Research on the Status of Quality Improvement of 3D-Printed Products

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Abstract. 3D printing, also known as additive manufacturing (AM), has emerged as a transformative technology that contrasts with conventional subtractive methods by building objects layer-by-layer from digital models. Since its development in the 1980s, it has revolutionized industries such as aerospace, healthcare, automotive, and consumer goods by enabling rapid prototyping, customization, and complex geometries with minimal material waste. Despite its advantages, challenges like thermal deformation, surface roughness, dimensional accuracy, and biocompatibility in medical applications hinder its broader adoption. Addressing these quality issues is crucial for improving performance and expanding industrial applications. This review examines recent advancements in 3D printing techniques, analyzes persistent limitations, and explores future trends, highlighting its role in sustainable manufacturing and next-generation production technologies. Understanding these developments is vital for researchers and industries seeking to optimize 3D printing for high-precision and functional applications

Keywords: 3D printing, Quality improvement, Additive manufacturing, Printing defects

1 Introduction

3D printing is a new type of additive manufacturing process. 3D printing creates physical objects by layering materials from the bottom up. The birth of 3D printing technology can be traced back to the 1980s. Originating from stereolithography, it has evolved through continuous exploration and development into technologies such as light curing, powder bed fusion, and 3D inkjet laser printing. Entering the 21st century, the open-source RepRap project emerged, driving the development of low-cost 3D printers. Founded in 2009, Makerbot propelled 3D printing into the mainstream market. It further commercialized 3D printing and expanded its market reach. Since the 2010s,3D printing technology has developed rapidly and been widely applied. Industries such as industrial design, architectural design, automotive design and manufacturing, aerospace, engineering design, and construction all rely on 3D printing technology. The advantage of 3D printing lies in its ability to handle complex products without increasing costs. In contrast, traditional mass production becomes more expensive as complexity increases. This means that 3D printing is better suited to meet personalized needs.

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3D printing represents a significant breakthrough for traditional manufacturing. It offers vast potential and great future prospects. China's attitude toward this technology is one of active support. It views it as an important tool for transforming and upgrading the manufacturing industry. Some people predict that 3D printing will drive the third industrial revolution. In the future, 3D printing will be more integrated with materials science, bioengineering, computer engineering, artificial intelligence and the Internet of Things to improve production efficiency and quality[1].

This article categorizes 3D printing technology from the perspective of printing materials and introduces the working principles of representative 3D printing technologies. The article identifies quality issues in various technologies and proposes solutions using existing techniques to address these problems, providing a detailed analysis of existing defects and future challenges. It systematically explains the working principles and current applications of different printing methods, discussing the quality defects associated with each method. Additionally, it reviews recent research advancements and offers an initial outlook on future development.

2 Classification of 3D printing technology

2.1 Non-metallic material: fused deposition modeling (FDM)

The basic principle of FDM technology is: heating thermoplastic polymer filaments to a molten state. Then, through algorithmic control, they are continuously pushed and deposited onto the printing platform. Finally, they cool to a solid state and bond together. After one layer is printed, the printing platform moves downward or the print head moves upward by the thickness of one layer. This process is repeated, layer by layer, ultimately forming an entire structure. Several major issues have been exposed during this process: temperature control. The molten filament requires un-melted filaments behind it for support. Therefore, the filament must withstand a certain degree of compression. During the compression process, bending deformation of the filament is inevitable, leading to lower mechanical properties. In addition to surface defects caused by step effects, there is also internal stress inhomogeneity due to uneven material density distribution after multiple solid-liquid phase transitions. This is the primary reason for reduced structural strength of the product.

As is well known, temperature has a significant impact on the viscosity of polymers. When the temperature is too low, the filament cannot become molten. This can lead to clogging of the extruder during feeding. Conversely, when the temperature is excessively high, the flowability of the filament significantly increases. Viscosity also improves within a certain temperature range. The speed at which the extruder extrudes the filament becomes uneven, leading to an inconsistent density distribution. Defects in surface glossiness become more pronounced. If the temperature is too high, the filament may even degrade or fail. Therefore, temperature control is a crucial prerequisite for the quality of products printed using FDM technology. Currently, the primary method used for temperature control is Proportional-Derivative-Integral (PID) control [2]. This method is simple in principle and structure, and relatively stable. However, its mathematical model is based on theory. In actual production, there is thermal lag and poor stability. To address the issues of thermal lag and poor stability in heating equipment during FDM printing, Qu Xingtian et al. adopted a fuzzy adaptive PID control method combined with matlab/Simulink software [3]. This method offers fast response and strong stability.

To address the issue of reduced mechanical properties due to filament deformation, a gear-driven feeding mechanism can be used. Under the engagement of gears, the filament can overcome flow resistance and continue to move forward under the effect of friction. Currently, commercial FDM printing equipment has non-adjustable gear diameters. The gap between the gear and the filament is also not adjustable. This results in poor adaptability to the filament. This problem can also cause bending deformation. Researchers have developed an "Mendel" gear-driven feeding mechanism. Its driving gear and driven gear have different diameters. The distance between the gear and the filament can also be adjusted. This significantly enhances the adaptability of the filament and increases printing speed. Additionally, some scholars have improved the equipment by using continuous fiber extrusion to enhance product mechanical properties. Matsuzaki et al. from the University of Tokyo adopted a method of adding a continuous fiber feeding mechanism on the side of the nozzle [4], allowing fibers and thermoplastic filaments to be extruded separately. They then converge within the nozzle tube. This method achieves in-situ polymerization of fibers. Tian Xiaoyong's team at Xi' an Jiaotong University also used a similar device to prepare carbon fiber/PLA printed parts [5]. When the fiber content reaches 27% (by mass), its flexural strength and flexural modulus can reach 335 MPa and 30 GPa.

