, and Rajarshi Banerjee, University of North Texas</i>	
<i>Paul McGrath, Clarkson University</i>		Directed-Energy Deposition Overview . . . . .	130
Classification and Characteristics of Additive Manufacturing for Medical Applications . . . . .	48	Multiphysics Computational Modeling of Layer-by-Layer Fusion-Based Directed-Energy Deposition Process . . . . .	130
Vat Polymerization and Its Characteristics . . . . .	50	Laser Surface Engineering of Biomedical Alloys via Directed-Energy Deposition . . . . .	135
Additive Manufacturing Applications to Medical Fields . . . . .	51		
Regulatory Challenges . . . . .	52		
Future Scope . . . . .	53		
Powder-Bed Fusion of Polymers . . . . .	57		
<i>Ruban Whenish, Pearlin Hameed, Revathi A, Joseph Nathanael A, and Geetha Manivasagam, Vellore Institute of Technology</i>			
Polymer Powder 3D Printing Processes Using Laser Fusion/Sintering . . . . .	57		

Directed-Energy Deposition of Biomedical Stainless Steels and Co-Cr-Mo Alloys . . . . .	141	<b>Biomaterials and Bioprinting . . . . .</b>	<b>223</b>
Directed-Energy Deposition of Biomedical Titanium Alloys . . . . .	144	In Situ Bioprinting—Current Applications and Future Challenges . . . . .	225
Novel Applications of Directed-Energy Deposition for Titanium-Base Biomedical Implants . . . . .	147	<i>Gabriele Maria Fortunato, Amedeo Franco Bonatti, Simone Micalizzi, Irene Chiesa, Elisa Batoni, Aurora De Acutis, Carmelo De Maria, and Giovanni Vozzi, University of Pisa</i>	
Forecast of Directed-Energy Deposition in Biomedical Applications . . . . .	150	In Situ Bioprinting Approaches and Technologies . . . . .	225
Development of Alloy Powders for Biomedical Additive Manufacturing. . . . .	160	Operating Workflow for Robotic-Based In Situ Bioprinting . . . . .	228
<i>Naoyuki Nomura and Weiwei Zhou, Tohoku University</i>		Case Studies of In Situ Bioprinting. . . . .	232
Powder Fabrication Methods for Metallic Biomaterials . . . . .	160	Future Perspectives on In Situ Bioprinting. . . . .	234
Development of Novel Alloy Powders for Biomedical Applications . . . . .	162	Rational Design of Materials for 3D Bioprinting of Bioinks for Fabricating Human Tissues . . . . .	237
Additive Manufacturing of Stainless Steel Biomedical Devices . . . . .	164	<i>Roland Kaunas, Texas A&amp;M University</i>	
<i>Nicholas Ury, Samad Firdosy, and Vilupanur Ravi, California State Polytechnic University</i>		Bioinks and Crosslinking. . . . .	237
Stainless Steels Overview . . . . .	164	Bioprinting Modalities. . . . .	237
Potential Benefits of Additive Manufacturing for Biomedical Devices . . . . .	166	Bioink Characteristics . . . . .	237
Additive Manufacturing Processes . . . . .	167	Rheological Properties of Bioink Sols . . . . .	238
Additive Manufacturing of Austenitic Stainless Steels for Biomedical Devices. . . . .	169	Rheological Measurements . . . . .	238
Additive Manufacturing of Martensitic and PH Stainless Steels for Biomedical Applications . . . . .	171	Mathematical Models of Bioink Rheology. . . . .	239
Challenges and Obstacles to Clinical Use of Additive Manufactured Parts . . . . .	172	Postfabrication Polymer Network Mechanics . . . . .	239
Additive Manufacturing of Cobalt-Chromium Alloy Biomedical Devices. . . . .	176	Assessing Mechanical Properties of Crosslinked Bioinks . . . . .	240
<i>Amit Bandyopadhyay, Jose D. Avila, Indranath Mitra, and Susmita Bose, Washington State University</i>		Assessing Printability of Bioinks . . . . .	241
Additive Manufacturing of Cobalt-Chromium Alloys . . . . .	177	Hydrogel Reinforcement Strategies. . . . .	241
Electrochemical Properties of Additive-Manufactured/Processed Cobalt-Chromium Alloys . . . . .	182	Emerging Bioink Formulations. . . . .	243
Evaluation of Biological Response to Cobalt-Chromium Alloys . . . . .	183	Stereolithographic Additive Manufacturing of Biological Scaffolds . . . . .	246
