Standards, Quality Control, and Measurement Sciences in 3D Printing and Additive Manufacturing

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Standards, Quality Control, and Measurement Sciences in 3D Printing and Additive Manufacturing addresses the critical elements of the standards and measurement sciences in 3D printing to help readers design and create safe, reliable products of high quality. With 3D printing revolutionizing the process of manufacturing in a wide range of products, this book takes account of key factors, such as design and fabrication in 3D printing, and explores the current state and future potentials and opportunities in the field.

In addition to an overview of 3D printing and additive manufacturing technologies, this book also provides an in-depth analysis on the importance of standards and measurement sciences to the field, from legal and regulatory to engineering perspectives.

With self-test exercises at the end of each chapter, readers can build their ability to take up challenges and become proficient in a number of topics related to 3D printing, including software usage, materials specification, and benchmarking in this exciting new discipline!

Key Features

- Helps readers in understanding the quality framework tailored for 3D printing processes
- Explains data formatting and process control in 3D printing
- Provides an overview of different materials and characterization methods
- Covers benchmarking and metrology for 3D printing

About the Authors

Chee Kai Chua is the executive director of the Singapore Centre for 3D Printing (SC3DP), and a professor of the School of Mechanical and Aerospace Engineering at Nanyang Technological University (NTU), Singapore. Prof. Chua has published over 300 international journal and conference papers and numerous books; and was awarded the "Academic Career Award" for his lifelong contributions to Additive Manufacturing (or 3D Printing) at the 6th International Conference on Advanced Research in Virtual and Rapid Prototyping (VRAP) in 2013.

Chee How Wong is the programme director for the Future of Manufacturing Programme in the SC3DP, and an associate professor of the School of Mechanical and Aerospace Engineering at NTU, Singapore. Prof. Wong is also currently serving as the associate dean (Academic) in the College of Engineering at Nanyang Technological University. He has extensive research experience of over 14 years in the area of modeling and simulation, and has published more than 70 technical papers in international peer-reviewed journals.

Wai Yee Yeong is the programme director for the Aerospace and Defence Programme in SC3DP, and an assistant professor at the School of Mechanical and Aerospace Engineering at NTU, Singapore. Having worked in both academic research and industry manufacturing, Prof. Yeong is committed to the translation of advanced technologies for industrial applications while applying the concept of standardization and quality systems.

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Chua Chee Kai is the executive director of the Singapore Centre for 3D Printing (SC3DP) and a full-time professor of the School of Mechanical and Aerospace Engineering at Nanyang Technological University (NTU), Singapore. Over the last 25 years, Prof. 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 recognized for his significant contributions in biomaterial analysis and rapid prototyping process modeling and control for tissue engineering. His work has since extended further into additive manufacturing of metals and ceramics for defense applications.

Prof. Chua has published extensively with over 300 international journals and conferences, attracting more than 6300 citations, and has a Hirsch index of 38 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 has also published two other books *Bioprinting: Principles and Applications* and *Lasers in 3D Printing and Manufacturing*. He is the world's number one 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 coeditor-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, Prof. 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.

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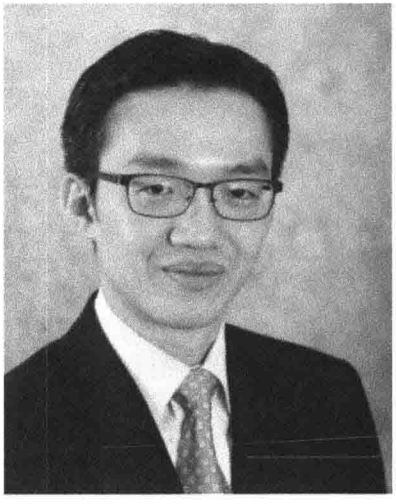

Wong Chee How is an associate professor at the School of Mechanical and Aerospace Engineering, Nanyang Technological University (NTU), Singapore. He has extensive research experience of over 14 years in the area of modeling and simulation.

He received his Bachelor degree in Manufacturing Engineering from University of Birmingham, United Kingdom, and Master and PhD degrees from Nanyang Technological University, Singapore respectively. Prior to joining NTU in 2008, he was a senior research fellow in Data Storage Institute, A*STAR. In 2014, he was conferred fellow of the NTU Teaching Excellence Academy. Between 2014 and 2016, he served as the associate chair (Students) of the School of Mechanical and Aerospace Engineering. In 2016, he was as appointed associate dean (Academic) of the College of Engineering and is responsible for undergraduate and postgraduate curriculum, admissions, and teaching of the college. His research interests encompass simulation and modeling, such as atomistic simulations of materials at nanoscale and modeling of additive manufacturing processes, such as selective laser melting. To date, he has published more than 70 technical papers in international peer-reviewed journals, attracting more than 1000 citations. He currently has H-index of 18. He is now serving as the program director of the Future of Manufacturing program in the Singapore Centre for 3D Printing (SC3DP), SLM Solutions joint lab and NAMIC@NTU. He is an ExCo member of the American Society of Mechanical Engineers (Singapore) and served as its chairman from 2013 to 2014. He is also a member of ASTM F42 and Additive Manufacturing Technical Committee (Singapore).