2.2 Biological materials: biological 3D printing

Biological 3D printing shares the same principles as non-biological material 3D printing, both being additive manufacturing processes. The forming principle of biological 3D printing is similar to that of FDM technology. Products are printed using bio-ink with biological cells as raw materials through deposition. The printing methods of biological 3D printing mainly include inkjet (droplet ejection), extrusion, and light projection [6]. The application scenarios of biological 3D technology are extensive. It has already been applied to the production, repair, and regeneration of animal tissues, plant tissues, and microorganisms. It provides new means for artificial meat, simulation models, customized wood, food production, pharmaceuticals, and health. Due to the complexity of biological tissue structures, printing is extremely challenging, with long production cycles and printing accuracy far from ideal. CHRISTENSEN et al. used an inkjet printing method to print alginate bio-ink containing fibroblasts in a calcium chloride cross-linked solution[7]. They successfully printed vascular-like products with intersecting vertical and horizontal structures, forming mesoporous tubular structures. However, this printing method has significant limitations when printing complex structures. It still faces issues of low efficiency and simple structure. HINTON et al. used thermally reversible [8], shear-thinning, and biocompatible granular hydrogels as support baths. They printed cell-laden hydrogel bio-ink in the support bath. Subsequently, by removing the support material, they obtained complex three-dimensional tissue-like structures. This method can solve the problem of supporting soft materials such as connective tissue during printing. It can achieve printing at a resolution of 20 micrometers. This approach enhances the precision and complexity of biological 3D printing. Currently, emerging light-projection-based biological 3D printing has high precision. However, light stimulation and the photoreceptor and initiator in the liquid chamber can reduce cell activity. The final product quality decreases. To address this issue, GRIGORYAN et al. screened out a biocompatible photoreceptor [9]. They achieved the printing of highly complex hydrogel tubular structures and demonstrated good cell compatibility. Future animal cell printing will focus on research in tissue and organ repair and regeneration. Plant cell printing aims to create an integrated model of 3D printing and plant tissue culture to improve production efficiency. Microbial 3D printing will show potential in medical health, exploration of microbial interaction mechanisms, and environmental monitoring and remediation.

2.3 Metal materials: selective laser sintering (SLS)

The essence of SLS technology is to sinter metal powders using the energy from a laser. Each layer is evenly spread with metal powder. Using a pre-set path, the laser melts, sinters, and bonds the metal powder into a thin layer. Then another layer of powder is laid down, repeating the process to combine the new layer with the previous one. This continues until the entire part is created. The main advantage of this technology lies in its ability to recycle powder, thereby improving raw material utilization. However, it also has drawbacks. Surface quality and dimensional accuracy are poor. Material properties do not meet the prerequisites for industrial applications. To address these issues, post-processing methods such as polishing, heat treatment, painting, and furnace infiltration have been employed [10]. During production, transient cooling modes can be used to control particle size and shape. This method can enhance the surface finish of the product.

The laser and sintering process includes multiple parameters such as laser scanning speed, power, temperature, and time, all of which can affect product quality. Products may experience warping, shrinkage, and cracking, impacting precision and surface finish. These process parameters often influence each other during actual forming. Yong-Ak Song et al. found through experimental studies that reducing the scanning speed and spacing or increasing the laser power can reduce surface roughness [11]. However, decreasing the scanning spacing increases the tendency for warping. Therefore, it is concluded that in the design phase, various parameters should be optimized to select the most effective parameter set for different products. Additionally, post-processing methods such as hot isostatic pressing HIP, liquid-phase sintering LPS, high-temperature sintering, and melt infiltration must be performed before the product can be put into practical use.

3 Future research direction

3D printing technology has broad prospects for development in the long term, but it still faces many challenges in the short term. 3D printers are expensive, and product design costs are high. Currently, most materials used in printing are chemical polymers. This limits the options and results in poor physical properties. There are also certain safety risks during use. Additionally, the production cycle for 3D printed products is long. During manufacturing, the precision of the products often fails to meet the requirements of high-tech fields. As 3D printing becomes more widespread in the future, replicating other products will become easier. The market may see a large number of counterfeit products, making the manufacturing environment more challenging. Therefore, intellectual property protection laws also need to be improved.

In the future, 3D printing machines will become more compact, desktop-friendly, and cost-effective, making 3D printing accessible to the masses [12]. The integration of software design, algorithm control, and manufacturing processes makes 3D printing easier to operate. In the future, 3D printing will integrate with AI. By analyzing and calculating through AI, it can determine the optimal printing direction and support methods, thus providing the best printing solution.

4 The impact on society and business development

3D printing is expected to become the dominant manufacturing model in the future. Currently, China lacks relevant standards for printing materials [13]. Among various technologies, especially 3D printing using metal materials, reliance on imports is significant. Therefore, the development of metal material 3D printing is constrained. Other materials have also revealed different issues in the application. One of the most pressing tasks now is to establish standards for printing materials. Increase funding and technical support for research and industrialization.

5 Conclusion

This article reviews the existing research findings on FDM, biological 3D printing: inkjet, extrusion, and light projection methods, as well as SLS technology, categorized by printing materials. 3D printing is expected to become the dominant manufacturing model in the future. Improving product quality is a challenge faced during the popularization of 3D printing. The improvement methods discussed in this paper contribute to enhancing the precision, mechanical strength, and thermal stability of products during manufacturing. China needs not only to establish relevant standards for printing materials but also to improve from the perspective of printing machines. The development of 3D printing will drive advancements in multiple fields such as aerospace, healthcare, and construction. 3D printing can propel China from a major manufacturing country to a strong manufacturing nation.

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