Suresh K. Bhargava
Seeram Ramakrishna
Milan Brandt
PR. Selvakannan *Editors*

Additive Manufacturing for Chemical Sciences and Engineering

Springer

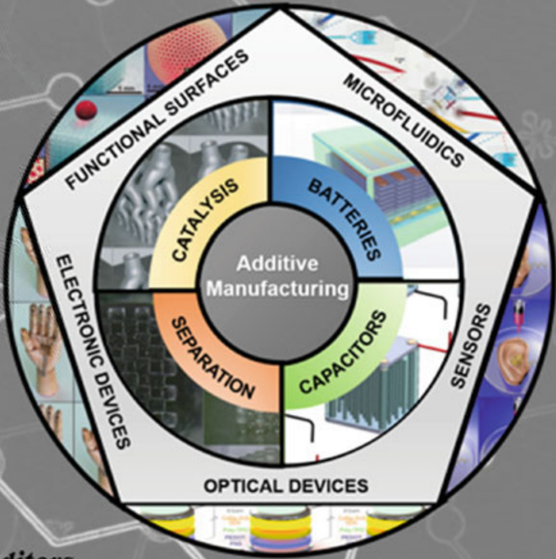
Additive Manufacturing for Chemical Sciences and Engineering

Additive Manufacturing for Chemical Sciences and Engineering

Editor-in-chief

Suresh K. Bhargava

Member of Order of Australia



Editors

Seeram Ramakrishna

Milan Brandt

PR. Selvakannan

Suresh K. Bhargava · Seeram Ramakrishna ·
Milan Brandt · PR. Selvakannan
Editors

Additive Manufacturing for Chemical Sciences and Engineering

Springer

Editors
Suresh K. Bhargava
Centre for Advanced Materials
and Industrial Chemistry
RMIT University
Melbourne, VIC, Australia

Milan Brandt
Centre for Additive Manufacturing
RMIT University
Melbourne, VIC, Australia

Seeram Ramakrishna
Centre for Nanofibers and Nanotechnology
National University of Singapore
Singapore, Singapore

PR. Selvakannan
Centre for Advanced Materials
and Industrial Chemistry
RMIT University
Melbourne, VIC, Australia

ISBN 978-981-19-2292-3 ISBN 978-981-19-2293-0 (eBook)
https://doi.org/10.1007/978-981-19-2293-0

This Springer imprint is published by the registered company Springer Nature Singapore Pte Ltd.
The registered company address is: 152 Beach Road, #21-01/04 Gateway East, Singapore 189721, Singapore

Students who were badly affected by COVID but accepted the challenges, became resilient and kept growing through their educational pathway.

The editor-in-chief and other editors have decided to donate the royalties of this book for the welfare of these students

Preface

Today we are witnessing the dawn of the fourth industrial revolution (4IR) which is fundamentally altering the way we live, eat, commute, work, and even celebrate. In its scale, outreach, and potential this revolution is unlike any other the humankind has seen before. Ushering a gradual metamorphosis of our modern society, the 4IR is rooted in powerful technological innovations ranging from Internet for global connectivity and information technology for data analytics and management to audacious technologies of the future such as Internet of Things, augmented reality, artificial intelligence, and additive manufacturing. This book analyzes one such technological innovation, *viz.,* additive manufacturing (AM) and elaborates upon the emerging paradigm shift brought about by AM in chemical sciences and engineering.

Chemical sciences and engineering play a paramount role in improving the quality of human life by manufacturing of essential commodities such as sanitizers, pharmaceuticals, textiles, plastics, rubbers, asphalt, and so on. Such manufacturing in turn relies on chemical technologies and processing equipment. While the automotive, aerospace, engineering, and biomedical industries have hastily adopted AM technologies for associated benefits, the chemical industries have been lagging in the uptake due to the lack of agility and adaptability in industrial chemical processes. AM is a manufacturing philosophy which uses incremental addition of material in a layer-by-layer fashion for fabrication of the object as per a digital design. As a result, use of AM engenders benefits such as complete design freedom, capability to manufacture sophisticated geometries, improved material utilization, tool-less fabrication, and shortened lead times. Due to the unmatched advantages of AM, it has tremendous potential in facilitating wide-scale upgradation, improvisation, and miniaturization of chemical processing equipment and plants in line with the ethics of Industry 4.0. Integration of AM with the chemical industry is anticipated to bring widespread process automation, improved feedstock and product inventories, and digital process control and process intensification. Future chemical reactors will be complex tailor-made devices with design optimized for fluid and particle flow, heat and mass transport, and reaction thermodynamics. This will lead to improved efficiencies of existing chemical processing technologies, improved process economics, environmental compatibility, reduced carbon footprint, and reduction in wastes and emissions.

The promise of AM in chemical sciences and engineering goes beyond the gradual reinvigoration and modernization of the chemical industry. AM is breaking the age-old barriers of localized engineering to enable decentralized engineering and production. It is now possible for design engineers to develop and analyze a model anywhere in the world and subsequently manufacture the matured model in an AM facility located in a different corners of the world altogether. Similarly, it is possible today to digitally store items and goods and mass produce at the point of high demand either in a large facility located in a developed nation or a temporary facility established in a developing nation facing an environmental, health, or political catastrophe. AM is also empowering mass customization and modular design movements which aim at tailor-designing of goods and services as per the requirements and demands of the customer. Thus, AM is a marvelous feat of modern technology and being hailed globally for enabling high standards of customer satisfaction, sustainability, resource utilization, and environmental protection.

This book elucidates all such unique aspects of AM and its enormous potential in shaping of the future of chemical sciences and engineering. Chapter 1 introduces AM to the chemical community followed by a description of the history and evolution of AM in Chap. 2. Chapters 3, 4, and 5 analyze the principles, challenges, and opportunities of different AM technologies in detail such as material extrusion, vat photopolymerization, laser powder bed fusion, and robocasting. Chapter 6 describes methods and technologies to impart chemical functionality to additive manufactured parts, components, reactors, and devices. Finally, the emerging technological applications of AM are described in Chap. 7 and the applications of AM in chemical engineering and micro-reaction technology are described in Chap. 8.

I sincerely hope that this book will channel the enthusiasm and focus of the chemical science and engineering community and the presented knowledge will empower them to build a better, greener, and brighter future for all humanity. As Abraham Lincoln once said, "*the best way to predict the future is to create it*". With this book, I want to give you some knowledge and tools of AM to create innovation in Chemical Engineering.

