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Application status and development trend of two-photon polymerization technology in 3D printing field

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Abstract:

Two-photon polymerization (TPP) technology has garnered significant attention in the field of 3D printing due to its exceptional sub-micron resolution capabilities. This paper provides a comprehensive overview of the fundamental principles of TPP, material development, system construction, and explores its applications in micro-optics, biomedicine, and micro-electromechanical systems (MEMS). Additionally, this study analyses the technological challenges and future development directions, highlighting the importance of material innovation and interdisciplinary integration. The findings suggest that TPP technology holds immense potential in the field of high-precision manufacturing.

Keywords: Two-photon polymerization, 3D printing, Micro-nano processing, High-precision manufacturing

1. Introduction

3D printing technology, as a revolutionary invention in the manufacturing industry, is leading the rapid transformation from design drawings to physical products. Among the many 3D printing technologies, two-photon polymerization (TPP) technology stands out for its ability to achieve high-precision manufacturing at the micro and nano scales. Since its initial reporting in the late 1990s, TPP technology has become a research hotspot in the field of three-dimensional micro and nano processing. This technology uses the high power density of femtosecond or picosecond lasers to initiate a local polymerization reaction in photosensitive resin through a two-photon absorption process, constructing three-dimensional micro and nano structures that traditional technologies cannot reach. The advantage of TPP technology lies in its ability to achieve nanometer-level resolution manufacturing, far exceeding the diffraction limit of traditional single-photon polymerization technology. In the TPP process, the light intensity at the laser focus is high enough for the photosensitizer molecules to be excited to the excited state after absorbing two photons, thereby initiating a polymerization reaction. This nonlinear absorption process is strongly dependent on the focusing characteristics of the beam, thus TPP technology can manufacture micro and nano structures with complex geometric shapes, including microfluidic channels, micro-optical elements, and micro-electromechanical systems (MEMS), etc.

With the continuous breakthroughs in 3D printing technology, the diversification of material types, and the significant improvement in printing precision and speed, TPP technology has shown tremendous potential in the field of high-precision manufacturing. This technology not only promotes the development of material science but also brings new manufacturing possibilities to fields such as microfluidics, optical devices, and bio-tissue engineering. Despite this, TPP technology still faces challenges in practical applications, such as slow printing speed and high equipment costs. To overcome these limitations, researchers are actively developing new photosensitive materials, improving optical system designs, and exploring new processing strategies to improve printing efficiency and reduce costs.

2. TPP 3D Printing Technology Advantages and Challenges

Two-photon polymerization (TPP) technology stands out among 3D printing technologies due to its ultra-high resolution and nonlinear processing capabilities. It achieves manufacturing at the nanometer resolution level, breaking through the diffraction limit of traditional optical manufacturing technologies [1]. This technology allows for precise control of material polymerization at the microscopic scale, creating complex three-dimensional structures that traditional techniques cannot achieve. Moreover, the development of TPP technology has promoted the design and synthesis of new photosensitive materials with better two-photon absorption characteristics and mechanical properties, providing possibilities for manufacturing more complex and functional micro and nano structures [2]. TPP technology shows great potential in applications such as microfluidics, optical devices, and bio-tissue engineering, promoting the integration of multiple interdisciplinary fields.

Despite its significant technical advantages, TPP technology also faces some challenges in practical applications. The relatively slow printing speed limits its application in mass production. The slow printing speed is partly due to the fine control required in the high-precision manufacturing process. In addition, the high cost of equipment for TPP technology, which requires the use of expensive pulsed lasers and precise optical systems, increases the threshold for the application of the technology. The selection of photosensitive materials for TPP technology is somewhat limited, requiring materials with specific two-photon absorption characteristics, which restricts the range of available materials. The micro and nano structures after printing may require complex post-processing steps, such as removing unreacted resin, cleaning, and curing, which may increase the complexity and cost of the manufacturing process.

3. TPP 3D Printing Materials and System Development

Two-photon polymerization (TPP) 3D printing technology has attracted widespread attention in the fields of materials science and micro-nano processing due to its outstanding resolution and high-precision control over materials. In recent years, TPP technology has made significant progress in material formulation, photosensitizer improvement, and printing system optimization.

