WSPC Book Series in 3D Printing

Lasers in 3D PRINTING AND MANUFACTURING

Chee Kai Chua, Murukeshan Vadakke Matham
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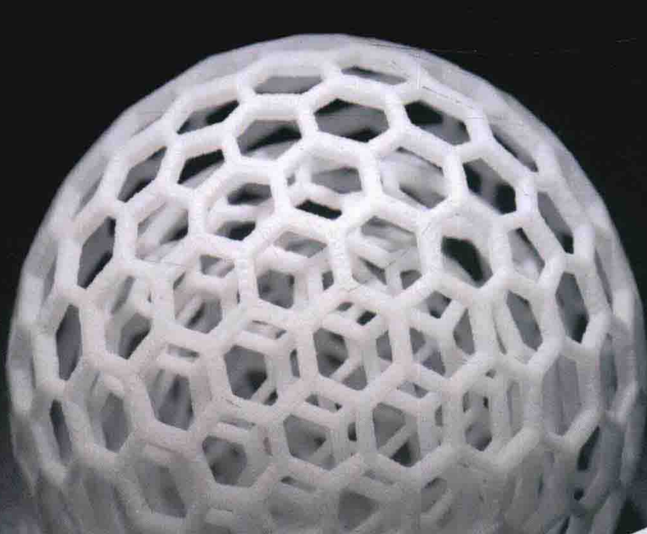

World Scientific

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Lasers in 3D PRINTING AND MANUFACTURING

World Scientific Series in 3D Printing

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Vol. 1 Bioprinting: Principles and Applications
by Chee Kai Chua and Wai Yee Yeong

Vol. 2 Lasers in 3D Printing and Manufacturing
by Chee Kai Chua, Murukeshan Vadakke Matham and Young-Jin Kim

FOREWORD

By Professor D.L. Bourell, The University of Texas, USA

Additive Manufacturing, also known as 3D Printing, has experienced an explosion of interest in the last 6 years. For many new to the field it is a bit startling to learn that the technology is almost 30 years old, with the first commercial additive manufacturing fabricator being delivered in 1987. The recent interest arises from multiple sources, including expiring founding patents which increased competition and government initiatives in advanced manufacturing which spotlight additive manufacturing. Media have covered the technology across the gamut: human interest stories, organ printing, home construction and food printing, to name a few.

The concept of building parts in an additive, layer-wise fashion dates back to the mid-1800s. In the period of 1968–1982, a number of additive manufacturing processes were invented, but they were not commercialised. This was largely due to the absence of distributed computing which became prominent in the early 1980s. Distributed computing is critical to additive manufacturing, as it captures the part's geometry, controls the fabricator and serves as the human–machine interface.

The vast majority of additive manufacturing fabricators are based on material extrusion. These popular, low-cost print machines have historically been used to print parts in reasonably accurate shapes but with properties substantially inferior to conventionally manufactured goods. The additive manufacturing processes covered in this book are associated with relatively expensive technologies that generate parts with relative accuracy and reasonable mechanical properties for engineering applications.

According to Terry Wohlers of Wohlers Associates, additive manufacturing has quadrupled in value worldwide over the last five years. It is anticipated that the industry will grow by a factor of five between 2015 and 2020. Accompanying this growth has been the development of standards writing committees such as the ISO TC261 and ASTM F42 Committees, who have provided a systematic framework for dealing with the critical aspects of additive manufacturing for industrial purposes.

The future of additive manufacturing is intriguing. Organ printing has received a lot of press coverage. While the technology is some years out, the potential of organ printing is staggering, impacting the entire organ transplanting infrastructure and health industries. Food printing will continue to grow and mature. Efforts are underway in research facilities and in the private sector to accelerate the rate at which additive manufactured parts are made. This is not only a convenience. It directly impacts part cost and therefore affects the utilisation of additive manufacturing in numerous market sectors. Part quality will improve over time, particularly for low-cost 3D printers.

Lasers are used commercially most popularly in two additive manufacturing processes: stereolithography and laser sintering/melting. The former uses a low-powered laser in the mW range to photolytically crosslink acrylic or epoxy thermoset polymers. Stereolithography is particularly attractive for parts where surface finish and transparency are desired. Laser sintering (polymers) and laser melting (metals) use varied types of lasers in the 20–250 W range to selectively melt pulverised feedstock in a powder bed. This process is very popular, particularly for structural service applications where part mechanical properties are important. In addition, lasers are used in other more niche applications in additive manufacturing such as the creation of extremely small parts in the 10–100s of micron size range.

Professor Chee Kai Chua is internationally known and is the leading AM researcher in Singapore. He has worked in the field for over 20 years. Currently, he is the Executive Director of the Singapore Centre for 3D Printing (SC3DP), housed within Nanyang Technological University, Singapore. The facilities and associated research are impressive, making a real contribution to the field, both inside and outside Singapore. I have known Professor Chua for almost 20 years. His research and contributions to the field of additive manufacturing are excellent. He is a world-recognised authority on the subject.

