

Application and Development of 3D Printing Technology in Flexible Circuits

Haobo Zhang¹

{hbzhang@hdu.edu.cn¹}

School of Automation(School of Artificial Intelligence), Hangzhou Dianzi University, Hangzhou, 310000, China¹

Abstract. Flexible circuits, as a key component of flexible electronic devices, hold vast application prospects across numerous sectors, including consumer electronics, healthcare, and aerospace. However, traditional manufacturing processes present significant challenges, including cumbersome workflows, difficulty in accommodating complex three-dimensional surfaces, and constraints on design innovation. The advent of 3D printing technology offers an innovative solution to these difficulties. This paper provides a comprehensive review of the research progress in 3D printing technology for flexible circuits. It begins by outlining the structural characteristics, application scenarios, and limitations of traditional manufacturing methods for flexible circuits. Subsequently, it focuses on analysing mainstream 3D printing technologies suitable for flexible circuits, including the working principles, technical advantages, and compatibility characteristics of material jetting and material extrusion techniques. It elaborates on the achievements of 3D printing technology in overcoming traditional manufacturing constraints and its applications in sensors and flexible displays, while also exploring the current limitations faced by the technology, including material properties, printing resolution, and efficiency. Ultimately, it outlines future development trends across three key directions: breakthroughs in process precision, innovations in material functionality, and the integration of intelligent systems. The paper systematically reviews technological applications and existing bottlenecks, offering crucial academic reference value and engineering guidance for technological innovation in flexible electronics, thereby accelerating the industrialization of related achievements.

Keywords: 3D Printing Technology; Additive Manufacturing; Flexible Circuit; Flexible Electronics; Manufacturing and Application

1 Introduction

Flexible electronic devices, owing to their inherent flexibility or extensibility alongside efficient and low-cost manufacturing processes, hold broad application prospects and unique value across numerous fields, including healthcare, defence and specialised operations, industry and energy, as well as information and intelligent services [1]. Within flexible electronics, flexible circuits constitute an extremely critical component. The manufacturing process for traditional flexible circuits is complex, presenting significant challenges in achieving highly integrated wiring

layouts on intricate three-dimensional curved surfaces. When circuits must conform to irregular surfaces, such as those found in soft robotic joints or wearable device casings, the limitations of conventional methods become particularly pronounced. These constraints have forced circuit design to accommodate manufacturing capabilities, thereby limiting breakthroughs in device structure and functionality. The advent of 3D printing technology offers a transformative solution for flexible circuit manufacturing. It enables the direct printing or deposition of electronic circuits onto flexible, ultra-thin, or even stretchable substrates, as well as three-dimensional object surfaces. With reduced constraints imposed by the substrate, it liberates circuit design from manufacturing limitations, making it more readily adaptable to the application demands of novel flexible electronics [2].

This paper conducts a comprehensive and detailed study on the technical path, material system, application progress, and bottlenecks encountered in the interdisciplinary field of 3D printed flexible circuits. It carefully analyzes the compatibility logic existing between the two 3D printing processes of material jetting and material extrusion, and flexible circuits. This research aims to provide crucial academic support and engineering guidance for 3D printing flexible circuit technology, thereby promoting breakthroughs in this technology.

2 3D Printing Technologies Applicable to Flexible Circuits

The manufacturing of traditional flexible circuits largely relies on mature processes such as lithography and etching. Although these methods can meet the basic manufacturing requirements of flat or low-curvature surfaces, they also have some limitations. This workflow needs to go through multiple operation stages and has very strict requirements for the production environment. It will also involve some issues related to the consumption of chemical reagents and waste disposal. In this way, the time and cost required for delivery are increased. The inherent planar manufacturing logic conflicts with the requirements of complex curved surfaces, which pose certain challenges to achieving high integration and wiring accuracy. When planar circuits are applied to curved surfaces, stretching and creasing often cause line breaks or inconsistent line widths. These restrictions make it necessary for circuit design to prioritize compatibility with traditional processes during the research and development process. Generally, the structure needs to be simplified, integration reduced, or some functional compromises made. This makes it very challenging to meet the demands of highly integrated, reliable, and flexible circuits. However, the emergence of 3D printing technology has provided a brand-new solution for the manufacturing of flexible circuits. Among them, material jetting and material extrusion technologies have a wide range of material adaptability and relatively mild processing conditions, which meet the requirements of flexible electronics for multi-material compatibility, structural freedom, and low-temperature processing. They have become the mainstream solutions for flexible electronics manufacturing[3].