3.1 Advances in Photosensitive Material Development

3.1.1 Synthesis and Performance of New Photosensitive Resins

Photosensitive materials, as the core of two-photon polymerization (TPP) 3D printing technology, directly determine the precision and quality of the printed structures. In recent years, researchers have developed new types of photosensitive resins through chemical modification strategies. These resins not only enhance photosensitivity but also improve mechanical properties and thermal stability [3]. For instance, by introducing functional monomers, the hydrophilicity, surface chemistry, and mechanical properties of printed structures have been regulated. Moreover, the development of water-soluble photosensitizers has provided possibilities for the manufacturing of biocompatible 3D microstructures, which is significant for fields such as tissue engineering and drug delivery systems. In the research and development of photosensitive materials, the research team at the Institute of Physics and Chemistry, Chinese Academy of Sciences, has made significant progress in the design and application of water-soluble two-photon initiators. They proposed a molecular design concept and strategy for high-performance water-soluble two-photon photo functional materials, effectively improving the two-photon absorption cross-section and biocompatibility, addressing the issue that non-water-soluble materials' two-photon absorption characteristics are difficult to reconcile with water solubility [4]. By designing and synthesizing a series of efficient water-soluble two-photon initiators and applying them to the construction of biomimetic 3D hydrogel structures, these research results have provided new pathways for the application of hydrogel materials in the field of tissue engineering.

3.1.2 Material Selectivity and Functionalization

In addition, two-photon polymerization 3D printing technology has also made progress in the study of structural colors. By preparing different photonic structures and adjusting their geometric parameters, vivid 2D and 3D struc-

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tural colors can be achieved in polymer nano-columns, gratings, woodpile structures, etc. [5]. These studies not only promote the development of material science but also provide new possibilities for applications in optical anti-counterfeiting, information storage, and optical sensing fields.

3.2 Advances in Printing Systems and Equipment:

As two-photon polymerization (TPP) technology continues to advance, the ability to construct high-precision printing systems has also been significantly enhanced. These systems typically employ optical components with low numerical apertures and high-throughput TPP systems to achieve efficient material polymerization and rapid structure formation [6]. Moreover, to enhance printing efficiency, researchers have explored technologies such as multi-photon absorption and holographic methods, which can significantly increase printing speed while maintaining high structural resolution.

3.2.1 Construction of High-Precision Printing Systems

The construction of high-precision printing systems relies on advanced optical technology and precision mechanical engineering. For example, the use of dynamic optical elements and adaptive optical systems can adjust the shape and direction of the beam in real-time to accommodate complex printing patterns and structures [7]. The integration and optimization of these technologies have significantly improved the precision and speed of TPP printing systems. High-precision 3D printing technology has clear advantages in processing precision connectors, such as high precision, low cost, and short cycles, helping the industry to break through technical barriers.

3.2.2 Improvement of Equipment Performance and Cost-Benefit Analysis

The improvement of equipment performance is not only reflected in printing speed and precision but also includes improvements in beam quality, scanning strategies, and data processing algorithms. These improvements help enhance the stability of the printing process and the precision of the structure. In terms of cost-benefit analysis, although the cost of TPP printing systems is relatively high, the cost is gradually decreasing with technological advancements and mass production. For instance, the PμSL technology using industrial-grade UV-LED as a light source, compared to traditional femtosecond lasers, has a longer service life, lower ownership costs, and fewer maintenance requirements. Moreover, as the implementation of significant equipment updates in the education sector gradually takes hold, the application of 3D printing equipment has become a key focus for universities, which may further promote cost-effectiveness [8].

