

3D Printing Technology and Its Development

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Abstract. In recent years, 3D printing technology has developed rapidly, with applications spanning traditional manufacturing, aerospace, and medical fields. Mainstream technologies include Binder Jetting, DED, and Power Bed Fusion. This paper discusses the principles, characteristics, and application cases of these three technologies. For example, Binder Jetting can be used to form silk powder combined with a binder, DED can achieve rapid manufacturing and repair of large metal components, and Power Bed Fusion can generate internal lattice structures that cannot be achieved with traditional processes. Additionally, the paper introduces applications of 3D printing in medical surgery planning, aerospace component lightweighting, and industrial material waste reduction. It highlights challenges such as quality stability, high certification costs, and insufficient material strength, emphasizing the trend toward transitioning from rapid prototyping to full-scale manufacturing technology. It concludes that as precision and material performance improve, 3D printing technology will leverage material innovation and process optimization to demonstrate breakthrough potential beyond traditional manufacturing across multiple fields, establishing a core position in high-end manufacturing and personalized applications.

Keywords: 3D Printing Technology; Binder Jetting; Directed Energy Deposition; Power Bed Fusion.

1. Introduction

In recent years, 3D printing technology has been developing rapidly, with a wide range of applications spanning traditional manufacturing, aerospace, healthcare, and other high-tech industries. The current mainstream technologies include binder jetting, directed energy deposition, and powder bed fusion. Among these, the advantage of binder jetting technology is its ability to print using multiple materials, meaning that multiple materials can be used in the same object, thereby overcoming the limitations of single-material performance. A more specific technology within Directed Energy Deposition is Laser Deposition, which enables printing at a very small scale. This is particularly useful for manufacturing complex microstructures or components with highly detailed features, such as microelectronic components, precision mechanical parts, and micro-implant applications in biomedicine. This method can meet the stringent requirements of these fields. The advantage of Power Bed Fusion technology is its ability to use multiple materials at a relatively lower cost, making it suitable for large-scale component production. For small-batch, customized products, it eliminates the high costs and time associated with mold manufacturing, thereby reducing production costs and lead times.

This paper will investigate the current applications and development of 3D printing technology, focusing on binder jetting, DED, and PDF technologies. By analyzing their principles, characteristics, and applications in fields such as medicine and aerospace, it aims to reveal the current state and challenges of these technologies.

2. Binder Jetting

Currently, binder jetting technology enables 3D printing by selecting different binders to spray composite materials. The key feature of this technology is the diversity of printable materials, including metals and ceramics. It also supports multi-nozzle parallel spraying, making it well-suited for mass production. Printing costs are lower compared to metal laser melting equipment (SLM).

Its working principle remains consistent with the original invention process. It primarily involves 3D modeling, which can be achieved through scanning or CAD design, followed by curing and

debinding, then sintering or infiltration, and finally removing excess powder and polishing the object's surface. Previously, some teams even developed a method using silk as raw material for printing. With polyvinyl alcohol (PVA) as the solid binder, we tested two different types of silk powder: fine silk powder (FSP), which had an average particle size of 20 μm , and super fine silk powder (SFSP), that had an average particle size of 5 μm . We discovered that FSP offered acceptable flow, spreadability, and printability [1]. The team studied the physical properties of SFSP and FSP and found that FSP exhibits fluidity, spreadability, and printability when combined with PVA solid adhesive.

The Maleksaeed team used binder jetting technology to fabricate bio-ceramic (hydroxyapatite) porous bone scaffolds. The roughness of the scaffold surface promotes cell adhesion, with a cell survival rate of approximately 90% after 7 days, compared to approximately 70% for traditional cast scaffolds. The energy content of hFOB cells on 3D-printed scaffolds was $92 \pm 4\%$ after 7 days of culture, while it was $68 \pm 6\%$ on traditional cast HA scaffolds ($p < 0.01$).

3. Directed Energy Deposition (DED)

DED is a process within the field of Additive Manufacturing (AM) technology. The core feature of this technology is its high deposition rate, making it suitable for rapid prototyping of large-scale parts. This process can be operated in open environments, making it ideal for field or on-site repairs, offering greater flexibility.

It can primarily be divided into two categories: powder-fed and wire-fed. The key characteristic of this technology lies in its ability to rapidly manufacture large metal components and perform repairs or add functional structures to existing parts. The primary process involves feeding metal powder or wire into a high-energy heat source (such as a laser or electron beam), causing the material to melt under the influence of energy and gradually accumulate.

A European defense contractor utilized this technology to manufacture titanium alloy aircraft wing spars, replacing traditional forging processes. This effectively addressed the issue of lengthy production times associated with traditional methods and achieved a 15% weight reduction. Wing spars and other aerospace components were successfully produced with a 15% weight reduce when compared to their conventional equivalents, indicating the possibility of producing mission-critical parts fast [2].

4. Power Bed Fusion

Power Bed Fusion (PBF) technology also uses powder as raw material. The principle of this technology involves first evenly spreading a layer of powder material on the workbench, then using a high-energy beam to selectively melt the powder based on the model interface data, and finally lowering the workbench thickness and repeating the previous steps until the part is formed. Forming a fixed layer This technology can produce internal lattice structures (such as honeycomb-shaped lightweight structures) that cannot be achieved through traditional machining. PBF technology can produce high-precision, high-performance components, improving production efficiency in the medical field and mold manufacturing industry. Harrysson's team uses laser powder bed fusion (LPBF) technology to manufacture customized titanium alloy orthopedic implants. In addition to encouraging osteoblast migration and vascularization, the porous structure (70% porosity) with pore diameters ranging from 300 to 600 μm decreased the effective elastic modulus to 3–4 GPa, which is very similar to that of real bone (1–30 GPa)[3]. An internal porous structure with a porosity of 60% to 80% was designed for patients with complex bone defects to promote bone tissue growth.