Test-Tube Testing (In Vitro) . . . . .	184	<i>Soshu Kirihara, Osaka University</i>	
Living Organism Testing (In Vivo). . . . .	186	Bioscaffold Processing . . . . .	246
Computer-Based Biological Simulations (In Silico) . . . . .	186	Cavity Arrangements. . . . .	247
Qualification and Certification of Additively Manufactured-Processed Medical Devices . . . . .	187	Microlattice Distributions . . . . .	247
Additive Manufacturing of Titanium and Titanium Alloy Biomedical Devices. . . . .	192	Laser-Induced Forward Transfer of Biomaterials . . . . .	252
<i>S.L. Sing, National University of Singapore</i>		<i>Marc Sole-Gras and Yong Huang, University of Florida</i>	
<i>S. Huang and W.Y. Yeong, Nanyang Technological University</i>		<i>Douglas B. Chrisey, Tulane University</i>	
Additive Manufacturing Techniques for Metallic Biomaterials . . . . .	192	Laser-Based Printing Process Introduction. . . . .	252
Titanium and Titanium Alloys by Additive Manufacturing. . . . .	194	Materials for Laser-Induced Forward Transfer Printing . . . . .	256
Challenges and Potential in Additive Manufacturing of Titanium and Its Alloys for Biomedical Devices. . . . .	195	Laser-Induced Forward Transfer Printing Applications . . . . .	259
Outlook for Biomaterials in Additive Manufacturing . . . . .	196	Inkjetting of Biomaterials . . . . .	266
Material Aspects of Additively Manufactured Orthopedic Implants of Titanium Alloys. . . . .	201	<i>Srimanta Barui, Indian Institute of Science Bangalore</i>	
<i>Abhijit Roy, Matthew Criado, John Ohodnicki, Howard Kuhn, and Prashant N. Kumta, University of Pittsburgh</i>		Inkjet Three-Dimensional Printing or 3D Inkjetting . . . . .	266
Design and Manufacturing Considerations of 3D-Printed, Commercially Pure Titanium and Titanium Alloy-Based Orthopedic Implants . . . . .	202	Key Components of Typical Inkjet 3D Printers . . . . .	267
Device Testing Considerations Following FDA Guidance . . . . .	210	Physics and Kinetics of Different Inkjetting Processes . . . . .	268
Outlook and Prospects. . . . .	218	Three-Dimensional Binder Jetting of Bioceramics and Metallic Biomaterials. . . . .	270
		Three-Dimensional Direct Inkjetting of Bioceramic and Polymeric Biomaterials . . . . .	273
		Cytocompatibility and Biocompatibility Assessment of 3D-Inkjet-Printed Scaffolds . . . . .	275
		Challenges and Troubleshooting Methodologies . . . . .	277
		Piezoelectric Jetting of Biomaterials . . . . .	285
		<i>Dachao Li, Zhihua Pu, Xingguo Zhang, Chengcheng Li, Xiao Su, Hao Zheng, and Zijing Guo, Tianjin University</i>	
		Piezoelectric Jetting of Biosensors . . . . .	285
		Piezoelectric Jetting for Tissue Engineering. . . . .	287
		Piezoelectric Jetting to Produce DNA . . . . .	288
		Piezoelectric Jetting of Biorobots . . . . .	290
		Challenges and Perspectives. . . . .	290
		Microvalve Jetting of Biomaterials . . . . .	292
		<i>Jiahui Lai and Min Wang, The University of Hong Kong</i>	
		Jetting Technologies and Working Process and Parameters for Microvalve Jetting. . . . .	292
		Biomaterials for Microvalve Jetting . . . . .	294
		Applications of Microvalve Jetting in Biomedical Engineering . . . . .	298

Micro/Nanoscale Plotting of Biomaterials . . . . .	302	Bone Structure and Bone Graft . . . . .	381
<i>Parthiban Rajan, North Carolina State University</i>		Bone Tissue Engineering . . . . .	382
<i>Michael Daniele, Ashley C. Brown, North Carolina State University</i>		Three-Dimensional Printing for Tissue Engineering	
<i>and University of North Carolina at Chapel Hill</i>		Applications . . . . .	382
Bioprinting/Bioplotting . . . . .	302	Current Challenges in Tissue Engineering . . . . .	385
Classification of Printing/Plotting Techniques . . . . .	303	Strategy of Forming Tissue-Engineered Grafts . . . . .	386