4. Application Field Analysis of Two-Photon Polymerization 3D Printing Technology

4.1 Micro-optics and Photonic Crystal Manufacturing

Two-photon polymerization (TPP) technology has shown significant application potential in the fields of micro-optics and photonic crystal manufacturing. TPP technology can manufacture micro and nano optical components with high precision and complex geometric shapes, which are difficult to achieve with traditional manufacturing techniques. For example, micro-lens arrays and photonic crystal structures manufactured by TPP technology have already demonstrated their unique advantages in optical communication and sensing technology [9]. In addition, TPP technology also has important applications in manufacturing microstructures with specific optical properties, such as manufacturing optical waveguides with specific refractive index distributions and high-performance optical filters. These applications not only promote the miniaturization and integration of optical devices but also provide new possibilities for the design of new optical systems.

4.1.1 Application Case Studies

In the field of micro-optics, TPP technology has been used to manufacture micro-lenses, fiber ends, and micro-optical components. For example, micro-lens arrays manufactured by TPP technology can be used to improve the performance of imaging systems and achieve high-resolution optical imaging. In addition, TPP technology can also be used to manufacture microfluidic devices with specific optical paths, which have important applications in chemical analysis and biological detection. In the field of photonic crystal manufacturing, TPP technology can precisely control the periodic structure and defects of photonic crystals, thereby achieving precise control of the photonic bandgap, which is of great significance for the development of new photonic devices and optical communication systems [10].

4.1.2 Technical Challenges and Solutions in Applications

Although TPP technology has great application potential in the fields of micro-optics and photonic crystal manufacturing, it also faces some technical challenges. For example, beam control and focusing accuracy during the manufacturing process are crucial for the performance of the final product, which requires high-precision optical systems and precise mechanical control [11]. In addition, the selection and optimization of photosensitive materials are also key to achieving high-performance micro-optical devices. To address these challenges, researchers are developing new photosensitive materials, improving beam quality, and optimizing printing process parameters to improve manufacturing efficiency and product quality [12].

4.2 Application in the Field of Biomedicine

The application of TPP technology in the field of biomedicine is another important research direction. TPP technology can manufacture customized medical devices that highly match the structure of human tissues, such as personalized dental correctors, artificial bones, and implants. These customized medical devices can better adapt to the needs of patients, improving treatment effects and the quality of life for patients. In addition, TPP technology can also be used in tissue engineering and drug screening, promoting tissue regeneration and the development of new drugs by precisely controlling the microenvironment in which cells grow [13].

4.2.1 Tissue Engineering and Microfluidic Systems

In the field of tissue engineering, TPP technology can manufacture scaffolds with specific microstructures, which can simulate the mechanical and biological properties of natural tissues and provide support for cell growth and tissue regeneration. For example, porous scaffolds manufactured by TPP technology can be used for the repair of cartilage and bone tissue [14]. In the field of microfluidic systems, TPP technology can manufacture high-precision microfluidic channels and reactors, which have important applications in drug screening and biological detection [15].

4.2.2 Application Cases and Technical Challenges

In the field of biomedicine, the application cases of TPP technology include the manufacture of personalized medical devices and the construction of tissue engineering scaffolds. For example, personalized dental correctors manufactured by TPP technology can precisely match the patient's oral structure, improving the correction effect [16]. In the field of tissue engineering, TPP technology can manufacture scaffolds with complex internal structures to promote the regeneration of blood vessels and nerves [17]. However, biocompatibility and biodegradability are key challenges that need to be addressed in the application of TPP technology in the field of biomedicine. Researchers are exploring new biocompatible materials and surface modification technologies to improve the biocompatibility and biodegradability of TPP-manufactured devices [18].

4.3 Micro-Electro-Mechanical Systems (MEMS) and Micro Robots

The application of TPP technology in the manufacturing of micro-electro-mechanical systems (MEMS) and micro-robots is also one of its important application fields. TPP technology can manufacture MEMS devices with high precision and complex geometric shapes, such as micro sensors, actuators, and micro-robots. These micro devices have a wide range of application prospects in precision instruments, medical equipment, and intelligent systems.

4.3.1 Application of Technology in MEMS Manufacturing

In the field of MEMS manufacturing, TPP technology can be used to manufacture micro sensors, actuators, and micro structures. These micro devices have important applications in consumer electronics, automobiles, and medical equipment. For example, micro pressure sensors manufactured by TPP technology can be used to monitor blood pressure and environmental pressure. In addition, TPP technology can also be used to manufacture micro optical devices, such as micro lenses and micro optical switches, which have important applications in optical communication and optical sensing.