Melbourne, Australia

Suresh K. Bhargava
Editor-in-chief

Contents

About the Editors

Distinguished Professor Suresh K. Bhargava, AM, RMIT University, Melbourne.
Editor-in-chief
Distinguished Professor Bhargava is a world-renowned interdisciplinary scientist. He completed his Ph.D. from the University of Exeter, UK under the supervision of the late Professor E W Abel. He then joined the Australian National University in 1983 as a Research Fellow and today is the Dean-Research & Innovation and Founding Director of the Centre for Advanced Materials & Industrial Chemistry (CAMIC), STEM College, RMIT University. He has successfully translated his research excellence into innovative technologies for industrial application, championed gender equality in STEM, and strengthened academia-industry relationships at an international level. He has an i-10 index of 412, over 600 highly cited journal articles, 2 books, 16 book chapters, and 12 patents with a h-index of 76, and over 21100 citations. Holding distinguished professorships at top universities across 6 countries, he has created platforms for nurturing high-quality, globally agile Ph.D. students through collaborative research and international engagement. His outstanding contribution to academia and industry has been recognized through many prestigious national and international awards including the "CHEMECA Medal", the most prestigious award in engineering in Australia and New Zealand, and Honoris Causa D.Sc. Degree from Rajasthan University, India which was presented by the President of India. Quoted as being among the top 1% of world scientists in industrial chemistry, he provides

consultancy and advisory services to many government and industrial bodies across the world including BHP Billiton, Alcoa World Alumina, Rio Tinto, and Exxon Mobil. He is a fellow of six world academies, including the American Association for the Advancement of Science and The World Academy of Sciences, UNESCO. His main research interests focus on CO_2 utilization, hydrometallurgy, mineral characterization and processioning, heterogeneous and homogenous catalysis, metallodrugs, nanotechnology, and chemical sensors. He introduced the concept of 3G catalysis using 3D printing through his recent research endeavors at RMIT University.

Distinguished Professor Seeram Ramakrishna National University of Singapore, Singapore.
Professor Seeram Ramakrishna, FREng is the Chair of the Circular Economy Taskforce at the National University of Singapore. He is an editorial board member of Nature Scientific Reports and an elected Fellow of major professional societies and academies in Singapore, UK, India, and USA. He is named among the World's Most Influential Minds and the Top 1% Highly Cited Researchers in Materials Science by Thomson Reuters and Clarivate Analytics. He has co-authored 1000 journal papers, authored 8 books, received 110,000 citations, and has a h-index of 158. His research interests include innovations in sustainable materials and evaluation of circularity by life cycle assessment.

Distinguished Professor Milan Brandt RMIT University, Melbourne.
Distinguished Professor Milan Brandt is the Technical Director of the Digital Manufacturing Facility and Director of the Centre for Additive Manufacturing, RMIT University. He is the lead Australian Researcher in macro-machining and additive manufacturing with lasers and has conducted work over the last 37 years in laser cladding, cutting, drilling, welding, and more recently additive manufacturing. This has resulted in technological advancements, patents, research papers, and commercial products, which have been recognized nationally and internationally in both scientific and industrial circles. He is a Fellow of the Laser Institute of America, Honorary Fellow of Weld Australia,

Professorial Fellow of the Department of Medicine, Melbourne University, and Adjunct Prof. at the University of Waterloo, Canada. In 2018, he was the President of the Laser Institute of America, the largest international association of researchers and industry involved with lasers and laser additive technology and in 2019 he was named the Engineers Australia Centenary Hero for his research which led to Australia's first locally manufactured 3D printed spinal implant that was implanted into a patient.

Dr. PR. Selvakannan RMIT University, Melbourne.
Dr. PR. Selvakannan is a middle career researcher at RMIT University, under the mentorship of Professor Bhargava. His major fields of interest are CO_2 utilization, methane activation, endothermic fuels for high-speed flight vehicles, surface-enhanced Raman scattering, and additive manufacturing in catalysis. He has 75 publications in international peer-reviewed journals and a h-index of 34. Before joining RMIT, he worked as a Research Fellow at University of Paris-Sud, France (2007–2009) and as a Research Scientist at the Innovation Centre, Tata Chemicals Ltd, India (2005–2007). He received his Ph.D. (2005) from the National Chemical Laboratory (University of Pune), India. He graduated from the American College, India with Master's and Bachelor's degrees in Chemistry (1996–2001).

Chapter 1
An Introduction to the World of Additive Manufacturing

Milan Brandt and Suresh K. Bhargava

Contents

Abstract Science and engineering have been instrumental in advancing the progress of humanity and are the key enablers that are shaping our very present and the future, improving our health and living standards, allowing humanity to leave the planet, walk on the moon, and explore distant stars and galaxies. Additive manufacturing (AM) or 3D printing is the latest technological marvel in manufacturing that is compelling us to think differently about how we design and manufacture parts and components, the location where the parts are being manufactured, the supply chains, environmental impact of manufacturing and sovereign capability. AM is now being perceived as a disruptive technology because of the benefits and opportunities it offers over the long-established traditional manufacturing technologies. It is a relatively young technology, some 30 years since the invention of the first 3D printer, compared to conventional subtractive technologies that have been around for centuries. Mainstream AM has in fact only been around the last 5 to 10 years as both the 3D printing technology and feedstock materials have evolved and become more robust, cheaper, and reliable giving manufacturers the necessary level of confidence to adopt them in serial production. The level of activity in AM is at an all-time high as various stake holders, company executives, investors, researchers, and government agencies

M. Brandt
Centre for Additive Manufacturing, RMIT University, Melbourne, VIC, Australia
e-mail: milan.brandt@rmit.edu.au

S. K. Bhargava (✉)
Centre for Advanced Materials and Industrial Chemistry, RMIT University, Melbourne, VIC, Australia
e-mail: suresh.bhargava@rmit.edu.au

S. K. Bhargava et al. (eds.), *Additive Manufacturing for Chemical Sciences and Engineering*, https://doi.org/10.1007/978-981-19-2293-0_1

try to predict its trajectory. Global organizations of all types are attempting to understand the role they can play in the AM space. This chapter presents an overview of AM and its enormous potential in the advancement of chemical sciences and engineering. In-depth discussion of fundamental and applied aspects of each individual AM technology and how they relate to chemical sciences and engineering are presented in subsequent chapters. To date AM has seen greater adoption by the aerospace, defense, and biomedical industries and to somewhat lesser degree in the chemical manufacturing and processing industries. Introduction of AM practices in this sector can improve the efficiencies of existing chemical processing technologies, allow sophistication of existing processes for manufacturing of new products, improve process economics, and address complex challenges and demands of our modern society such as environmental compatibility, reduction in wastes and emissions and localized production. AM in chemical sciences has enormous potential in process intensification which enables efficient heat and mass transfer, large reduction in the footprint of chemical manufacturing and processing and reduce environmental pollution.

Keywords Additive manufacturing · 3D printing · Rapid prototyping · Customization · Chemical manufacturing · Process intensification · Energy storage · Reactors