This book is an excellent compendium of information relating to the employment of lasers in additive manufacturing. The background information on laser optics, types of lasers and radiation safety will be useful particularly to readers who are new to the field and whose experience with lasers is limited. The coverage of manufacturing is broad, including both traditional additive manufacturing using lasers as well as related areas of machining, nanoscale patterning and ultra-short pulse manufacturing.

D.L. Bourell

Professor, The University of Texas, Austin, TX, U.S.A.

PREFACE

Technology and science have never failed to capture our fascination over the years and their advancement has obviously made our life easier. Change is something we all embrace and welcome into our lives, and science has paved the way for it. Additive Manufacturing (AM), popularly known as 3D printing, is one such technological advancement, which is playing an increasingly significant role in the manufacturing arena currently. AM has revolutionised how parts are made these days and how manufacturing can be carried out. With the advent of sophisticated and efficient laser systems, Laser-Assisted Manufacturing (LAM) and AM technologies have attracted significant interest over conventional machining methods. In fact, commercially available laser systems and 3D printing equipment have projected this to the top of the latest thrust of manufacturing technologies.

The major learning outcome of this book will be in the understanding of basics of lasers, optics and materials used for manufacturing and 3D printing. While the first part of the textbook focuses on the basics and insights to today's key laser-assisted manufacturing, the remaining chapters detail different laser-assisted 3D printing technologies and equipment. Materials in 3D printing and relevant manufacturing details are categorised in terms of material aspects into polymer, metal and ceramics. The textbook also gives a good account on the fundamentals of continuous wave (CW) and pulsed laser-assisted manufacturing with illustrative examples. Printing on semiconductor materials and photoresists become the target for a technological roadmap in meeting the forecasted technological nodes of sub-45nm. From this perspective, patterning and the printing of 2D and 3D structures on different materials are illustrated with fundamentals of interference and how they can be used for achieving the forecasted technological nodes. Finally, laser-assisted 3D printing and manufacturing generally employs high-power lasers; hence a complete understanding of the safety procedures in handling lasers and laser-based systems is very essential. A detailed account of this is given in the textbook and is expected to provide a better understanding of handling laser-based equipment with full safety to all end users.

In order for the graduate and undergraduate students in mechanical and precision engineering to practise the concepts and related contents in-depth, many problems with different perspectives have been included in this textbook.

This book will help tertiary lecturers, university professors and researchers in the related fields of LAM and 3D printing to practise and train, as well as help practitioners in the art to solve industry-relevant problems. We believe that the information and detailed illustrations presented in this book will also be of immense use to scientists and practitioners of AM technologies and LAM.

This book is expected to open newer pathways in both fundamental and applied research frontiers in the years to come.

Chua C. K.
Professor

Murukeshan V. M.
Associate Professor

KIM Y.-J.
Nanyang Assistant Professor

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Your suggestions, corrections and contributions will be appreciated and reflected on the later editions of this book.

Chua C. K.
Professor

Murukeshan V. M.
Associate Professor

KIM Y.-J.
Nanyang Assistant Professor

ABOUT THE AUTHORS

CHUA Chee Kai is the Executive Director of the Singapore Centre for 3D Printing (SC3DP) and a full Professor of the School of Mechanical and Aerospace Engineering at Nanyang Technological University (NTU), Singapore. Over the last 25 years, Professor Chua has established a strong research group at NTU, pioneering and leading in computer-aided tissue engineering scaffold fabrication using various additive manufacturing techniques. He is internationally recognised for his significant contributions in bio-material analysis and rapid prototyping process modelling and control for tissue engineering. His work has since extended further into additive manufacturing of metals and ceramics for defence applications.

Professor Chua has published extensively with over 300 international journals and conferences, attracting close to 6000 citations, and has a Hirsch index of 37 in the Web of Science. His book, *3D Printing and Additive Manufacturing: Principles and Applications*, now in its fifth edition, is widely used in American, European and Asian universities and is acknowledged by international academics as one of the best textbooks in the field. He is the World No. 1 Author for the area of Additive Manufacturing and 3D Printing (or Rapid Prototyping as it was previously known) in the Web of Science, and is the most 'Highly Cited Scientist' in the world for that topic. He is the Co-Editor-in-Chief of the international journal, *Virtual & Physical Prototyping* and serves as an editorial board member of three other international journals. In 2015, he started a new journal, the *International Journal of Bioprinting* and is the current Chief Editor. As a dedicated educator who is passionate in training the next generation, Professor Chua is widely consulted on additive manufacturing (since 1990) and has conducted more than 60 professional development courses for the industry and academia in Singapore and the world. In 2013, he was awarded the "Academic Career Award" for his contributions to Additive Manufacturing (or 3D Printing) at the 6th International Conference on Advanced Research in Virtual and Rapid Prototyping (VRAP 2013), 1–5 October, 2013, at Leiria, Portugal.

Dr Chua can be contacted by email at mckchua@ntu.edu.sg.