2.1 Material Jetting

Material jetting technology has the ability to flexibly utilize a variety of different materials in a single molding process, and can also switch materials in real time during the construction stage. It can precisely spray conductive silver paste and flexible photosensitive resin simultaneously. During the printing process, it can form embedded conductive paths and insulating encapsulation. This makes material jetting technology particularly suitable for manufacturing

high-precision flexible circuits with complex multi-layer structures. This technology uses oscillating nozzles to transform materials into droplets, which are then sprayed onto the build platform. It uses charged deflection plates to charge the droplets, thus enabling precise positioning. This continuous injection mechanism ensures high precision in droplet control and placement, and those unused droplets will enter the recovery system.

On-demand jetting technology is a very crucial part of this printing method. Its essence is to precisely distribute materials in the form of droplets to pre-set areas. It relies on point-by-point positioning and layer-by-layer accumulation to ultimately achieve physical manufacturing. The formation characteristics of droplets impose certain restrictions on material selection. Generally, it requires that the polymer or wax-based materials have an appropriate viscosity so that droplets can be stably formed. The viscosity of the material is a very crucial parameter, as it directly affects the replenishment speed in the material warehouse, which in turn restricts the printing efficiency. Unlike the continuous material extrusion method, the on-demand spraying method only releases droplets when needed. It uses thermoelectric or piezoelectric actuators to change the pressure of the nozzle. The thermoelectric method uses thin-film resistors to generate droplets, which enables very high-frequency jetting. However, because the piezoelectric method has a wider range of material compatibility, people generally think that the piezoelectric method is superior in terms of technology [4].

In the post-press processing stage, the supporting materials used in this technology can be removed by using a sodium hydroxide solution or the water jet method. Since this process itself has relatively high forming accuracy, there is no need for subsequent complex processing steps. The functional characteristics and surface quality of the manufactured parts To a large extent, it was actually decided during the printing stage.

At present, researchers have made significant progress in the relatively cutting-edge fields of piezoelectric inkjet printing technology, such as the droplet formation mechanism and jet dynamics. They have adopted a combination of numerical simulation and experimental verification to systematically study the impact of process parameters on print quality and have determined the optimization approaches. This work has demonstrated crucial application value in many high-tech fields, such as micro-mechanical systems, biomedical engineering, electronic component manufacturing, and microfluidic device manufacturing.

2.2 Material Extrusion

The working principle of material extrusion technology involves forcing materials such as polyester and plastics through a nozzle, where they are heated and deposited layer by layer to form the structure. The nozzle can move horizontally, while the build platform elevates vertically after each layer is completed. This technology is widely employed in numerous low-cost, domestic, and hobbyist-grade 3D printers. Its distinctive feature lies in the continuous extrusion and deposition of material under constant pressure through the nozzle. Maintaining stable pressure and consistent speed is essential to ensure dimensional accuracy. Although numerous factors can influence the final model's quality, when these are effectively controlled, the process demonstrates significant application potential and feasibility.

In fields such as flexible sensors and electronic skin, direct ink writing enables the integrated moulding of conductive materials with elastic substrates. The technology's key advantage lies in its capability to precisely deposit functional inks exhibiting shear-thinning properties—such

as conductive polymers and liquid metals—on demand, while also supporting multi-material integration and the fabrication of complex three-dimensional structures [3].

2.3 Compatibility Analysis with Flexible Circuits

Material jetting technology offers flexible switching between multiple materials, micron-level precision forming, mild processing conditions and straightforward post-treatment. It enables real-time switching between conductive silver paste and flexible photosensitive resin within a single forming process, directly forming embedded conductive pathways and insulating encapsulation without complex subsequent processing. Furthermore, it achieves precise droplet positioning and can even perform conformal printing on complex curved surfaces. This precisely aligns with the requirements of flexible circuits, which often necessitate complex multilayer structures, high-precision conductive pathways, and low-temperature processing suitable for flexible substrates.

Material extrusion technology, characterised by broad material adaptability, enables the integrated moulding of conductive materials with elastic substrates. It supports multi-material integration and the fabrication of complex three-dimensional structures. Through on-demand precise deposition of materials, it fulfils the requirements of flexible circuits for combining conductive and elastic materials, integrated moulding, and complex structure construction. It is particularly well-suited for manufacturing flexible circuit products such as flexible sensors and electronic skin, making it an ideal choice.