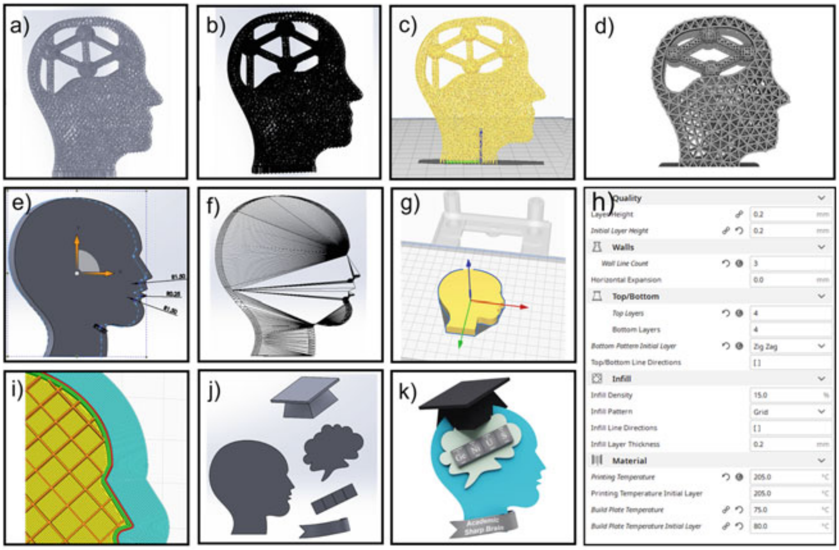
Abbreviations

2D	Two-dimensional
3D	Three-dimensional
AM	Additive Manufacturing
ASB	Academic Sharp Brain
BJT	Powder Bed Inkjet printing
CAD	Computer Aided Design
EPBM	Electron Beam Melting
FDM	Fused Deposition Modelling
Ge	Germanium
LPBF	Laser Powder Bed Fusion
MJT	Material Jetting
Ni	Nickel
SLA	Stereolithography
SLM	Selective Laser Melting
SLS	Selective Laser Sintering
STL	Standard Tessellation Language
S	Sulfur
U	Uranium

1.1 Background to Additive Manufacturing

Additive Manufacturing (AM), commonly known as 3D printing, is a manufacturing methodology wherein the material is added to form a desired solid geometry instead of subtraction or casting as in conventional manufacturing processes. Other common names for AM include solid free form fabrication, direct digital manufacturing, desktop manufacturing, additive technology and layered additive manufacturing. The AM technologies were initially developed to meet the demand of rapid prototyping and testing in the industrial manufacturing of sophisticated objects and components. The fundamental working principle behind most AM technologies is essentially a layer-by-layer fabrication method. AM process typically starts with a digital design of the component using a computer aided design (CAD) software. The design is then converted into a stereolithography file format (.STL), wherein the component surfaces are tessellated into triangles, and a database of the triangle nodes stored. In the next step, layers are generated from the created database wherein each layer governs the deposition of material in two dimensions (2D) and the layer thickness and interweaving govern the deposition of material in the third dimension. All geometric information about the desired solid object to be manufactured is now available in the form of a g-code which can be subsequently fed into a material deposition device. When the object is manufactured, material deposition takes place in a layer-by-layer fashion wherein each layer is manufactured according to the deposition scan implementation in the g-code and is repeated until the entire component is built. Thus, the additive process flow in AM alleviates the constraints associated with traditional manufacturing methods and provides tremendous opportunities for the design of novel geometries and complex internal structures to enhance component properties such as its strength-to-weight ratio or cooling in comparison with traditional manufacturing methods.

AM also allows fabrication of 3D objects in a variety of material compositions such as metals, alloys, ceramics, polymers, tissues, and cells. However, each AM technology is accompanied by its own benefits and limitations which may constrain the design and manufacturing process flow. For instance, Fig. 1.1 illustrates the differences in design elements and manufacturing process flow involved in the realization of a design concept the 'Academic Sharp Brain (ASB)' into a 3D object composed of metal or plastic and fabricated using AM. At the design stage, the designer develops a complete layout and geometrical design of an object based on the project objective, availability of feedstock material, available funds and resources and desired characteristics of finished product such as weight, strength, visual appeal, and shelf life. This stage is depicted for metallic ASB in Fig. 1.1a and plastic ASB in Fig. 1.1e. Varying degree of infills are commonly employed in AM for reduction of material wastage since the desired strength and shelf-life can be easily achieved by fabrication of hollow objects with solid shells. For the metallic ASB, the designer gives a masculine form to ASB and imbibes the infill requirement directly in the design stage by designing a meshed object with interwoven triangular lattice. Such a design allows optimization of object strength by controlling the geometry of the mesh element



https://www.youtube.com/watch?v=ZS_vQ0ObqaY

Fig. 1.1 Illustration of different design elements and process flow involved in the realization of a bespoke design concept into a metallic (a–d) and plastic (e–k) 3D object ‘Academic Sharp Brain Logo (ASB)’ using additive manufacturing; **a** CAD design of the metallic ASB composed of triangular meshes to control the weight, reduce material wastage, reduce print times and improve visual appeal; **b** Tessellation of the CAD design file into STL file format for supplying the geometric information to laser position stage; **c** Adjusting the build orientation to vertical based on the requirements of SLM; **d** Image of the finished metallic ASB after post processing and finishing; **e** Design of a single component of the plastic ASB using Solidworks CAD software; **f** Conversion of the 3D model to a STL file wherein all component surfaces are tessellated into triangles and data stored in a g-file; **g** Import of g-file into an open-source and free to use process modelling software ‘Cura’ available under public license LGPLv3; **h** An example of different printing parameters that govern the quality of finished printed object such as layer height, wall thickness, number of top and bottom layers, infill type and density, printing speed, bed temperature etc.; **i** Use of 15% infill volumetric density and a grid infill pattern to reduce print times and consumption of feedstock material; **j** Assembly of the final object using different printed components; and, **k** The final object after painting and post processing. The Academic Sharp Brain event was hosted as a part of the Royal Australian Chemical Institute Centenary Congress in July 2017 (https://www.youtube.com/watch?v=ZS_vQ0ObqaY)

such as size, thickness, and shape. Moreover, the designer incorporates symbols of the four elements, Germanium (Ge), Nickel (Ni), Uranium (U) and Sulfur (S) to communicate ‘GENIUS’. Figure 1.1b depicts the tessellation of the CAD design file into the STL file format. The STL file can then in turn be converted into a g-code which provides positioning coordinates to the fabrication device such as the laser positioning stage in selective laser melting (SLM). At this stage the fabricator must decide the orientation of the build which impacts the build quality as demonstrated in Fig. 1.1c for fabrication of the metallic ASB in a vertical build orientation. Finally, an image of the finished object after the SLM process and post manufacturing cleanup is depicted as Fig. 1.1d.

For the plastic ASB, the designer has given a feminine form to the design concept and decided to add décor such as a graduation hat and an ASB collar. Instead of printing the object as a whole, the designer decided to print each component separately and assemble in the last stage. Figure 1.1f depicts the tessellation of the CAD design into STL file format and data storage in a g-file. Considering the efficacy of the Fused Deposition Modelling (FDM) process, the fabricator decided to print in a horizontal build orientation as shown in Fig. 1.1g which was controlled through an open-source and free to use process modelling software 'Cura'. The process modelling software also allows control over printing parameters such as layer height, wall thickness, number of top and bottom layers, infill type and density, printing speed and bed temperature as depicted in Fig. 1.1h. In contrast to the metallic ASB where infill was incorporated directly into the design, for the plastic ASB the fabricator incorporates an infill of 15% volumetric density and a grid infill pattern in the process modelling stage as depicted in Fig. 1.1i. The design of different components of the desired object are shown in Fig. 1.1j and an image of the finished object after assembly, finishing, and painting is depicted in Fig. 1.1k. This example illustrates the efficacy of additive manufacturing in enabling total design freedom and free form fabrication.