Contact Printing Methods . . . . .	304	Anatomical Modeling at the Point of Care . . . . .	390
Noncontact Printing Methods . . . . .	310	<i>Victoria Sears and Jonathan Morris, Mayo Clinic</i>	
Biomaterials . . . . .	313	Brief History of Anatomical Modeling . . . . .	390
Pneumatic Extrusion of Biomaterials . . . . .	318	Anatomical Modeling Workflow and Considerations . . . . .	391
<i>Mahsuis Sami, Prativa Das, and Rahim Esfandyarpour, University</i>		Case Studies—3D-Printed Anatomical Models at the Point	
<i>of California—Irvine</i>		of Care . . . . .	395
Additive Manufacturing . . . . .	318	Advancing Communication in Medicine . . . . .	398
Types of Additive Manufacturing Technology . . . . .	320	Archiving Complex Medical Anomalies, Pathologies, and	
Types of Extrusion-Based Approaches . . . . .	325	Historical Specimens . . . . .	399
Research on Extrusion-Based Printing . . . . .	327	Limitations and Pitfalls of 3D Printing Anatomical Models	
Comparison of Extrusion-Based Approach With		at the Point of Care . . . . .	399
Other Approaches . . . . .	327	Current and Future Innovations of Anatomical Modeling	
Extrusion-Based Three-Dimensional Bioprinting Technology . . . . .	334	at the Point of Care . . . . .	399
<i>Kanchan Maji and Krishna Pramanik, National Institute of</i>		Personalized Surgical Instruments . . . . .	402
<i>Technology Rourkela</i>		<i>Alejandro A. Espinoza Orias, Rush University</i>	
Strategies for Printing Tissue Engineering Scaffold . . . . .	334	Fundamentals of Personalized Surgical Instruments . . . . .	402
Parameters for Extrusion Bioprinting Process . . . . .	336	Benefits of Personalized Surgical Instruments . . . . .	403
Current Status of Bioink Material for Extrusion		Manufacturing of Personalized Surgical	
Bioprinting . . . . .	337	Instruments . . . . .	406
Recent Advances—Integration of Microfluidic		Other Application Examples beyond	
Techniques . . . . .	337	Orthopedics . . . . .	408
Future Perspective . . . . .	337	Outlook of Additive Manufacturing in Biomedical	
High-Throughput Electrospinning of Biomaterials . . . . .	341	Applications . . . . .	408
<i>Fateh Mikaeili, Owen O. Abe, and Pelagia-Irene Gouma, The</i>		Additive Manufacturing of Medical Devices . . . . .	416
<i>Ohio State University</i>		<i>Takayoshi Nakano and Koji Hagihara, Osaka University</i>	
Electrospinning Principle, Setup, and Factors That Affect		Additive Manufacturing Methods and Market Size . . . . .	416
Electrospinning . . . . .	341	Benefits of Using 3D-Additive Manufacturing Technology in	
High-Throughput Electrospinning of Nanofibers . . . . .	342	the Medical Field . . . . .	416
Applications of Electrospun Nanofibrous Mats . . . . .	344	Specific Examples of Medical Devices Fabricated by Additive	
Electrospinning Future Insights . . . . .	349	Manufacturing (Past to Present) . . . . .	418
Bioprinting/Biofabrication with Alginate/Gelatin-		Recent Trends in Metal Implant Development Using Additive	
Based Bioinks . . . . .	353	Manufacturing . . . . .	421
<i>Sonja Kuth, Faina Bider, and Aldo R. Boccaccini, Friedrich-</i>		Future Prospects for the Development of New High-	
<i>Alexander University of Erlangen-Nuremberg</i>		Performance Medical Devices via Metal 3D-Additive	
Basic Alginate/Gelatin and Alginate Dialdehyde/Gelatin . . . . .	354	Manufacturing . . . . .	428
Advanced Compositions to Enhance Functionality and/or		Additively Manufactured Orthotics . . . . .	434
to Optimize Hydrogels for 3D Bioprinting . . . . .	356	<i>Harish Kumar Banga, National Institute of Fashion Technology,</i>	
Advanced Printing Techniques for Alginate/Gelatin-Based		<i>Mumbai, India</i>	
Bioinks . . . . .	358	<i>Parveen Kalra and R.M. Belokar, Punjab Engineering College</i>	
Applications of Alginate/Gelatin-Based Bioinks . . . . .	359	<i>Rajesh Kumar, Panjab University</i>	
