Engineering 2015, 1(1): 85–89
DOI 10.15302/J-ENG-2015012

Research
3D Printing—Perspective

Development Trends in Additive Manufacturing and 3D Printing

Bingheng Lu*, Dichen Li, Xiaoyong Tian

ABSTRACT Additive manufacturing and 3D printing technology have been developing rapidly in the last 30 years, and indicate great potential for future development. The promising future of this technology makes its impact on traditional industry unpredictable. 3D printing will propel the revolution of fabrication modes forward, and bring in a new era for customized fabrication by realizing the five "any"s: use of almost *any* material to fabricate *any* part, in *any* quantity and *any* location, for *any* industrial field. Innovations in material, design, and fabrication processes will be inspired by the merging of 3D-printing technology and processes with traditional manufacturing processes. Finally, 3D printing will become as valuable for manufacturing industries as equivalent and subtractive manufacturing processes.

KEYWORDS additive manufacturing, 3D printing, fabrication modes, customized fabrication, innovative design

1 Introduction

As a new manufacturing technology, 3D printing is gradually starting to attract interest in both the academic community and the business world. In terms of manufacturing technology, 3D printing is an additive manufacturing process during which the mass change of the part is positive ($\Delta M > 0$). Accordingly, processes with $\Delta M = 0$ and $\Delta M < 0$ are called equivalent manufacturing and subtractive manufacturing, respectively. The development of equivalent manufacturing has occurred over more than 3000 years. An early example of this type of manufacturing is the bronze casting technique that was used in Sanxingdui (a major Chinese city during the Bronze Age). Other examples such as the Gan Jiang and Mo Ye swords, forged in the Spring and Autumn Period (770 B.C. to 403 B.C.), as well as the bronze chariots and horses of Qin Shi Huang also mark the long history of metal heat treatment and welding techniques. With the development of mechanical power (especially the invention of the electromotor, based on electromagnetic theory), subtractive manufacturing technologies such as machine tools and machining technologies emerged over a period of more than 300 years. In comparison with equivalent and subtractive manufacturing, the history of additive manufacturing is relatively short. The first prototype of a stereolithography machine for 3D printing was created less than 30 years ago, indicating great potential for future development in 3D printing. However, the promising future of this technology also makes its impact on traditional industry unpredictable. Therefore, in the following sections, we will discuss some possible development directions of 3D printing in the near future.

2 3D printing propels the revolution of fabrication modes

2.1 The five "any"s of 3D printing

Today, inventions and creations in 3D printing are becoming more and more prevalent. Numerous studies have been performed on 3D-printing processes and equipment for a wide range of materials, including plastic, metal, ceramic, wood, edible material, electric fiber, magnetic materials, and graphene [1]. 3D printing uses the additive method to transform the fabrication of three-dimensional components into the creation of multiple two-dimensional cross sections, so that parts with any complex shapes can be fabricated, even parts with a cavity inside [2].

3D printing has excellent flexibility, which makes it appropriate for production tasks on any scale. Not only can it be used to print customized artificial human teeth and bones, but it can also be used to create molds for manufacturing [3]. 3D printing has the advantages of low cost and short fabrication cycle time, and may become a major mold fabrication method in the future automobile industry. Moreover, 3D printing is also suitable for medium- to high-volume production.

The development of 3D-printing processes and equipment makes it possible to fabricate parts in an enterprise, an office, or a home—any place can become a 3D-printing workshop.

Xi'an Jiaotong University, Xi'an 710049, China
* Correspondence author. E-mail: bhlu@mail.xjtu.edu.cn
Received 3 March 2015; received in revised form 25 March 2015; accepted 31 March 2015

Now 3D printing is gradually becoming a technology that can be learned and mastered by the general public. People can easily learn the use of 3D-printing machines and then self-design and fabricate simple objects such as desk lamps, hangers, and so on. This technology has also been researched and explored for outer space applications. In the future, satellites, spacecraft service parts, and even buildings could be directly fabricated away from the earth using 3D-printing technology [4–6].

3D printing has already been accepted by and used in many industries. For example, in the aerospace industry, it has been used to fabricate large flexible structural parts and load-bearing parts with complex shapes and low volume fraction. This technology can also be used to fabricate precision parts in aerospace engines and their controllers [7]. In architecture, 3D printing is being used to fabricate architectural design models. Architects divide architectural structures into load-bearing structures and embellishments [6]. 3D printing, with its ability to fabricate complex structures, will no doubt play an important role in embellishment design in this field.