Today AM is the fastest growing sector of manufacturing globally. Wohlers Associates' 2021 annual Report [1], the most recognized and comprehensive account of the current state of the global additive manufacturing industry, estimated that the global 3D printing industry has grown to a total of US $12.8 billion in 2020 as shown in Fig. 1.2. The 374-page report also discusses the impact of COVID-19 on the additive manufacturing industry and estimates that the annual growth was down

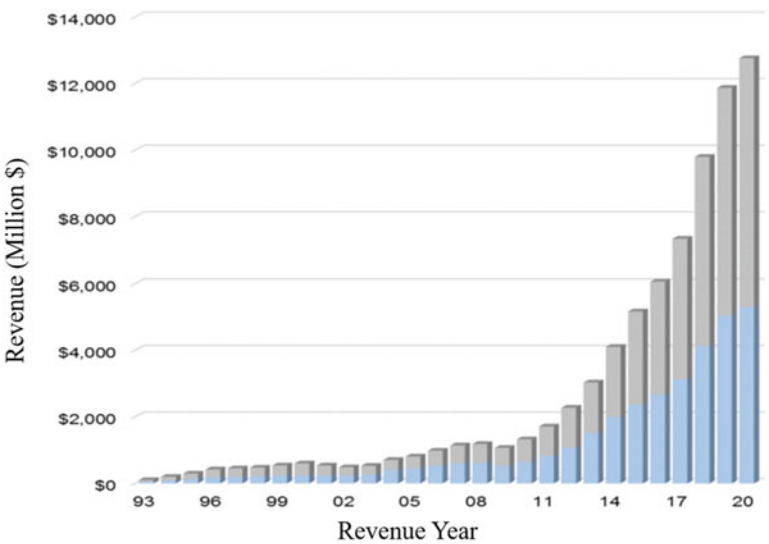


Fig. 1.2 Global revenue generated from AM products and services since 1993 over the years. The lower (blue) segment of the bars represents products, while the upper (grey) segment represents services. *Source* Wohlers Report 2021 [1]

considerably from an average growth of some 27% over the previous 10 years but nevertheless, the marked grew by some 7.5%. The report also includes commentary on 74 early-stage investments and 35 acquisitions and public offerings. Additive manufacturing startups and established companies have received substantial funding in 2020. For example, Desktop Metal, received $575 million as part of a merger with a special acquisitions company. After going public in December 2020, Desktop Metal's market capitalization exceeded $7.5 billion in February 2021.

Despite COVID-19, many engineering industrial giants such as Stryker, Audi, BMW, Boeing, Ford, General Electric, Hewlett-Packard, Nike, Airbus and Alcoa to name a few as well as many small and medium-sized enterprises globally, are on the path of partial to complete adoption of additive manufacturing technologies. In 2020, many companies quickly pivoted to additive manufacturing technologies in response to the shortage of personal protection equipment, testing equipment and ventilators caused by COVID-19 pandemic. Popular press, technical and trade journals are reporting new innovations and advancements in 3D printing almost every day such as launch of new and innovative printers, sophisticated parts additively manufactured in both metallic alloys as well as polymers and design and manufacturing of modern components that challenge the imagination. Many countries have initiated large national programs in the last few years to further accelerate the development of new AM technologies, feedstock materials and their applications.

In the modern age, the global shift from mechanical and analogue electronics to digital electronics is being called the digital revolution or the fourth industrial revolution. 3D printing is the manufacturing component of this digital revolution wherein manufacturing of a solid object from a digital design is being branded as direct digital manufacturing. The global inclination towards direct digital manufacturing can be traced back to some five years ago. COVID-19 has provided further impetus to this movement by posing a serious threat to supply chain logistics, sovereign capability, and national security. All these factors are changing the nature and economics of global manufacturing, particularly in "first-world" countries and will continue to do so in the future. Thus, it is critical for companies in "first-world" countries to leverage advanced technology and latest research for addressing the challenges of modern global economics and competitive manufacturing to remain in business and make profits. AM is being increasingly seen as 'the solution' to such challenges owing to the benefits it offers compared to conventional subtractive manufacturing. Unlike the early days of rapid prototyping, latest additive manufacturing technologies are capable of directly manufacturing functional polymers and metal components from computer generated models or based on measurements taken to re-engineer existing components. As such AM has truly bypassed traditional manufacturing processes such as cutting, milling, and grinding in most aspects. Various benefits and advantages of AM shown in Fig. 1.3, include: (1) capability to manufacture new and sophisticated designs not possible using conventional subtractive technology, (2) dramatic savings in time, materials, wastage, energy, and other costs in producing new components, (3) significant reductions in environmental impact, and (4) faster time to market for products.

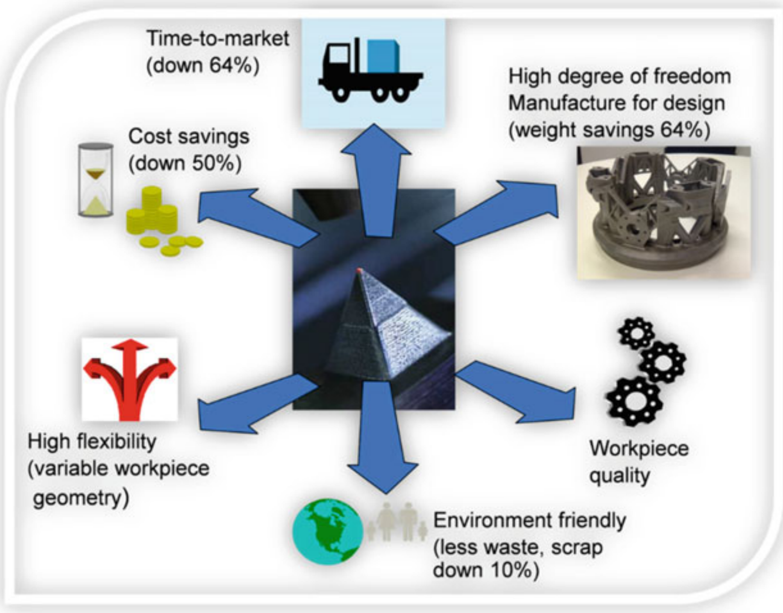


Fig. 1.3 Various benefits and advantages of additive manufacturing. Figure in brackets refers to savings in aerospace and defense sectors. Permission pending from [2]

1.2 Standardization of Additive Manufacturing Technologies

In common with the conventional subtractive technologies, there has been a push in recent years to standardize the AM technologies to ensure part quality, repeatability, and consistency across builds and machines. According to the American Society for Testing and Materials (ASTM F52900-15) [3] there are over 50 different AM technologies, which were classified into 7 standard processes as binder jetting, material jetting, material extrusion, vat photopolymerization, powder bed fusion, energy deposition and sheet lamination as shown in Fig. 1.4. Besides the standard classification, AM technologies are often classified based on feedstock materials such as metals, polymers and other materials and the method used to fuse the materials as shown in Fig. 1.5. A number of these technologies are now quite mature, such as fused deposition modeling (FDM), selective laser sintering (SLS), stereolithography (SLA), powder bed inkjet 3D printing (BJT), and their variants (Material jetting (MJT)) and laser (LPBF) and electron beam melting (EBM) [4–6].