Murukeshan Vadakke Matham is an Associate Professor at the School of Mechanical and Aerospace Engineering, Nanyang Technological University (NTU), Singapore. He has extensive teaching experience of over 17 years in the area of optical engineering and laser machining. In addition, Dr Murukeshan has published heavily in the area of long, short and ultrashort pulse based laser material processing, micro and nanoscale patterning using conventional and near-field interference concepts. He has delivered over 50 keynote, plenary and invited talks at international workshops, conferences or forums and is the author of over 270 international articles, which include 157 international journal papers, more than 120 international conference proceedings papers or conferences and six book chapters. He has also published four papers in Nature Publication group journals as a lead corresponding author. Dr Murukeshan is also inventor or co-inventor of six awarded or filed patents and holds eight innovation disclosures. He serves in the editorial boards of international journals such as Nature publication group's journal, *Scientific Reports*; is joint editor of the *Journal of Holography and Speckle* (JHS) and the *International Journal of Optomechatronics* (IJO). He was also associate editor of the *Journal of Medical Imaging and Health Informatics* (JMIHI) until 2015. He also leads a research group which focuses on cutting edge research on Laser-assisted Fabrication, Nanoscale Optics, Biomedical Optics and Applied Optics for Metrology. His research has fetched more than S$10 million through competitive and industry funding in the recent years. For his contributions, Dr Murukeshan has won many international recognitions and awards. He has supervised or co-supervised over 25 PhD students and many of his research students' papers have won awards at international conferences. He is currently the Deputy Director of the Centre for Optical and Laser Engineering (COLE), NTU, and a Fellow of the Institute of Physics.

Dr Murukeshan V M can be reached at mmurukeshan@ntu.edu.sg

KIM Young-Jin is a Nanyang Assistant Professor and NRF Fellow at the School of Mechanical and Aerospace Engineering, Nanyang Technological University (NTU), Singapore. For more than a decade, he has been actively involved in advancing ultrafast laser technologies over a broad spectral bandwidth and has applied them to high-impact metrological and manufacturing applications. He developed a series of crystal- and fibre-based frequency comb systems by stabilising to the atomic clock of a frequency standard; established the 'definition of a metre' by precisely measuring absolute distances and surface profiles using frequency combs; expanded the wavelength regime of the frequency comb from infrared to extreme ultraviolet regime by field enhancements; demonstrated the world's first femtosecond laser system in outer space and successfully operated the system over two years. He is the author of more than 175 publications, including peer-reviewed journal articles and conference proceedings. He also holds 21 patents under his name and his publications have been cited more than 1700 times. He currently has a H-index of 16.

Dr Kim Young-Jin can be reached at yj.kim@ntu.edu.sg.

LIST OF ABBREVIATIONS

2D	= Two-Dimensional
3D	= Three-Dimensional
3DP	= Three-Dimensional Printing
ABS	= Acrylonitrile Butadiene Styrene
AEL	= Accessible Emission Level
AM	= Additive Manufacturing
AOM	= Acousto Optic Modulator
BBO	= beta-BaB_2O_4
CAD	= Computer-Aided Design
CAGR	= Compound Annual Growth Rate
CCD	= Charge-Coupled Device
CMOS	= Complementary Metal-Oxide Semiconductor
CNC	= Computer Numerical Control
CNT	= Carbon Nano-Tube
CW	= Continuous-Wave
DIW	= Direct Ink Writing
DMD	= Direct Metal Deposition; Digital Mirror Device
DMLS	= Direct Metal Laser Sintering
DLP	= Digital Light Processing
DUV	= Deep Ultra-Violet
EB	= Electron Beam
EBM	= Electron Beam Melting
EM	= Electro Magnetic
FDM	= Fused Deposition Molding
FEA	= Finite Element Analysis
FEM	= Finite Element Method
FESEM	= Field Emission Scanning Electron Microscopy
FFF	= Fused Filament Fabrication

FWHM	= Full Width Half Maximum
GTT	= Glass Transition Temperature
GO	= Graphene Oxide
HAZ	= Heat Affected Zone
HG	= Harmonic Generation
HHG	= High Harmonic Generation
HWP	= Half-Wave Plate
IEC	= International Electrotechnical Commission
IL	= Interference Lithography
IOT	= Internet Of Things
IR	= Infra-Red
KTP	= $KTiOPO_4$
LENS	= Laser Engineered Net Shaping
LAM	= Laser-Assisted Manufacturing
LBM	= Laser Beam Machining
LBO	= LiB_3O_5
LOM	= Laminated Object Manufacturing
MEMS	= Micro-Electro-Mechanical Systems
MPE	= Maximum Permissible Exposure
MQC	= Material Quality Centre
NA	= Numerical Aperture
NC	= Numerical Control
NIR	= Near Infra-Red
NTM	= Non-Traditional Manufacturing
OFCS	= Optical Fibre Communication Systems
OD	= Optical Density
OPD	= Optical Path-length Difference
OLPC	= Online Laser Power Control
PCB	= Printed Circuit Board
PLA	= Polylactic Acid
PVA	= Polyvinyl Alcohol
QWP	= Quarter-Wave Plate
RGO	= Reduced Graphene Oxide
RP	= Rapid Prototyping
SDL	= Selective Deposition Lamination
SHG	= Second Harmonic Generation