In conclusion, 3D printing can use almost *any* material to fabricate *any* complex part, in *any* quantity and in *any* location, for *any* industrial field. These five "any"s are the main advantages of 3D printing. Interdisciplinary research will tremendously accelerate the development of this technology.

2.2 3D printing: A new era for customized fabrication

When 3D printing is used to fabricate complex parts, no molds, complex manufacturing procedures, special fixtures, or tools are required. This technology will be widely used to create prototypes in the aerospace and aeronautics industry, and for mechanical-electrical product development. R&D on industrial products and key equipment will more and more depend on 3D-printing technology and on the Internet of Things (IoT). 3D printing is particularly suited for customized fabrication, such as the fabrication of artificial implants (artificial bones and teeth, etc.) and medical rehabilitation equipment and devices. Moreover, the development of information technology has brought us to a new era of wearable information products. Customized fabrication is always necessary for these wearable products, and 3D printing will be the most appropriate manufacturing method.

Fordism, a concept of mass production originally based on the large-scale manufacturing of cars, is a typical phenomenon of the second industrial revolution. At present, however, the demand for customized goods is increasing. The development of information technology provides us with accessible ways to achieve this goal. The third industrial revolution, which is expected to involve customized fabrication, is ready to emerge.

Based on network platforms, distribution and demand can be integrated in order to rapidly provide various creative designs and solutions to customers. Manufacturing resources are also distributed, allowing customers to be part of the network and participate in the manufacturing process (even finishing the manufacturing in their own homes). In this way, it is possible to fabricate numerous creative products, and to guarantee that the fabrication cycle time and costs of these products are similar to those of products fabricated by high-volume production. This customized fabrication mode will finally be able to integrate public demand with public innovation and ideas. Meanwhile, this process will also be able to take full advantage of social innovation resources and manufacturing resources. All of these changes contribute to a revolution in terms of both business model and social production mode. In traditional manufacturing, it is always necessary to optimize numerous technological parameters, choose from various manufacturing procedures, use a variety of manufacturing equipment, and complete many steps. As a result, computer-aided process planning (CAPP) is difficult or impossible to achieve in traditional manufacturing. 3D printing, with its coherence of data, technological parameters, and flexibility, will be the best choice for distributed manufacturing.

3D printing and associated software technologies that can be used by the general public still need to be developed, and a cloud platform for design and manufacturing needs to be established. There is no doubt that 3D printing will be a strong force to expedite the emergence of the third industrial revolution.

3 Development trends in 3D printing

3.1 Innovative design: Redesigning leads to innovative products and equipment

In engineering, the key economic benefits of 3D printing may come from the redesigning of products and equipment, based on this new technology. Traditionally, designers only consider the manufacturability of a structure from the point of view of equivalent manufacturing and subtractive manufacturing. However, as additive manufacturing becomes more prevalent, many product and equipment structures can be reconsidered from its perspective. Product and equipment design needs to focus more on functional optimization and less on manufacturability limitations, and 3D printing will make this possible.

Structures that would benefit from this kind of redesign include heat-exchange structures, lightweight structures, and macro-micro integrated structures. 3D printing has already been used in a variety of explorations involving redesigning. For example, the jet nozzle of an aircraft engine developed by GE achieved a 15% reduction in fuel ratio due in part to components made by 3D printing [8]; a miniature sports car designed by Canadian undergraduates using 3D printing achieved a fuel consumption of only 1.17 liters per hundred kilometers [9]; and a concept by Airbus achieved a 65% weight reduction in components through a structural redesign involving 3D printing [10]. For IT products, aircraft engines, air conditioners, and nuclear facilities, heat exchange components are indispensable; redesigning these components using 3D printing can result in valuable economic benefits.

We anticipate that scientists and engineers from the academic community and from all industrial sectors will embrace these new innovations. The strong ability of 3D printing to create technology for IoT will propel social innovation in the manufacturing industry.