The wide interest and enormous potential in the dynamic field of AM has led to development and commercialization of new technologies and feedstock materials rapidly and on a regular basis. In the recent years it has become possible to manufacture objects with an ever-expanding library of printable materials in shorter

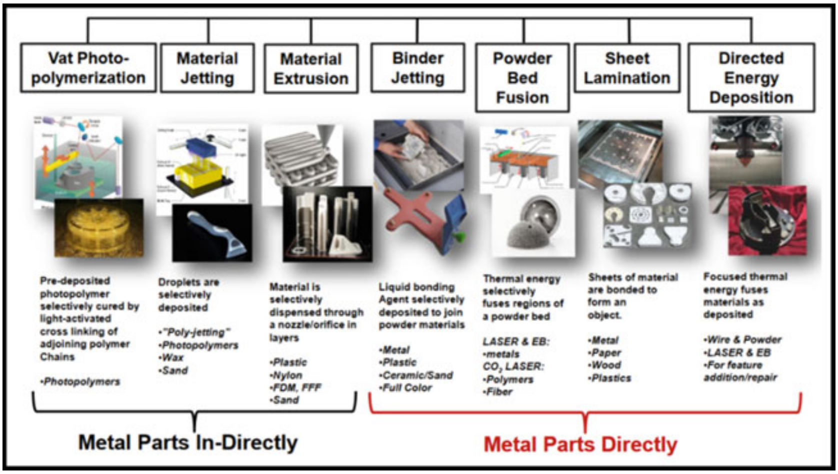


Fig. 1.4 Standard classification of AM technologies according to ASTMF52900-15. *Source* https://insights.globalspec.com/article/7447/factors-to-consider-when-3d-printing-or-additive-manufacturing-metal-parts [7]

production times and at lower cost which was not feasible before. A more detailed description of each technology, its benefits, and limitations in terms of print resolution, component manufacturability and part properties, examples of innovative component designs and range of current applications in relation to chemical science and engineering are presented in the following chapters.

1.3 Additive Manufacturing—Features and Characteristics

Like any manufacturing technology, all AM technologies have some common attributes which are characteristic of the direct digital and layer-by-layer manufacturing methodology such as the need of a CAD and process modelling software, processable feedstock materials and quality of manufactured objects in comparison to conventional manufacturing technologies. For additive manufacturing to become a global household phenomenon it is critical that CAD design and process modelling software are made available to the user with an interactive and intuitive user interface at an affordable price or free of cost. The AM community is already responding to this need and the latest generation open-source software are revolutionizing how 3D objects are designed and modelled for 3D printing. While the developments in commercially available AM software have been significant over the last five years in terms of their design and process modelling capability, they are still lacking in the ability to easily model or analyze multiple material geometries and their accompanying anisotropy.

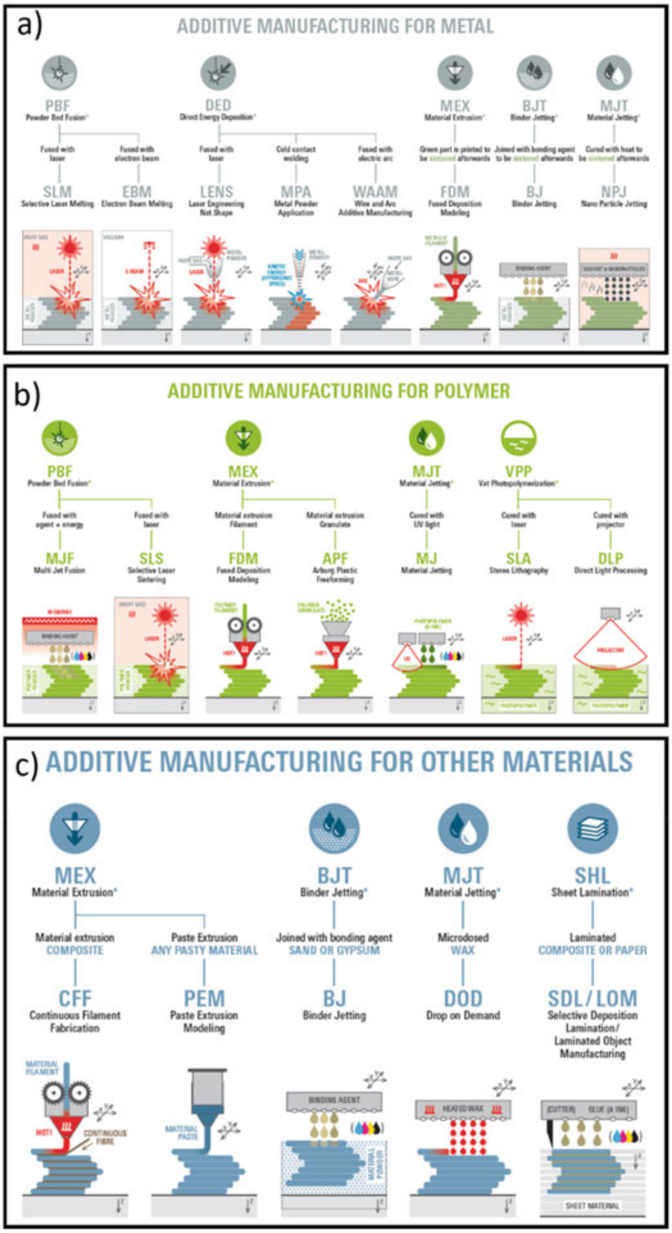


Fig. 1.5 Classification of AM technologies based on the method of fabrication and processable feedstock materials as **a** metal; **b** non-metals and **c** other materials. *Source* Ritter, Steffen (2020). Formnext AM field Guide compact 2021. Frankfurt Main: Mesago Messe Frankfurt GmbH ISBN 978-3-9,823,018-7-3 [8]

A vital characteristic of AM technologies is the need for adequate feedstock material in the required form such as powder, filament, pellets, granules, sheets, and resins. The range of feedstock materials for AM technologies is expanding exponentially and new materials are constantly coming into the market [4–6, 9]. The materials can be broadly classified as metals and non-metals and come in a variety of forms depending on AM technology ranging from powder to resins. The properties of feedstock material such as particle size, shape, density, composition, and purity are governed by the operational requirements of individual AM technologies and are specified by the manufacturer of the technology. Specific materials can and have been developed for an individual AM technology for dedicated applications with material properties. A more detailed description of the different feedstock material characteristics and properties for each AM technology is provided in the following chapters.

Another very important characteristic feature of AM is the surface roughness of manufactured parts and components and anisotropic mechanical properties arising from the layered nature of the build. The variation in mechanical properties for example can arise from the directional solidification of the melt pool in the case of metallic feedstocks and interlayer bonding deficiencies in the case of polymer feedstocks. In general, the quality of a printed part's surface is mainly determined by the thickness and overlap of each printed layer. Larger layer thickness and overlaps result in a rougher surface especially when building at an angle. Employing smaller layer thicknesses result into corresponding increase in object production time which can seriously impact the process economics. This adverse effect arising from the layer-by-layer manufacturing methodology in AM is also called the "stair-stepping" effect and governed by the underlying deposition technology. Extrusion-based AM systems typically have the largest layer thicknesses (0.2 mm) due to the large diameter of the deposition nozzle. Alternatively, powder bed fusion and vat photopolymerization AM technologies systems have much smaller layer thicknesses ($\sim$0.1 mm), and thus result in smoother surfaces because of the system ability to precisely focus the energy beam radius. Material jetting systems also offer fine layer thicknesses (as low as 0.02 mm) due to the ultrasmall size of jetted droplets. Surface quality of the manufactured objects also depend on the employed feedstock materials. AM processes employing metallic powders have poorer surface quality than others due to large and partially melted powder particles that adhere to the surface of manufactured object. The surface roughness of powder bed systems is also a function of the build orientation where the sides of the build have different surface roughness in comparison to the top and bottom of the build. A large majority of AM systems still employ only a single material at a time. New multi-material AM systems are now emerging that allowing manufacturing with functionally graded materials in both polymer and metal. However, the technology is very much in the research phase with limited data on material behavior at the interface and a lack of design software support [10, 11].

