Applications and research in 3D printing

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Abstract. In recent years, three-dimensional (3D) printing, an emerging manufacturing method, has garnered widespread attention due to its prototyping capabilities, low cost, and high flexibility. 3D printing has a profound impact on various fields, including industry, healthcare, education, aerospace, and engineering. This paper discusses three applications in 3D printing, future development, and their advantages and disadvantages. A detailed introduction to the principles and construction of 3D printing technology will be included. This paper will also present academic achievements and cases from the past 5 to 10 years. The research is conducted primarily through a literature-based analysis of recent scholarly studies and industrial case reports. However, studies have shown that the types and properties of materials are limited, a lack of production efficiency, and the difficulty in scaling up. 3D printing is accelerating the transformation to intelligence and personalized production. Future research should focus more on the material improvements, cost reduction, and integration with advanced technologies.

1 Introduction

Over the past few years, with the deepening of digital and intelligence technologies in the manufacturing industry, traditional manufacturing processes have gradually exposed the problem of low efficiency and the lack of flexibility. Therefore, 3D printing, as an additive manufacturing method, has received increasing attention. Its core concept is to transform a digital model directly into a physical product by gradually building up materials layer by layer. Products are typically first created as three-dimensional models in computer-aided design (CAD) software and then materialized through 3D printing. This is a low-production method, suitable for situations where highly accurate mass production is required, and it also consumes less energy [1].

The fundamentals of the 3D printing process typically involve these three steps: first, using CAD to build a 3D model; second, using slicing software to convert the model into data; finally, the printing equipment gradually accumulates the materials according to the information until the predetermined component is formed.

The structure of modern 3D printing equipment can be divided into four modules: a mechanism skeleton, a material deposition system, a control and drive unit, and an auxiliary function module. The mechanical skeleton mainly contributes to supporting and motion positioning, including the frame motion mechanism and the platform. The material

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deposition system is responsible for solidifying the material and printing the final product. The control and drive unit controls the process by directing the operation of each mechanism and sensor. The auxiliary module and its software not only promote the printing environment but also convert the 3D model into printing instructions, therefore, accomplish the precise transformation from digital to physical.

The importance of 3D printing applications is also becoming apparent. In the industry, 3D printing allows the rapid production of accessories, further reduces production costs, and shortens the production cycle. In healthcare, this technology is used to create a prosthesis to help disabled patients and improve the treatment effect. The aerospace field has also benefited from 3D printing. By printing parts of a rocket, it not only reduces the weight of the aircraft but also improves the flexibility and production efficiency. In recent years, scholars have made significant progress in material improvement, printing precision, and the development of new processes. However, there are still drawbacks. For example, materials are fragile, and large-scale applications are difficult to achieve in a big project such as aerospace. These problems show that although 3D printing has great potential, research in various fields still needs in-depth study and more suitable solutions.

Despite its significant advantages, it still faces many challenges in practical applications. The development of 3D printing remains limited by the types of materials and their properties, particularly in terms of carrying capacity and long-term reliability. For example, the fatigue resistance of ABS parts processed by FDM is usually lower than that of comparable parts produced by injection molding [2]. Therefore, when designing 3D-printed products, it is essential to consider both the material and the combination of printing processes to ensure reliability. For carrying capacity or long-term use, conventional FDM printing alone may not meet performance requirements. So, other additive manufacturing technologies can be used to promote strength. In addition to the challenges, the significance of this study lies in the value and potential in different fields. First, the research helps to understand the properties of the material and the printing process. Secondly, the industrial, healthcare, and aerospace fields can all benefit from it, such as improving the accuracy, reducing the cost, and promoting the durability.

The main research question explored in this paper is to what extent the improvement of material and the reduction of production costs can address the constraints of 3D printing in essential application fields such as industry, healthcare, and aerospace. Most current research tends to focus on a single direction, for example, only focusing on the modification of the material and improvement of the production process. To address this shortcoming, this paper will analyze in a more comprehensive view, to provide a reliable and practical reference for different scenarios, thereby improving the development of 3D printing.

This paper will use a case study and comparative research. Also, this paper will select three applications- industry, healthcare, and aerospace- and analyze the advantages and disadvantages of 3D printing in material, resource cost, drawing on typical case studies. Comparing different fields allows this paper to identify issues and challenges more accurately and provide more comprehensive support for the research.

The paper will focus on three areas: first, to conclude the status of 3D printing; second, to study the role and limitations of material and cost in solving problems; third, the future trends of 3D printing and possible research directions are proposed to provide reference for subsequent applications.

2 Applications of 3D printing

2.1 Construction industry

3D printing has become an essential tool in modern industrial manufacturing due to its ability to facilitate customized production, accelerate product development, and minimize the consumption of raw materials and resources. Through the principle of additive manufacturing, digital models are directly transformed into tangible components via successive layering of materials, enabling the fabrication of geometrically complex structures while simultaneously reducing waste [3]. Unlike traditional subtractive processes, this technique allows the realization of intricate designs with high accuracy, offering greater flexibility in production.