3.2 Innovative processes: From shape control to integrated fabrication

Initially, 3D printing put more emphasis on the shape of a part (or shape control of the part), and was primarily used for prototyping applications. However, with deep research on metal-material 3D printing, researchers have begun to focus on the metallographic phase under high non-equilibrium conditions, and on the distribution of internal stress inside the part (or performance control of the part). For example, by controlling laser-beam power and scan speed during 3D printing, we can control both the shape and the performance of the fabricated components (integrating fabrication with controllable shape and performance). Thus, 3D printing is now being transformed from a prototyping technology into a shape- and performance-controllable manufacturing method. The transient heat that occurs during the 3D-printing process, and its historical influence on the performance of the fabricated components, will be intensively investigated in order to achieve efficient fabrication with high accuracy and good surface quality of the part. Meanwhile, 3D printing is at the foundation of intelligent additive manufacturing equipment.

With the assistance of 3D-printing technology, materials can be printed where they can be of best use. Nature has miraculously created many materials and structures that are lightweight but have great strength, such as bamboo and human bones. With 3D printing, we can learn from and apply these miracles from nature to create high-performance materials and products. We can create materials that are lightweight and have high strength, and design inner structures with void and honeycomb sandwich structures, in order to achieve maximum specific strength and stiffness; afterward, corrosion- and abrasion-resistant materials can be printed onto the surface of fabricated parts.

By using 3D printing to fabricate products and equipment with functionally gradient materials and structures, high performance can be achieved with minimal materials. 3D printing is currently transforming from a single-material additive manufacturing technology to a multi-material additive manufacturing technology. The creation of functionally gradient or meta-material structures, and the optimal design of such structures, will create great opportunities for product and equipment innovation, and will attract significant attention from researchers in various fields. For example, researchers have demonstrated the fabrication of special auxetic structures (with negative Poisson ratio) using multi-material 3D printing [11].

3.3 Innovative processes: Extending fabrication to micro and nano scales

3D printing of micro and nano structures has also shown great application potential. 3D printing is an effective method for manufacturing various miniature transducers, and is far more flexible than current microelectronics manufacturing. The MEMS transducers that have been fabricated by 3D-printing technology will have an important role in the development of sensor networks and the intelligent manufacturing of discrete systems. Professor Minlin Zhong from Tsinghua University has used an ultrafast scanning laser beam to induce the growth of graphene on a substrate of a certain material, and has shown that the control of the scan path can realize the patterning of the graphene [12]. Various high-performance transducers such as temperature transducers, vibration transducers, and pressure transducers can be fabricated using this technology. The bottom-up growing fabrication mechanism is fundamentally consistent with the additive manufacturing process for 3D printing.

Another emerging additive manufacturing technology in this field is electronics printing using processes such as inkjet printing and aerosol jet printing [13]. Initially, these processes were developed as a 2D-printing technique for fabricating single-layer electronics. Recently, with advances in ink materials and machine control, such additive manufacturing processes are being transformed into 3D-printing processes for fabricating multi-layer complex electronic devices.

3.4 Processes merging: Combining additive and traditional manufacturing processes

In the future, industries are likely to combine different fabrication techniques together, including additive, equivalent, and subtractive processes, and integrate them into a single piece of equipment. Or, by combining these techniques in the production chain, an integrated process could be established to achieve the efficient fabrication of complex products such as prototypes, molds, electrodes, and casting patterns. Or, simple molds could be used to assist the additive manufacturing process, in order to take advantage of both traditional and 3D-printing processes.

3.5 Materials innovation: Bringing significant scientific and technical innovation

An inspiring development of 3D printing involves research into new alloy materials. Because the energy of 3D printing is highly centralized, it can generate ultrahigh temperatures in a very small region, while other regions remain at normal temperatures. When using 3D printing on metal materials, this highly non-equilibrium metallurgy process will provide an innovative platform for research into alloys with excellent performance in high-temperature conditions. Advantageous applications include the NASA rocket engines that can endure a high temperature of 3315 °C [14], and modified surfaces printed by Professor Huamin Wang that can resist high-temperature corrosion more than 700 times [15]. 3D printing will become a hotbed for the development of high-performance alloys. It is now possible to use material genomic theory to design new materials, and to use 3D-printing technology to develop alloy materials with ultrahigh strength, ultrahigh temperature resistance, ultrahigh resilience, and ultrahigh corrosion and attrition resistance.