1.4 Additive Manufacturing in Chemical Sciences and Engineering

A chemical is a substance with a characteristic composition and distinct property. Chemicals are the building blocks of our modern technological society and it would be impossible to sustain our current lifestyle without them. Chemical sciences refer to the group of fundamental sciences which deal with the scientific study of all aspects of chemicals such as their properties, production, storage, and transportation. Thus, the advancement and practice of chemical sciences is essential for the production of medicines that allow us to recover from illness, health supplements that shape and improve our body, perfumes and air-fresheners for our sensory pleasures, soaps, and detergents to clean us and our clothes, artificial fabrics such as nylon, terylene, velvet and velcro for our fashion needs, paints, and varnishes for the beautification of objects all around us, plastics for storage, fuels for electricity, heating, cooking and vehicles, fertilizers, and pesticides for the production of the food we eat, the asphalt in our roads and so on. Due to the multidisciplinary nature of applications involved, chemical sciences operate at the interface of chemistry, physics, biology, and material science. Chemical engineering uses the fundamental knowledge from chemical sciences and deals with the design, manufacturing, safety, operation and maintenance of chemical processing instruments, equipment, and plants. Thus, chemical engineering operates at the interface of chemical sciences, mathematics, economics, mechanical and civil engineering. Continuous progress in the chemical sciences and engineering is clearly critical to:

1. Future advances in sustainable production, storage, and supply of energy
2. Conservation of the environment and mitigation of climate change
3. Increase in food production and its sustainability with less demand on arable land
4. Advanced diagnostics and novel disease prevention therapies based on exploitation of the human genome
5. Designing processes and products that preserve resources
6. Provision of accessible clean drinking water for all

As the leaders of process-based manufacturing, chemical scientists and engineers must face the modern challenges of chemical production such as process economics, competitiveness, supply chain and logistics, environment protection and sustainability. To meet these challenges a continuous evolution of chemical industries is required which relies on the fast and innovative development of modern and cutting-edge manufacturing processes, materials, and products. In addition to the customary demands of low price and best quality, the cut-throat market competition demands products that are intricate, possess shorter life cycles, exhibit shorter delivery times, involve customization, and require less skilled workers. In fact, the current breed of products is highly sophisticated and challenging to design. Accordingly, there is a strong incentive toward the design, development, and implementation of new and ingenious chemical manufacturing processes which can be realized by employing additive manufacturing technologies [12, 13].

By 2030 the world's population is expected to increase to over eight billion, with the majority of those people living in cities. Global energy requirements will continue to increase along with the pressure on Earth's natural resources to provide this rapidly expanding population with enough food, water, and shelter. It is estimated that more than one billion people now live-in poverty without sufficient food, water or adequate sanitation and healthcare provision. The newly industrialized nations of Asia and Latin America are undergoing rapid industrial expansion and experiencing large economic growth but also contributing to modern society's environmental problems such as waste disposal, air, water, noise, and light pollution. The human ambition to grow and expand has seriously impacted the earth's ecological system and climate change is getting wide recognition as the number one threat to humanity. Mitigation and permanent resolution of these challenges will rely on adoption of sustainable development principles i.e., development of capabilities to meet the needs of the present without compromising the ability of future generations to meet their own needs. The foundation of this sustainable society must be laid down with eco-efficient processes and products that the chemical sciences can provide. Advances in chemical sciences will be needed to develop functional materials to construct our homes and buildings and develop lightweight, safe and energy efficient vehicles which will help reduce greenhouse gas emissions. The chemical sciences, therefore, have a clear role in enabling sustainable development and providing technological solutions to face the challenges of society today and in the future. The technologies that the chemical sciences engender will improve the quality of daily life, underpin prosperity, and increase our readiness to face the challenges of the future.

The adoption of AM technologies in some industry sectors such the aerospace, defense and bioengineering has been significant over the last five years with new AM products or AM based processes being reported in the open press on a regular basis. However, the use of AM technologies within the chemical sciences has not seen the same level and scale of adoption. Nevertheless, the potential is significant in the context of health, energy and food production and laboratory scale demonstrations of the application of the AM technology have now started to emerge in the chemical sciences [5, 14]. A thorough and critical review summarizing the most frequently applied AM technologies in the context of design and functional prototypes, the printing materials and technologies is given in [15]. In the chemical sciences, polymeric materials have found a larger acceptance due to their favorable processing and post-processing options, range of product properties, low cost of printing, and accessibility of printers. Designed and manufactured objects have been successfully applied as lab-scale reaction ware, for optimization of reactors and reaction protocols and development of operation units for process scale-up. This union of AM from the mechanical sciences and chemical reaction engineering from chemical sciences opens doors for design of smart reactors that enable high conversion, superior product selectivity and favorable process economics. Thus, through the synergistic utilization of computational fluid dynamics and AM technologies, a new generation of batch and continuous reactors will emerge for chemical reactions. For example, Zhao et al. [16] designed a fractal type photobioreactor based on bifurcation tree algorithm and fabricated it using SLA technology as shown in Fig. 1.6. The novel design improved mass transfer, photosynthetic conversion and CO_2 capture efficiency enabling high growth rates for biomass.

The scope of AM in chemical reaction engineering is not just limited to manufacturing of sophisticated reactor designs but also allows multi-device integration, rapid prototyping and testing and improvisation of lab scale continuous and batch reactors which can be manufactured in polymers and metals. For instance, Fig. 1.7 depicts a state-of-the-art 3D printed split-and-recombine stainless-steel reactor with an integrated cooling shell and oxygen sensors for online reaction monitoring of the oxidation reaction of a Grignard reagent in homogeneous phase. The reactor