With sectors as automotive, machinery, and electronics, 3D printing is predominantly employed for the rapid fabrication of prototypes, functional components, and specialized molds [4]. Automotive manufacturers, for instance, leverage additive methods to create prototype parts, engine components, and other complex parts that can be quickly tested during the design stage, thereby substantially reducing development timelines.

In the field of architecture, the potential of additive manufacturing technology is increasingly being recognized. Research by Wu et al. (2016) shows that 3D printing can significantly reduce the use of concrete, cement, and other building materials, while also lower labor costs and improving construction efficiency [5]. Compared to traditional construction methods, additive manufacturing demonstrates significant advantages in terms of construction precision and design flexibility. By printing prefabricated walls, bridge components, stair structures, and even entire buildings, architects and engineers can explore nonlinear structures, complex geometric shapes, and personalized designs more freely, thereby promoting the implementation of green building and sustainable development concepts.

However, additive manufacturing in the construction industry still faces numerous challenges. First, material performance limitations remain a key factor. Different types of concrete, composite materials, and polymers exhibit significant differences in strength, durability, crack resistance, and thermal stability, which directly impact the reliability and safety of building components. Second, printing scale and speed remain bottlenecks. High equipment costs and maintenance expenses, coupled with stringent requirements for the professional skills of operators and design engineers, limit the widespread adoption of this technology to some extent.

To overcome these challenges, researchers and engineering practitioners are exploring multi-directional technological innovations. Multi-material printing technology enables a single building component to achieve functional distribution across different performance zones, such as enhancing strength in structural critical areas and reducing weight in non-load-bearing regions, thereby improving overall component performance. The maturation of metal additive manufacturing technology provides high-strength and high-durability material options for special building components, such as bridge joints, support beams, and special structural components. At the same time, integrating artificial intelligence, the Internet of Things, and real-time sensing technology with additive manufacturing can predict component performance and optimize construction paths during the design phase, and enable real-time monitoring and quality feedback during construction, forming a traceable and intelligent building construction process.

Additionally, additive manufacturing has a profound impact on supply chain management and production models in the construction industry. Traditional construction relies on large-scale material reserves and on-site manual processing, while the use of digital printing files enables companies to produce on-demand, reducing material inventory and transportation costs. Each printing process can be digitally recorded, enabling end-to-end quality tracking and control, thereby improving construction precision and engineering safety. This on-demand production model accelerates the iteration cycle from design to construction in building projects while enhancing the flexibility of construction teams to respond to design changes and unexpected demands.

With the continuous development of materials science, printing technology, and intelligent construction systems, additive manufacturing technology in construction can support efficient resource utilization, complex structure manufacturing, and on-demand production. By optimizing material performance, enhancing equipment process capabilities, and integrating digital design with intelligent construction, construction companies can achieve higher precision in component production, lower resource consumption, and more flexible construction scheduling in actual projects, providing practical technical pathways for green buildings and personalized design.

2.2 3D printing in surgery and implant design

In healthcare, 3D printing technology is starting to demonstrate its significant impact on clinical practice. One of its main advantages is that it can quickly make personalized products based on a patient's imaging data, which is super helpful for diagnosis, surgery, and recovery. This transformation is particularly evident in craniofacial surgery, orthopedics, and cardiovascular disease treatment.

Additive manufacturing has been widely used in prosthetics and implants and is gradually expanding into the fields of tissue engineering and drug delivery. In other words, 3D printing is not only a manufacturing tool, but also an important technological path to achieving precision medicine [6].

In surgical practice, the value of 3D printing is equally significant. A review of existing studies suggests that patient-specific three-dimensional models can help surgeons develop more reasonable surgical plans before surgery and provide structural references during surgery [7]. Studies have shown that this 3D-printed model-based approach enhances surgical precision, reduces surgical duration, and lowers the risk of complications. For example, in cases of complex cardiac malformations and craniofacial reconstruction, preoperative simulation using 3D models has been proven to significantly improve clinical outcomes.

Orthopedic trauma repair is another typical application scenario. Research shows that personalized implants generated based on patient CT or MRI data can better match the actual conditions of the fracture site [8]. Compared to generic metal implants, these customized products enhance the stability of osseointegration, improve postoperative functional recovery, and reduce the risk of secondary surgeries. This finding highlights the role of additive manufacturing in driving the shift from normalized to customized approaches in orthopedic treatment.

Beyond its direct applications in clinical treatment, 3D printing has demonstrated irreplaceable value in medical education and surgical training. Traditional anatomical specimens are limited in quantity and pose challenges in preservation and usage. In contrast, printed human anatomical models not only closely resemble real tissue in appearance and structure but can also be scaled up or sectioned according to teaching needs, significantly enhancing instructional flexibility and visual clarity [7]. This approach not only optimizes medical students' learning experiences but also reduces reliance on actual patients for clinical training.

Despite its promising prospects, the application of 3D printing in healthcare faces practical constraints. First, the biocompatibility, mechanical properties, and long-term stability of printing materials still fall short of clinical requirements [6]. Second, the medical device regulatory framework lacks mature standards for personalized manufacturing, creating barriers to clinical adoption.