By using smart and biological materials, 3D printing is currently developing from 3D to 4D, and is going as far as fabrications that involve living things. In 4D printing, printed structures using smart materials can change shapes when stimulated by the surrounding environment (such as changes in temperature, pressure, and electromagnetic field). 4D-printing technology can help to realize assembly technologies that are unachievable with current technologies, and to simplify the process and equipment of 3D-printing technology. For example, three-dimensional structures can be achieved by printing two-dimensional structures while changing the working environment.

Bio-active materials are also utilized in 3D-printing processes to fabricate tissue engineering scaffolds. With active cell growth, support material can degrade *in vivo*, and the organism's own tissue cells can grow to replace it. This technology is undergoing medical verification, and may be put into medical application in the near future. Tissue scaffold printing and cell printing are becoming the major methods of recreating human organs. Just as 4D printing involves changes in the shape of 3D-printed structures that are made with smart materials when the surrounding environment changes (e.g., changes in temperature or magnetic field), 3D-printed tissue scaffold and cell structures that are placed in biochemical environments will grow over time into living tissues, and will develop in shape and function, realizing the printing and fabrication of living tissues. The biochemical environments built by 3D printing are of great importance to the oriented conversion of stem cells, and will boost the development of research in biological organ recreation.

Cell printing is also becoming a method for research into life growth and development in space environments. In future, the printing of genes inside cells will become an important tool in the development of transgenosis research and life science. Of course, this technology will be faced with ethic controversy and trade-offs.

3.6 Intelligent equipment: 3D-printing processes and machines become smarter than ever

At present, researchers look forward to developing more usable materials for 3D printing, and to enhancing the quality of the 3D-printed products. For example, the printing speed of metal materials is several kilograms per hour. Normally, the printing speed and the quality of a part (shape accuracy, roughness, metallographic structure, internal stress, etc.) have an inverse relationship. More research is required to achieve rapid manufacturing with higher quality at lower cost. We also need to put more emphasis on studying technological parameters and achieving intelligent control by integrating shape and performance control into software.

In addition, the application of 3D printing to equipment maintenance and re-manufacturing, on-site maintenance, and fabrication can significantly reduce transportation costs and guarantee the safe operation of equipment. This application will promote the development of intelligent maintenance and re-manufacturing. Moreover, 3D printing is the best way of realizing energy-saving manufacturing by making fabrication processes smarter and cleaner.

4 3D Printing: From a technological concept to part of a manufacturing trifecta

A value comparison between 3D-printing technology and traditional manufacturing technologies raises many questions. However, these questions are usually unscientific, since they are always based on differences in fabrication cycle and cost between the two kinds of technologies when fabricating a specific part. We present a more structured comparison here.

First, different manufacturing technologies have their own advantages and disadvantages. For example, we cannot simply compare equivalent manufacturing (casting, forging, and soldering) with subtractive manufacturing (milling, turning, and grinding); rather, different manufacturing technologies should be applied where they can be of best use. Die forging is suitable for mass fabrication; machining is suitable for parts with smaller batches and higher precision; and 3D printing is suitable for single-piece trial-manufacture prototyping, and for the rapid manufacture of complex parts that are difficult or impossible to produce with more traditional manufacturing processes. With this benefit, additive manufacturing is increasingly applied to the rapid development of products and equipment, where it can substantially save time and cost, and thus increase profit.

Second, a fusion of 3D-printing technology with equivalent manufacturing and subtractive manufacturing will create additional benefits for advanced manufacturing. Different technologies can be incorporated into a single piece of equipment so as to achieve the integration of complex-shape fabrication and high-precision fabrication. For example, DMG developed a 3D printer that combines laser-cladding additive manufacturing with milling subtractive manufacturing [16]. In addition, 3D-printed prototypes can be processed further using complex treatment technologies (e.g., electroforming, silastic molding, spray molding, and polishing) to achieve rapid and economic mold manufacturing.

Third, we cannot compare different manufacturing technologies using current designs, because such designs are based on existing equivalent manufacturing and subtractive manufacturing technologies. For example, in the fabrication of aircraft engine nozzles, GE used 3D printing to integrate 20 parts into a single component, thus avoiding the processing of many junction surfaces with high-precision coupling. This new design substantially reduced fabrication cost and cycle time. However, if the traditional design and manufacturing process plan were still followed, but with 3D printing being used instead to print these 20 separate parts, the fabrication cost would greatly increase, and the accuracy requirement of matching surfaces could not be fulfilled [17]. Using new designs that are based on the capabilities and flexibility of 3D printing can yield significant savings in fabrication cost and cycle time.