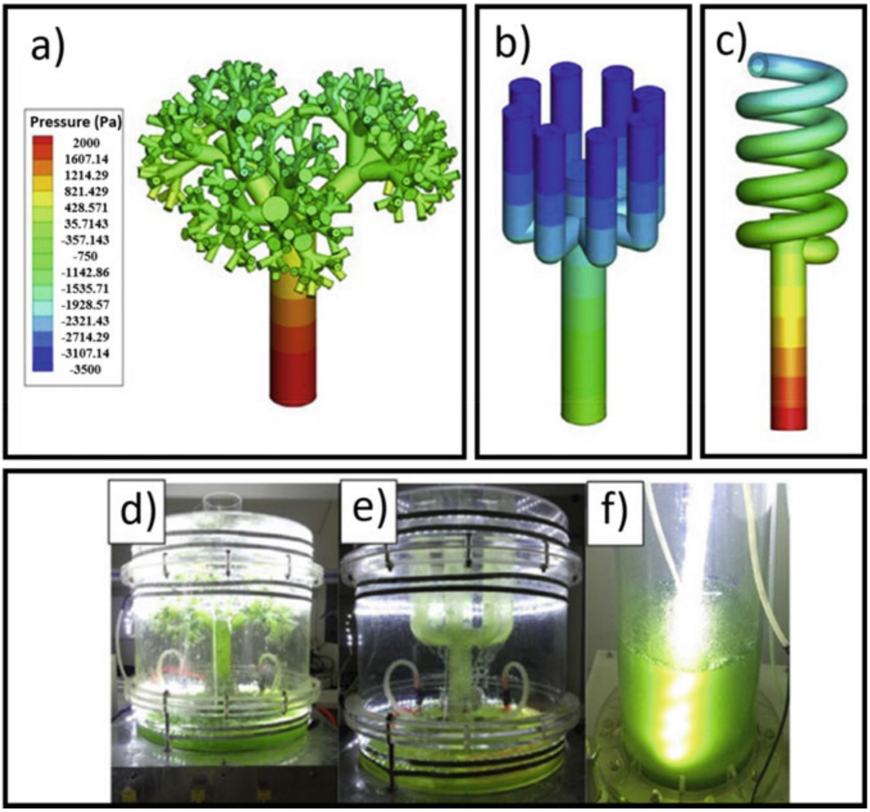


Fig. 1.6 A fractal type photobioreactor (PBR) designed based on bifurcation tree algorithm and manufactured using stereolithography; (Top) Time averaged relative pressure in three-types of PBRs modelled using CFD; **a** Fractal tree-like PBR; **b** multitubular PBR; **c** tubular reactor with a spiral column; (Bottom) Chlorella culture in the different PBRs on the 4th day in the **d** Fractal tree-like PBR; **e** multitubular PBR; and **f** tubular reactor with a spiral column. Reproduced from Ref. [15] with permission from Elsevier

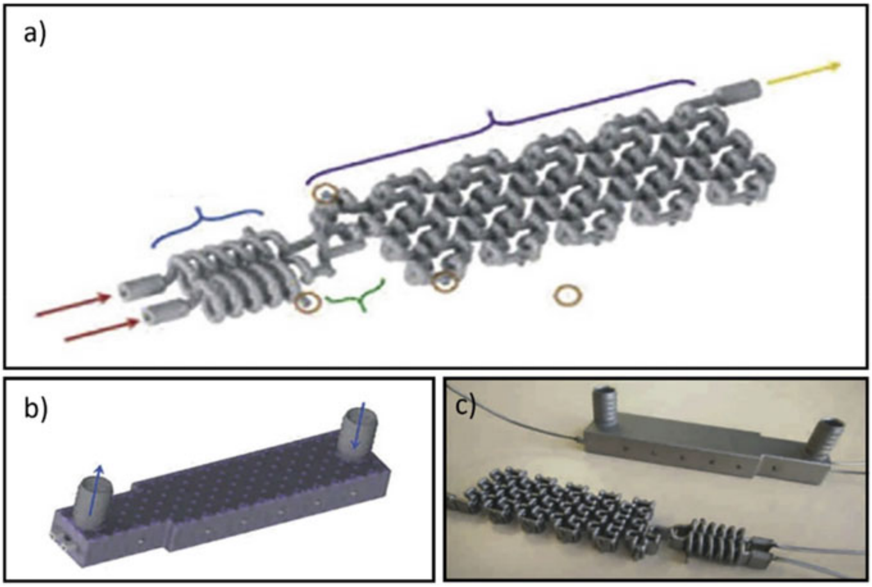


Fig. 1.7 A stainless-steel split and recombine reactor fabricated by additive manufacturing **a** Overview and CAD design of reactor section in the split and recombine reactor. Repetition of the structural elements in any direction allow arbitrary scaling of the reactor; **b** Design of the cooling jacket encapsulating the reactor section; and **c** Image of the reactor with and without the external cooling shell. Reproduced from Ref. [17] with permission from the Royal Society of Chemistry

comprises pre-cooling sections, a series of split-and-recombine mixing elements which can be increased in numbers or scaled for larger reactor lengths or volumes, a cooling shell for recirculating coolant encapsulating the entire reactor, and multiple fiber optic oxygen sensors for online reaction monitoring. Compared to a plug flow micro coiled reactor, the novel reactor exhibited comparable conversion levels but significantly higher product selectivities. The developed AM rector allowed product yields up to hundred's milliliter range per day [17].

Another vital component of chemical reaction engineering, heterogeneous catalysis is an integral part of our large-scale energy, fuel, chemical, and pharmaceutical industries. Implementation of alternative, small-scale AM technologies in heterogeneous catalysis can potentially change the entire technological landscape and anticipated to have an enormous and immediate impact. A detailed review of the different aspects and application of various AM technologies in heterogeneous catalysis such as functionalization of printed structures with catalysts, direct printing of catalytic materials or catalyst supports and rapid prototyping and printing of reactionware is available in the literature [18]. One of the major objectives in chemical manufacturing is the development of microreactors which enable superior process efficiencies and allow sustainable production of chemicals on demand and onsite. This objective has taken the center stage in the wake of COVID-19 pandemic where disruptions in global supply chains and international border closures have put extraneous pressure on the local manufacturing sector and provided impetus for localized production of pharmaceuticals, fine chemicals, food additives and other similar chemicals of importance. Thus, just a reduction in the scale of chemical operations achieved at comparable process efficiencies using AM technologies can address this major objective. Secondly, traditional large-scale chemical manufacturing units and plants are difficult to adapt once built as the cost for modifications at the large scale are quite steep. Thus, in the case of poor resource management, hazardous processing practices or poor environmental sustainability resulting from the final design, implementation of the necessary modifications can prove to be unviable and non-profitable. Therefore, introduction of AM in heterogeneous catalysis and the chemical industry can dramatically improve plant adaptability by employing modular design and smaller sized equipment and reactor components to reduce manufacturing and design costs. In addition, the relative cost efficiency of AM technologies for short production runs makes them ideal for late-term adjustments to chemical plants either due to unknowns in the process, or just the need for new process functionality. Images of some of these AM devices in metals and polymers which were developed at RMIT university for various catalytic, separation and sensing applications, are shown in Fig. 1.8.