Summary and General Conclusions . . . . .	360	Ankle-Foot Orthosis . . . . .	435
Three-Dimensional Bioprinting of Naturally Derived		Passive Ankle-Foot Orthosis . . . . .	435
Protein-Based Biopolymers . . . . .	363	Methodology . . . . .	435
<i>Gabriele Griffanti and Showan N. Nazhat, McGill University</i>		Design Phase of Ankle-Foot Orthosis . . . . .	436
Printing Technologies . . . . .	363	Design Analysis . . . . .	436
Scaffold Property Requirements . . . . .	364	Additively Manufactured Biomedical Energy	
Protein-Based Bioinks . . . . .	366	Harvesters . . . . .	440
Collagen . . . . .	366	<i>Saima Hasan, M.A. Parvez Mahmud, and Abbas Z. Kouzani,</i>	
Silk . . . . .	368	<i>Deakin University</i>	
Fibrin . . . . .	370	Materials for Energy Harvesting . . . . .	440
Examples of Other Biopolymer Bioprinting . . . . .	372	Structures and Working Mechanisms of Energy	
Future Perspectives . . . . .	372	Harvesters . . . . .	442
<b>Biomedical Applications of Additively Manufactured</b>		Additively Manufactured Implantable Energy	
<b>Materials . . . . .</b>	<b>379</b>	Harvesters . . . . .	434
Bioprinting for Bone Tissue Engineering . . . . .	381	Additively Manufactured Wearable Energy	
<i>Chi Chun Pan, Carolyn Kim, Jiannan Li, Elaine Lui, Brett Salazar,</i>		Harvesters . . . . .	444
<i>Stuart B. Goodman, and Yunzhi P. Yang, Stanford University</i>		Additively Manufactured Self-Powered Sensors . . . . .	446
<i>Masahiro Maruyama, Stanford University and Yamagata</i>		Discussion . . . . .	448
<i>University</i>		Additive Manufacturing in Medicine and Craniofacial	
		Applications of 3D Printing . . . . .	454
		<i>Carole S.L. Spake and Albert S. Woo, Brown University</i>	

Creating a 3D-Printed Model from Medical Images—Acquisition, Segmentation, and Printing . . . . .	454	Additive Manufacturing Processes . . . . .	475
Craniofacial Applications of 3D Printing . . . . .	458	Review and Future Directions . . . . .	477
FDA Regulations and Other Guidelines . . . . .	459	Zirconia for Dental Implants . . . . .	479
Preoperative Planning and Operative Assistance . . . . .	459	<i>Saurabh Gupta, The International Academy of Ceramic Implantology, Universitat Jaume I, COHO Biotechnology, Clean Implant Foundation</i>	
Surgical Guides . . . . .	460	Background, Rationale, and Properties of Zirconia . . . . .	479
Implants and Prostheses . . . . .	461	Manufacturing Processes of Zirconia . . . . .	480
Surgical Simulators and Education . . . . .	461	Surface-Modification Techniques . . . . .	481
Medical Reimbursement . . . . .	462	Pharmaceutical 3D Printing . . . . .	486
Additively Manufactured Dental Appliances . . . . .	466	<i>Peyton Hopson, Johnson &amp; Johnson</i>	
<i>Roos Khosravi, University of Washington</i>		Materials Overview . . . . .	486
Additive Manufacturing in Dentistry . . . . .	466	Extrusion Technologies . . . . .	487
Current Three-Dimensional Printing Technology in Dentistry . . . . .	466	Fused Deposition Modeling . . . . .	487
Dental Resins . . . . .	468	Pressure-Assisted Microsyringe . . . . .	491
Various Types of Appliances . . . . .	469	Powder-Bed Fusion . . . . .	492
In-Office Appliance Fabrication . . . . .	470	Binder Jetting . . . . .	493
Fourth-Dimension Printing . . . . .	470	Selective Laser Sintering . . . . .	497
Personalized Dentistry . . . . .	470	Stereolithography . . . . .	502
Additively Manufactured Dentures, Crowns, and Bridges . . . . .	472	Additional Technologies . . . . .	504
<i>Zhaohui Geng, The University of Texas—Rio Grande Valley</i>		Design Considerations . . . . .	505
<i>Bopaya Bidanda, University of Pittsburgh</i>		<b>Reference Information . . . . .</b>	<b>509</b>
General Dental Production System . . . . .	473	Index . . . . .	511
Digitization Process . . . . .	473		
Material Selection . . . . .	474		