Consequently, material jetting and material extrusion technologies possess unique advantages precisely aligned with the core requirements of flexible circuits. The inherent demands of flexible circuits for multi-material integration, complex structure fabrication, high-precision moulding, and mild processing conditions further enable these two processes to fully leverage their strengths, achieving a perfect match.

3 The Application of 3D Printing Technology in Flexible Circuits

3.1 The field of sensors

Within the field of sensors, the scope of application for 3D printing technology continues to expand. Researchers, including Yongkun Sui, have systematically reviewed various electrochemical sensors fabricated using material jetting techniques, encompassing gas, ion, pH, glucose, and biomolecular sensors [5].

The application of 3D-printed flexible circuit technology to wearable device sensors demonstrates particularly pronounced advantages. Its core strength lies in perfectly meeting the stringent requirements of wearable devices for comfortable fit, personalised customisation, and functional integration. Traditional rigid circuit boards struggle to adapt to the irregular and dynamically changing contours of the human body. In contrast, 3D printing enables the direct fabrication of bendable and stretchable circuits on flexible substrates. This allows sensors to conform like a second skin to areas such as the wrist and joints, significantly enhancing wearability and signal acquisition stability. More importantly, 3D printing offers unparalleled design freedom, enabling rapid customisation of sensor morphology and circuit layouts for specific users or applications. It even allows the integrated printing of circuitry and sensor units

combining multiple functions, such as bioelectric signal acquisition, temperature monitoring, and motion sensing, achieving high integration that eliminates complex assembly processes while reducing device size and weight.

This additive manufacturing approach also supports the use of biocompatible materials, paving the way for long-term, health-conscious monitoring. Consequently, 3D printing stands as the pivotal enabling technology driving the development of next-generation high-performance, personalised, comfortable, and discreet wearable sensors.

3.2 The field of flexible displays

Ruitao Su and colleagues have successfully manufactured the world's first flexible organic light-emitting diode (OLED) display using a custom-built printing apparatus. This display, formed through 3D printing technology, breaks away from traditional production methods reliant on costly microfabrication equipment. The core principle of OLED display technology lies in utilising organic material layers to convert electrical energy into light energy. Its applications are remarkably diverse, extending beyond large electronic devices such as televisions and monitors to encompass portable terminals like smartphones. With its outstanding characteristics—lightweight construction, low energy consumption, thin and flexible texture, wide viewing angles, and superior contrast, OLED technology has garnered significant market favour[6].

3.3 Multiple novel printing methods further optimise the fabrication of flexible circuits

Guo Hengrui proposed a novel 3D printing technique for liquid metal flexible circuits in wire-bonded packaging, based on controlled dissolution of the PI substrate. This technique achieves excellent integration between the encapsulation layer and substrate by adjusting the line width of the encapsulation layer and the degree of imidisation of the substrate, thereby effectively preventing excessive circuit subsidence caused by over-dissolution [7].

Moreover, aerosol microjet printing technology has emerged, offering high precision and efficiency. This contactless printing method achieves line accuracy at the micrometre level, enabling high-resolution precision forming. It facilitates conformal printing on complex curved surfaces and holds broad application prospects [8].

Concurrently, Liu Junjie and colleagues developed a novel process for fabricating high-precision copper-based flexible transparent circuits. This technique integrates EFD micro-scale 3D printing with wet etching technology, forming a hybrid manufacturing strategy that combines additive and subtractive processes. First, a copper-clad flexible substrate is selected. Using EFD micro-3D printing technology, a high-resolution photoresist pattern is fabricated on the copper surface to serve as a mask. Subsequently, wet etching is employed to remove the copper layer not covered by the photoresist. Finally, the photoresist is stripped away, yielding a precise circuit pattern. This approach fully leverages the additive manufacturing advantages of EFD printing alongside the subtractive processing capabilities of wet etching, achieving high-precision, high-efficiency circuit fabrication [9].

4 Analysis of Strengths and Limitations

4.1 Strength Analysis

3D printing of flexible circuits offers three key advantages. Foremost among these is the breaking of spatial constraints and the revolutionisation of manufacturing methods. Traditional processes are constrained by two-dimensional planes, leading to stretching and wrinkling when circuits are applied to complex curved surfaces such as soft robotic joints or the curved casings of wearable devices. However, 3D printing requires no moulds, enabling an integrated forming process from subtractive to additive manufacturing. This directly achieves conformal layouts for highly integrated wiring.