Researchers have proposed multiple solutions to address these challenges. First, multi-material printing enables performance distribution across distinct functional zones within a single device—such as joint implants combining high strength with flexibility. Second, integrating artificial intelligence with additive manufacturing facilitates intelligent production. AI algorithms can predict the mechanical performance of printed products during the design phase and monitor manufacturing processes in real time, forming a closed-loop quality management system. Third, bioprinting, as a branch of regenerative medicine, is exploring the use of cells and bio-inks to construct blood vessels, cartilage, and even organ prototypes. This direction holds promise to fundamentally transform medical treatment models in the future.

The impact of 3D printing on the healthcare system extends beyond the technological level to supply chains and management models. Traditional medical device production often requires large inventories, whereas digital printing files enable hospitals and companies to produce on demand, reducing storage and transportation burdens. The production process of each printed item can be fully documented, enabling traceable quality control. This model not only accelerates the R&D iteration of new devices but also enhances the healthcare system's responsiveness to emergencies and personalized needs.

Research indicates that 3D printing in healthcare has evolved from early exploratory stages toward clinical application and systematic development. Despite ongoing challenges in materials, costs, and regulation, its role in surgery, orthopedic treatment, medical education, and regenerative medicine will expand as technology matures and interdisciplinary collaboration advances.

2.3 3D printing in aerospace

Throughout the development of aerospace, production technology has consistently been an essential factor influencing efficiency and safety. As mission complexity continues to increase, spacecraft components face increasingly stringent requirements for lightweight design, structural complexity, and reliability. The emergence of additive manufacturing offers novel solutions to these challenges. By directly forming digital models through layer-by-layer material deposition, it significantly reduces the time required for transitioning from design to production [9]. Compared to subtractive methods, this approach substantially minimizes material waste while expanding design boundaries without compromising structural performance [10].

However, the further adoption of this technology in aerospace applications remains constrained by material and process limitations. First, the metal powders and composite materials currently in use have yet to fully meet the demands of extreme operating conditions in terms of high-temperature resistance, fatigue resistance, and long-term stability. Although research into ceramics and high-performance composites has commenced, it has not yet matured into systematic engineering applications [10]. Second, defects such as microcracks, porosity, and residual stresses may arise during the printing process, posing potential threats to spacecraft safety. Third, the insufficient forming efficiency of large components makes it difficult to replace traditional processes in mass production; meanwhile, the procurement and maintenance costs of high-end equipment add to the operational burden of enterprises. Furthermore, both operation and design require involvement from highly skilled professionals, making talent shortages one of the limiting factors [11].

To address these challenges, academia and industry are pursuing multidimensional technological explorations. First, multi-material printing is viewed as a key breakthrough. By integrating distinct performance zones within a single component—such as enhancing strength in load-bearing areas while reducing weight in secondary regions—it improves overall structural performance [9]. Second, artificial intelligence is being progressively integrated into additive manufacturing workflows. Algorithms for topology optimization and real-time monitoring enable the dynamic detection and correction of defects during production, thereby establishing traceable, feedback-driven intelligent manufacturing processes [10].

Beyond the technology itself, the impact of 3D printing on aerospace supply chains and production organization cannot be overlooked. Traditional aerospace manufacturing relies heavily on global suppliers and redundant parts inventories, whereas digital on-demand manufacturing can reduce inventory backlogs and mitigate risks associated with transnational transportation. Particularly during long-duration deep-space exploration missions, the ability for astronauts to instantly manufacture required parts using onboard printing equipment would significantly reduce dependence on ground resupply, enhancing mission autonomy and safety [11]. This paradigm not only transforms the logic of production chains but also provides sustainable support for deep-space exploration endeavors.

In future aerospace manufacturing systems, additive manufacturing is poised to integrate deeply with artificial intelligence, the Internet of Things, and automated systems, providing crucial support for the efficiency, safety, and sustainability of space missions.

3 Conclusion

In summary, additive manufacturing, as a disruptive manufacturing method, is profoundly impacting multiple industrial sectors. In industrial production, its characteristics of digital modeling and layer-by-layer deposition enable high-precision production of complex parts while enhancing design flexibility and product iteration efficiency. In the automotive, mechanical, and electronics industries, its application not only shortens R&D cycles but also reduces raw material waste and mold dependency, offering viable solutions for customization and small-batch production. In medical settings, 3D printing is increasingly applied to develop personalized surgical guides, implants, and prosthetics. By precisely modeling patient anatomy, its outputs enhance surgical precision and fit, advancing personalized healthcare trends. In aerospace engineering, 3D printing technology is utilized for manufacturing lightweight, high-strength structures such as engine nozzles, load-bearing components, and satellite assemblies. It demonstrates unique value in weight reduction, cost control, and reliability enhancement. As materials science, artificial intelligence, and smart manufacturing systems continue to converge, the application prospects of 3D printing across industrial, medical, and aerospace sectors will expand continuously. It will provide critical technological support for achieving efficiency, flexibility, and sustainability in manufacturing.

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