Fourth, redesigning products and equipment based on 3D-printing technology will result in innovative products and equipment that would not otherwise be developed using traditional manufacturing.

It may take a long time for the fabrication quantity undertaken by 3D printing to catch up with that of equivalent manufacturing and subtractive manufacturing. However, 3D-printed structures, components, parts, products, and equipment will all be placed at the high end of the value chain. The respective quantities of fabricated products by additive, subtractive, and equivalent manufacturing processes may be considered in terms of a pyramid, with the smallest quantity, produced by additive manufacturing, at the top and the largest quantity, produced by equivalent manufacturing, at the base. However, the respective unit prices of these products constitute an inverted pyramid, with the greatest price going to high-value 3D-printed structures. Thus, we can foresee that with further research and development, industrialization, application, maturation, and promotion, additive manufacturing or 3D printing will develop from a technological concept to part of a valuable manufacturing trifecta along with traditional equivalent and subtractive manufacturing processes.

Compliance with ethics guidelines

Bingheng Lu, Dichen Li, and Xiaoyong Tian declare that they have no conflict of interest or financial conflicts to disclose.

References

1. T. Wohlers. *Wohlers Report 2013: Additive Manufacturing and 3D Printing State of the Industry. Annual Worldwide Progress Report*. America: Wohlers Associates, Inc., 2013
2. Y. M. Xie. Designing orthotropic materials for negative or zero compressibility. *Int. J. Solids Struct.*, 2014, 51(23–24): 4038–4051
3. A. Sutradhar, J. Park, D. Carrau, M. J. Miller. Experimental validation of 3D printed patient-specific implants using digital image correlation and finite element analysis. *Comput. Biol. Med.*, 2014, 52: 8–17
4. R. P. Hoyt. SpiderFab: An architecture for self-fabricating space systems. In: *AIAA SPACE 2013 Conference and Exposition*, 2014: 1–17
5. K. Short, D. Van Buren. Printable spacecraft: Flexible electronic platforms for NASA missions. Pasadena, California: California Institute of Technology, 2012
6. G. Cesaretti, E. Dini, X. De Kestelier, V. Colla, L. Pambaguian. Building components for an outpost on the Lunar soil by means of a novel 3D printing technology. *Acta Astronaut.*, 2014, 93: 430–450
7. General Electric Company. Advanced manufacturing is reinventing the way we work, 2014. http://www.ge.com/stories/advanced-manufacturing
8. K. Bullis. A more efficient jet engine is made from lighter parts, some 3-D Printed. *MIT Technology Review*, 2013-05-14
9. J. Bargmann. Urbee 2, the 3D-printed car that will drive across the country, 2013. http://www.popularmechanics.com/
10. P. Olson. Airbus explores building planes with Giant 3D Printers. *Forbes*, 2012-07-11
11. K. Wang, Y. H. Chang, Y. W. Chen, C. Zhang, B. Wang. Designable dual-material auxetic metamaterials using three-dimensional printing. *Mater. Design*, 2015, 67: 159–164
12. X. Ye, J. Long, Z. Lin, H. Zhang, H. Zhu, M. Zhong. Direct laser fabrication of large-area and patterned graphene at room temperature. *Carbon*, 2014, 68: 784–790
13. D. Zhao, T. Liu, M. Zhang, R. Liang, B. Wang. Fabrication and characterization of aerosol-jet printed strain sensors for multifunctional composite structures. *Smart Mater. Struct.*, 2012, 21(11): 115008
14. L. Kratochwill. NASA tests largest 3-D printed rocket part ever: 3-D printed engines could support human missions to deep space. *Popular Science*, 2013-08-29
15. H. Wang, L. Zhang, A. Li, L. Cai, H. Tang. Rapid solidification laser processing and forming of advanced aeronautical metallic materials. *Journal of Beijing University of Aeronautics and Astronautics*, 2004, 30(10): 962–967
16. DMG MORI. LASER TEC 65 3D. 2014-11-13. http://www.3D.dmgmori.com
17. Alec. GE 3D prints and test fires a fully functional miniature jet engine. 2014-11-12. http://www.3ders.org/articles/20141112-ge-3d-prints-and-test-fires-a-fully-functional-miniature-jet-engine.html