At the same time, it can provide a wide variety of rich materials for people to choose from, and can produce components with particularly good performance. Inkjet printing will use precious metals such as gold, silver, and platinum to manufacture porous electrodes, which can improve the performance of sensors. It can also prepare millimeter-sized electrodes on flexible films. These electrodes can be used to simultaneously monitor different parameters such as temperature, conductivity, and dissolved oxygen[4]. Aerosol micro-spray printing uses nano-silver particle ink, achieving a circuit width of $72\text{ }\mu\text{m}$; this precision exceeds that achievable by traditional processes[8].

It also grants more freedom in design and promotes functional innovation by changing the traditional logic of manufacturing circuit boards before installing them. Conversely, circuits can be embedded into complex three-dimensional elastic structures, just like the human nervous system. This approach provides greater room for the design of wearable devices and bionic robots, and also promotes the development of flexible structures, such as electronic textiles and bionic skin, which can adhere tightly to the skin, used for dynamic physiological monitoring[8].

4.2 Constraint Analysis

3D printing of flexible circuits currently faces three primary constraints. Firstly, material properties impose limitations. Whilst printing with metals such as gold, silver, and platinum, alongside aerosols, yields satisfactory results, the process must simultaneously balance circuit performance with flexural strength. Some materials are highly sensitive to the environment. For instance, hydrogels with a relatively high water content in flexible electronic products are particularly prone to dehydration under dry conditions and thus fail to function properly[3]. The second limitation is in terms of printing resolution. When the material jetting method is used, satellite droplets often appear. As a result, the resolution of the print cannot meet our expected standard. We need to thoroughly study how factors such as the structure of the equipment and the substrate affect the behavior of droplets, so as to reduce these adverse effects[8]. The last limitation is the issue of efficiency. Although 3D printed flexible circuits seem to have decent efficiency, the point-by-point or layer-by-layer printing method has physical limitations. Essentially, this has affected the efficiency of production. We need to develop optimized printing methods or algorithms to increase the printing speed. Only in this way can we enhance its practical application and also raise the possibility of its industrial use.

5 Future Development Trends Outlook

5.1 Breakthroughs in Craftsmanship and Precision

In future development, the continuous improvement of printing technology and the enhancement of precision are the driving forces that play a key role. Currently, mainstream technologies like material jetting, although they can achieve line printing at the micrometer level, still frequently encounter problems such as satellite droplets. The existence of these issues limits the improvement of resolution. In terms of research, the focus should be placed on controlling the dynamic principles during the printing process. This can be achieved by optimizing the structure of the print head, adjusting the driving mode, and precisely controlling the flight status and deposition behavior of the droplets. These methods can be used to pursue higher consistency and accuracy. The emerging aerosol micro-jet printing technology shows great potential. It can achieve high-resolution conformal printing on those complex curved surfaces. However, to improve this technology, it is necessary to conduct systematic research on process parameters. To address the potential efficiency bottlenecks in the layer-by-layer printing mode, innovations will be made in the future to explore parallel printing strategies and also to study intelligent path planning algorithms. These methods can not only enhance manufacturing efficiency but also ensure accuracy. This way, favorable conditions can be created for large-scale industrial applications.

5.2 Materials and Functional Innovation

In the realm of material and functional innovation, future developments will extend beyond mere conductivity towards multifunctional, high-performance composite systems. Current materials, such as precious metal inks, while exhibiting excellent conductivity, still face challenges in durability under repeated bending and stability in specific environments—for instance, hydrogels readily lose moisture in arid conditions. Research and development will prioritise novel inks that combine outstanding electrical properties, mechanical flexibility, environmental stability, and specific functionalities such as self-healing, biodegradability, or biocompatibility. The future may see increased availability of multifunctional materials ready for immediate use post-printing. This could enable the simultaneous integration of electronic components like resistors and capacitors during the printing of basic circuits, transforming printed flexible circuits themselves into electronic devices such as sensors[10]. This approach would achieve true functional integration in manufacturing.

5.3 System and Intelligent Integration

All technological advancements converge towards the higher-level developmental trend of system and intelligent integration. The key advantage of 3D-printed flexible circuits lies in their ability to transcend the physical constraints of traditional circuit boards, achieving conformal moulding with the three-dimensional structure of products. In the future, we shall witness the deep integration of printing systems based on AI-driven generative design with digital design platforms, enabling rapid and intelligent realisation from concept to functional prototypes. In domains such as wearable devices, soft robotics, and bio-integrated devices, circuits will function like neural systems embedded within objects, achieving true dynamic adaptability.