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FOREWORD

Transformative technology is a rare thing, perhaps seen once in a generation. The acceptance of technology by the marketplace in question is largely dependent upon the degree of certainty associated with its application. How consistently it performs? How repeatable and reproducible are its results? How much confidence it instills within those who choose to use it? In many cases, the gap between a technology's research stage and its market application is vast, and in some cases never bridged. Wonderful and innovative advances may never achieve their full potential due to the lack of market access, in many cases determined by the quality, pace, and timing of a consensus standards program to build that elusive but critical bridge.

Additive manufacturing defined in ISO/ASTM 52900 as a process of joining materials to make parts from 3D model data, usually layer upon layer, as opposed to subtractive manufacturing and formative manufacturing methodologies, ranks high on the transformative scale.

In recent years, use of additive technologies has evolved within a variety of mainstream manufacturing sectors, including aerospace, automotive, biotechnical/medical, and consumer products. Despite this growth, the pace at which consensus standards (and the measurement science upon which they are based) are being developed hasn't mirrored the accelerated evolution of the technologies and their ever-expanding industry applications. In response to this disparity, accelerated standards development models are becoming increasingly necessary to satisfy needs associated with the expansion of additive manufacturing methodologies into these new market segments.

There is so much work to be done. Given the relatively finite collection of technical experts with a sufficient depth of knowledge and experience to identify and develop these much-needed standards, collaboration and its resulting lack of duplication becomes critical. Leading the pack in the standards space is ASTM International Committee F42 on Additive Manufacturing Technologies and ISO TC261 on Additive Manufacturing. Via a Partner Standards Development Organization (PSDO) agreement between their parent organizations, these global standards developers have maximized their bandwidth in both process and expertise applications. The marriage of horizontal and vertical relevance inherent in the infrastructure of the respective committee populations has created an environment ideally suited to tackle the challenges associated with "standardizing" an area in dire need of a high quality and market relevant bridge. Needs currently being addressed to include the ability to comparatively

benchmark the performance of different additive processes, improvement of the buyer/seller dynamic by enabling increasingly accurate specification of production requirements, and offering the research community a mechanism to provide repeatable results capable of independent verification.

Standards come in many shapes and sizes, and one size rarely fits all. Within the world of additive manufacturing, the types of standards needed are almost as diverse as the applications served by the AM technologies. Examples of standards include specifications, test methods, classifications, practices, guides and terminology. Specifications are needed for physical, mechanical, or chemical properties, as well as safety, quality, or performance criteria. Test methods are critical for identification, measurement, and evaluation of one or more qualities, characteristics, or properties. There is a need to create Classifications of materials, products, systems, or services into groups based on similar characteristics, such as origin, composition, properties, or use. Practices should be standardized for application, assessment, decontamination, inspection, installation, preparation, sampling, screening, and training. Guides will be helpful to increase the awareness of information and approaches in a given subject area. Standardized terminology is necessary to establish a uniform and consistently applied language for industry consumption.

The value of a consensus standards program is beyond contestation, but within the rapidly evolving world of additive manufacturing, not just any program will do. To be truly effective, standards development must be nimble, flexible, open, transparent, living, and timely. The marriage of these attributes creates an environment where standards development for additive manufacturing technologies will thrive, putting to rest the contention that standards stifle innovation. Quite to the contrary, a robust, inclusive, and well fleshed out standards program will enable innovation by creating an environment where measurable points of distinction don't come from simply meeting the standard, but via exceeding it and by how much. Competition such as this drives innovation. Innovation expands markets. Markets thrive under well-constituted standards programs.

Standards are multifaceted things. While based on sound and reliable science possessing enormous technical sophistication, they are also, in many respects, enablers and gatekeepers of market access. This combination of technical and economic relevance is incredibly powerful, and is vital to the transformative technology, that is, additive manufacturing achieving its maximum potential.

Pat A. Picariello, J.D., CStd
Director, Developmental Operations, ASTM International

PREFACE

Additive manufacturing, also known as 3D printing, is revolutionizing the landscape of manufacturing, creating new opportunities in design and generating new routes of fabrication for various products. In recent years, additive manufacturing plays a strategic role in the future of manufacturing for both the consumer products and high value products. 3D printers are installed in households, classrooms, and in the production floor of high-tech manufacturing sights. This new technological trend is even more evident in highly regulated industries, such as biomedical and aerospace industries. Quality systems and quality assurance are prerequisite for successful adoption of 3D printing into the value chain of these services and products.

On the research front, additive manufacturing technology is creating new paradigm in research fields, such as bioprinting, electronic printing, as well as environmental-related fields. These are highly translational technology domains, which require a concerted effort between different institutes and collaborations across different disciplines. Therefore, it is equally critical to apply the principles of quality management coupled with reliable measurement techniques when creating new sciences in additive manufacturing research.

However, there has been limited progress in the standard and measurement sciences in additive manufacturing. This textbook aims to present the critical components and current progress of standards and measurement sciences in additive manufacturing. This will be the first textbook on standards, quality, and measurement sciences in additive manufacturing.

Through this textbook we aim to achieve fundamental understanding in these aspects:

- The importance of standards and measurement sciences in additive manufacturing.
- The current landscape of standards in additive manufacturing.
- The quality framework tailored for additive manufacturing processes.
- The data format and process control in additive manufacturing.
- Overview of different materials and characterization methods.
- Overview of equipment qualification activities and safety consideration regarding to different 3D printing systems.
- Benchmarking and metrology for 3D printing systems and printed parts.

This book is suitable for students, researchers, engineers, general public, and regulatory specialists from all industry sectors.

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