The Abele team used PBF technology to directly manufacture injection molds with conformal cooling channels for all personnel. The geometry of the cooling channels shortened the injection molding cycle and reduced energy consumption, thereby reducing the mold cooling time. By using laser powder bed fusion (LPBF) to combine conformal cooling channels with helical geometry,

injection mold cooling times were shortened by 35% when compared to traditional straight channels, and energy consumption was reduced by 15% [4].

5. Applications of 3D Printing in Various Fields

5.1. Medical Field

Researchers at the University of Minnesota have used 3D printing technology to develop highly realistic organ models. These models not only simulate the appearance of real organs, but also simulate their mechanical properties and contain sensors to provide real-time feedback. These organ models can help students perceive real organs and learn surgical techniques. These organ models, in our opinion, have the potential to revolutionize surgical planning and practice. By lowering surgical errors, we hope this will save lives," McAlpine continued [5].

Researchers from Pakistan studied the application of 3D printing in orthopedic surgery. Through comparing multiple clinical cases and combining literature, they argued that 3D printing technology plays a significant role in orthopedic surgery. The literature pointed out that it is difficult to make suitable templates for complex fractures of the pelvis and acetabulum using traditional 2D X-ray and CT images, but 3D images and 3D-printed models can achieve greater success in this regard. The ability for surgeons to become familiar with tactile and visual comprehension of patient-specific anatomy and pathology is the main benefit of these models [6].

5.2. Aviation Sector

In the aviation industry, Thompson, S.M., and his team focus on researching process optimization and applications of aerospace additive manufacturing (AM), particularly on how to achieve lightweighting and performance enhancement of complex components through 3D printing technology. Taking GE Aviation's fuel nozzles as a typical example, the team analyzed process parameter optimization for laser powder bed fusion (LPBF) technology in aerospace component manufacturing and provided a process-performance correlation model for the aerospace sector. This model helps engineers optimize printing parameters, demonstrating that 3D printing can significantly reduce component weight and thereby improve fuel efficiency. Compared to the conventional multi-part assembly, the new single-piece nozzle met all performance requirements while achieving a 25% weight reduction [7].

DebRoy, T. leads a multidisciplinary team that has been conducting long-term research on the physical mechanisms and industrial applications of metal additive manufacturing, particularly in the field of high-temperature alloys for aviation. They have analyzed supply chain transformations, how 3D printing supports distributed manufacturing, and proposed a "full-process closed-loop control" framework that combines online monitoring with machine learning to optimize print quality in real time. Using this technology, GE fuel nozzles have been reduced in weight by 25%. When tested under high pressure, the integrated design maintained mechanical performance while reducing component weight by 25% [8].

5.3. Industrial Sector

In the industrial sector, Simon Ford and others studied the impact of 3D printing on industrial sustainability through life cycle analysis (LCA). When compared to traditional a subtractive process, additive manufacturing can reduce material waste by up to 40% and helping near-net-shape production [9]. Additive manufacturing (AM) reduces material waste by up to 40% compared to traditional building methods. Compared to traditional manufacturing, the application of 3D printing technology has effectively improved the raw material utilization rate of additive manufacturing.

In several EU industrial 3D printing projects led by professors from the Polytechnic University of Catalonia in Spain, actual industrial cases have verified the reduction in mold costs due to fewer processing steps and the shortening of delivery times through the use of printed molds. A working

engine part with same mechanical performance was 3D printed in 72 hours as opposed to 6 weeks for conventional CNC machining [10].

6. Challenges and Development

6.1. Challenges

Currently, achieving high-quality and consistent printing results in 3D printing remains a significant challenge. While there are various technologies available, each has its limitations. Overall, for additive manufacturing (AM), certification processes are costly and time-consuming, which hinders the widespread adoption of AM components. For 3D printing, the strength and long-term stability of many materials still cannot compete with traditional manufacturing processes. For example, in metal printing, residual stress and porosity may render components unusable.

6.2. Development

Since the development of 3D printing technology in the 1980s, the technology has gradually expanded from its early use in rapid prototyping to various fields such as aerospace, medicine, and engineering. From the initial rapid prototyping technology to the development of new materials, these advancements have driven the progress of 3D printing technology. These increasingly mature technologies have brought significant convenience to people's daily lives and production processes. As printing precision continues to improve and material strength continues to increase, 3D printing has become a revolutionary manufacturing technology, reshaping production models and industrial landscapes worldwide, and continuously driving the development of manufacturing. It holds an irreplaceable position in high-end manufacturing and personalized fields.

7. Conclusion

This paper investigates three 3D printing technologies: Binder Jetting, DED, and Power Bed Fusion. The results indicate that through material innovation and process optimization, these technologies demonstrate the potential to break through traditional manufacturing in fields such as medicine, aviation, and industry. However, these technologies still face challenges such as insufficient stability in high-quality printing, high certification costs, and limited material strength. The significance of this study lies in its systematic analysis of the technical principles, applications, and bottlenecks of these technologies, providing theoretical and practical references for process optimization and application expansion. In the future, with breakthroughs in materials and improvements in precision, 3D printing is expected to play a significant role in various manufacturing industries, including bio-tissue printing and high-precision component manufacturing. As 3D printing technology advances into more advanced fields, an increasing number of related products will appear in the consumer market, making it no longer an expensive and high-threshold technology. Through standardized technology and interdisciplinary integration, 3D printing technology will become a core technology in global manufacturing, reshaping the industrial landscape. While dominating the manufacturing sector, it will also become an integral part of daily life, playing a crucial role in future living.

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