6 Conclusion

This paper provides a systematic review of the technical methods, application progress, and future development trends of 3D printing technology in the field of flexible circuit manufacturing. Comprehensive analysis shows that 3D printing technology, with its unique additive manufacturing method and highly digitalized characteristics, has brought revolutionary breakthroughs to the development of flexible circuits. It can effectively overcome the inherent limitations of traditional manufacturing processes in achieving conformal molding of complex three-dimensional surfaces and realizing high-density integrated circuits.

3D printing technology, relying on processes such as material jetting and extrusion, fundamentally liberates circuit design from the constraints of manufacturing. It can directly and precisely deposit conductive materials on flexible and stretchable substrates to form functional circuits, granting designers unprecedented freedom. As a result, Circuits can be embedded into the complex three-dimensional structures of products such as wearable devices and soft robots, just like a nervous system, achieving a relatively high degree of unity between form and function. Research and practice on a global scale, taking the industrial application of liquid metal additive manufacturing as an example, have fully demonstrated that this technology has great potential in shortening the manufacturing cycle, reducing costs, improving circuit accuracy, and enhancing bending resistance. However, the current development of this technology still faces a series of challenges. In terms of materials, it is necessary to develop new types of composite materials with excellent electrical properties, mechanical flexibility, and specific functions. In terms of technology, the printing resolution is limited by issues such as satellite droplets, while the printing efficiency is constrained by the inherent physical limitations of layer-by-layer manufacturing. This requires future research to study the dynamics of the printing mechanism and optimize the equipment structure and intelligent control algorithms. The development of 3D printed flexible circuits will continue to deepen along three key trajectories. They are, respectively, the breakthrough in process precision, the innovation in material functions, and the integration of intelligent systems. With the integration of multiple disciplines and the close combination with technologies such as artificial intelligence and digital twins, the entire process from design to manufacturing is expected to achieve intelligent automation. This will drive the emergence of more integrated and multi-functional flexible electronic systems. As electronic devices develop towards miniaturization, high reliability, and functional integration, 3D printing flexible circuit technology will continue to play a very crucial role and has a very broad development prospect.

References

- [1] Jia, Y., Bian, S.: Current Status and Trends in Flexible Electronics Technology. Science and Technology China. pp. 17-20 (2021).
- [2] Yu, Y., Liang, S., Zheng, K.: Additive Manufacturing Technology and Industrial Applications of Liquid Metal Flexible Circuits. China Scientific and Technological Achievements. vol. 25, no. 3, pp. 1-2 (2024).
- [3] Yang, X., Wu, Q.: Research Progress in 3D Printing of Gel Elastomers for Flexible Electronic Devices. Journal of Inner Mongolia University for Nationalities (Natural Science Edition). vol. 40, no. 04, pp. 1-9+105 (2025).

- [4] Niu, Y., Zhou, Y., Li, Q., et al.: Research Progress on Inkjet Printing Applications in the Optoelectronic Field. *Digital Printing*. no. 03, pp. 29-40+91 (2021).
- [5] Sui, Y., Zorman, C. A.: Review-Inkjet Printing of Metal Structures for Electrochemical Sensor Applications. *Journal of the Electrochemical Society*. vol. 167, no. 3, p. 037571 (2020).
- [6] Su, R., et al.: 3D-printed flexible organic light-emitting diode displays. *Sci. Adv.* vol. 8, p. eabl8798 (2022).
- [7] Guo, H.: 3D Printing Technology for Liquid Metal Flexible Circuits in Wire-Bonding Packaging Based on PI Substrate Dissolution Control. Master Thesis, Qingdao University of Technology (2025).
- [8] Zhu, T., Zhang, Y., Song, S., et al.: Research on Flexible Circuit Fabrication Process Using Aerosol Microjet Printing. *Precision Forming Engineering*. vol. 15, no. 06, pp. 183-192 (2023).
- [9] Liu, J., Zhang, Y., Zhang, H., et al.: High-Precision Copper-Based Flexible Transparent Circuits Manufactured via Additive and Subtractive Hybrid 3D Printing Driven by Electric Fields. *Transactions of the Chinese Society for Mechanical Engineering*. (2025).
- [10] Sun, J., Fuh, J. Y., Thian, E. S., et al.: Fabrication of electronic devices with multi-material drop-on-demand dispensing system. *International Journal of Computer Integrated Manufacturing*. vol. 26, no. 10, pp. 897-906 (2013).