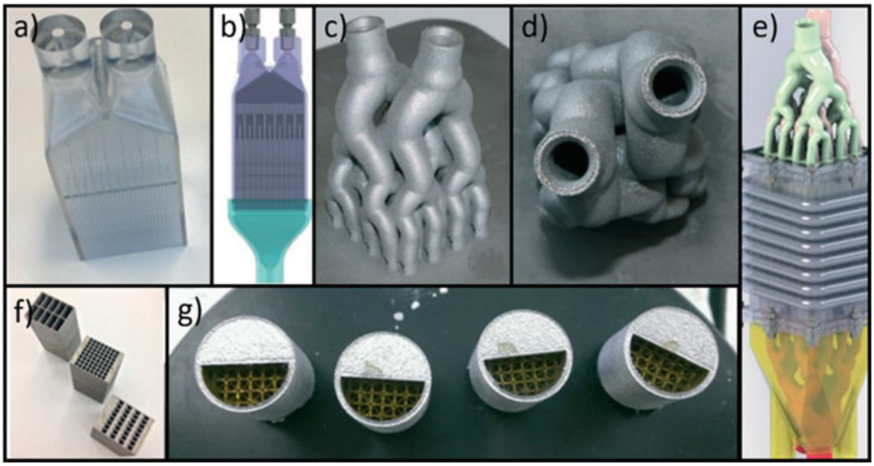


Fig. 1.8 Images of the additively manufactured flow devices, monoliths and reactionware developed at RMIT university; **a** Perspective view of the concept of a dual inlet fractal 3D micromixer with decrease in channel cross section with reactor depth; **b** Front view of the fractal micromixer; **c** Image of the 3D micromixer fabricated using selective laser melting; **d** Top view of the fractal 3D micromixer; **e** The concept of the complete reactor assembly with micromixer inlets and outlets; **f** rectangular monolith reactors; **g** cylindrical monolith reactors. (*Source* RMIT Centre for Additive Manufacturing)

1.5 Summary

Additive Manufacturing is truly an enabling technology and its enormous potential in generation of new products and processes with improved process economics has only started to emerge in the chemical manufacturing sector. Implementation of AM technologies in chemical reaction engineering has enabled the development of state-of-the-art automated reactor systems with online reaction monitoring and sophisticated reactor designs with functionalized surfaces. The design freedom allows control of reactant stoichiometry by modification of the reactor geometry and incorporation of desired features, such as proton exchange membranes and purification columns. AM also has enormous potential in catalyst exploration, material development and advanced catalytic systems with gradient catalytic activities as multi-material AM systems become commercialized and accessible. While the application of AM to chemical sciences and engineering is still in an early stage, the reported research and developments in the field demonstrate that AM will become an integral tool in chemical science and engineering and shape the manufacturing processes of the future. New innovations in materials, technology and software will ensure that such progress will only be accelerated in the future.

1.6 Test Your Knowledge

After reading the above chapter you should be able to answer the following questions:

1. *What are the three most common manufacturing philosophies used for fabrication of complex shaped objects?*
2. *What is the typical process flow involved in additive manufacturing of an object from a design concept?*
3. *What are the seven standard additive manufacturing processes according to ASTM F52900-15 committee on additive manufacturing?*
4. *What is stair-stepping effect in additive manufacturing and what is the consequence of this effect on the surface finish of the printed object?*

References

1. Wohler (2021) 3D Printing and additive manufacturing, global state of the industry
2. Brandt M (2017) The role of lasers in additive manufacturing. In: Brandt M (ed) laser additive manufacturing. Woodhead Publishing, pp 1–18. https://doi.org/10.1016/B978-0-08-100433-3.02001-7
3. ISO/ASTM52900-15, standard terminology for additive manufacturing—general principles—terminology ASTM international, West Conshohocken, PA (2015), www.astm.org

4. Gao W, Zhang Y, Ramanujan D, Ramani K, Chen Y, Williams CB, Wang CCL, Shin YC, Zhang S, Zavattieri PD (2015) The status, challenges, and future of additive manufacturing in engineering. Comput Aided Des 69:65–89. https://doi.org/10.1016/j.cad.2015.04.001
5. Zhakeyev A, Wang P, Zhang L, Shu W, Wang H, Xuan J (2017) Additive manufacturing: unlocking the evolution of energy materials. Adv Sci 4(10):1700187. https://doi.org/10.1002/advs.201700187
6. Molotnikov A, Kingsbury A, Brandt M (2021) 23—current state and future trends in laser powder bed fusion technology. In: Yadroitsev I, Yadroitsava I, du Plessis A, MacDonald E (eds) Fundamentals of laser powder bed fusion of metals. Elsevier, pp 621–634. https://doi.org/10.1016/B978-0-12-824090-8.00011-1
7. Kardys G (2017), https://insights.globalspec.com/article/7447/factors-to-consider-when-3d-printing-or-additive-manufacturing-metal-parts
8. Formnext AM Field guide compact, https://formnext.mesago.com/frankfurt/en/themes-events/am-field-guide.html. (2020)
9. Bourell D, Kruth JP, Leu M, Levy G, Rosen D, Beese AM, Clare A (2017) Materials for additive manufacturing. CIRP Ann 66(2):659–681. https://doi.org/10.1016/j.cirp.2017.05.009
10. Walker J, Middendorf JR, Lesko CCC, Gockel J (2021) Multi-material laser powder bed fusion additive manufacturing in 3-dimensions. Manuf Lett,https://doi.org/10.1016/j.mfglet.2021.07.011
11. Wei C, Sun Z, Chen Q, Liu Z, Li L (2019) Additive manufacturing of horizontal and 3D functionally graded 316L/Cu10Sn components via multiple material selective laser melting. J Manuf Sci Eng 141(8), https://doi.org/10.1115/1.4043983
12. Chang F, Zhang X, Zhan G, Duan Y, Zhang S (2020) Review of methods for sustainability assessment of chemical engineering processes. Ind Eng Chem Res 60(1):52–66. https://doi.org/10.1021/acs.iecr.0c04720
13. Boydston AJ, Cui J, Lee C-U, Lynde BE, Schilling CA (2020) 100th anniversary of macromolecular science viewpoint: integrating chemistry and engineering to enable additive manufacturing with high-performance polymers. ACS Macro Lett 9(8):1119–1129. https://doi.org/10.1021/acsmacrolett.0c00390
14. Femmer T, Flack I, Wessling M (2016) Additive manufacturing in fluid process engineering. Chem Ing Tec 88(5):535–552. https://doi.org/10.1002/cite.201500086
15. Zentel KM, Fassbender M, Pauer W, Luinstra GA (2020) Chapter four—3D printing as chemical reaction engineering booster. In: Moscatelli D, Sponchioni M (eds) advances in chemical engineering, vol 56. Academic Press, pp 97–137, https://doi.org/10.1016/bs.ache.2020.08.002
16. Zhao L, Zeng G, Gu Y, Tang Z, Wang G, Tang T, Shan Y, Sun Y (2019) Nature inspired fractal tree-like photobioreactor via 3D printing for CO_2 capture by microaglae. Chem Eng Sci 193:6–14. https://doi.org/10.1016/j.ces.2018.08.057
17. Maier MC, Lebl R, Sulzer P, Lechner J, Mayr T, Zadravec M, Slama E, Pfanner S, Schmölzer C, Pöchlauer P, Kappe CO, Gruber-Woelfler H (2019) Development of customized 3D printed stainless steel reactors with inline oxygen sensors for aerobic oxidation of Grignard reagents in continuous flow. React Chem Eng 4(2):393–401. https://doi.org/10.1039/c8re00278a
18. Hurt C, Brandt M, Priya SS, Bhatelia T, Patel J, Selvakannan PR, Bhargava S (2017) Combining additive manufacturing and catalysis: a review. Catal Sci Technol 7(16):3421–3439. https://doi.org/10.1039/c7cy00615b