4.3.2 Cases and Challenges in Micro Robot Manufacturing

In the field of micro-robot manufacturing, TPP technology can manufacture micro-robots with complex structures and high precision. These micro-robots have a wide range of application prospects in biomedicine, environmental monitoring, and micro assembly. For example, micro robots manufactured by TPP technology can be used for drug delivery and minimally invasive surgery [19]. However, the driving and control of micro robots are key challenges that need to be addressed in the application of TPP technology in this field. Researchers are exploring new driving materials and intelligent control strategies to improve the performance and application range of micro robots [20].

5. Challenges and Future Directions of Two-Photon Polymerization 3D Printing Technology

5.1 Technical Bottlenecks and Innovation Needs

Two-photon polymerization (TPP) technology has made

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significant progress in achieving high-precision 3D printing, but it still faces some technical bottlenecks. Among them, the relatively slow printing speed is a major limiting factor, which restricts its application in mass production. In addition, due to the need for expensive pulsed lasers and precision optical systems, the equipment cost of TPP technology is high. To overcome these limitations, the development of new photosensitive materials, the improvement of optical system design, and the exploration of new processing strategies to improve printing efficiency and reduce costs is a significant demand.

5.2 Development Trends of Material Science and Process Technology

Material science plays a key role in the development of TPP technology. The development of new photosensitive materials, such as photoinitiators with enhanced two-photon absorption and biocompatibility, as well as soft responsive hydrogels, provides the possibility of manufacturing micro and nano structures with complex geometric shapes and dynamic functions [21,22]. At the same time, a deeper understanding of reaction mechanisms, computational analysis, and optical system development is driving the expansion of manufacturing speed and application range.

5.3 Interdisciplinary Integration and Exploration of New Application Fields

5.3.1 Technical Challenges and Response Strategies

Interdisciplinary integration brings new challenges and opportunities for TPP technology. In the field of biomedicine, TPP technology is used to manufacture three-dimensional microstructures that simulate the multi-cellular environment of the human body, which requires an in-depth understanding of cell mechanics, material science, and micro-processing technology. To meet these challenges, new materials and processes are being developed, such as using IP-PDMS and BIO INX bio-resins to achieve high-fidelity 3D organotypic cell culture.

5.3.2 Future Development Trends and Research Directions

The future development trend will focus on improving the printing speed, resolution, and material diversity of TPP technology. At the same time, as interdisciplinary research deepens, the application of TPP technology in fields such as biomedicine, microfluidic devices, micro-optics, and microelectronics will be further expanded. In addition, with the development of new photosensitive materials and the improvement of optical systems, TPP technology will show greater potential in manufacturing more complex and functional micro and nano structures.

6. Conclusion

The contributions of two-photon polymerization (TPP) technology in the field of 3D printing are multifaceted. It has not only broken through the diffraction limit of traditional optical manufacturing technologies, achieving the manufacture of three-dimensional structures with nanometer-level resolution, but also promoted the integration of multiple disciplines such as material science, optical engineering, and biomedicine. The development of TPP technology has provided new solutions for high-precision manufacturing, fostered the design and synthesis of new photosensitive materials, and driven innovation in optical system design. In the field of biomedicine, the application of TPP technology has demonstrated its tremendous potential in tissue engineering, drug delivery systems, and the manufacture of microfluidic devices, providing new tools for personalized medicine and drug development. Furthermore, the application of TPP technology in the manufacturing of MEMS and micro robots has also proven its key role in promoting the development of precision instruments and intelligent systems.

Looking to the future, the research and application prospects of TPP technology are broad. With the continuous development of new photosensitive materials and the further optimization of optical systems, the printing speed and efficiency of TPP technology are expected to be significantly improved to meet a wider range of industrial and commercial application needs. In-depth interdisciplinary research will make the application of TPP technology in fields such as biomedicine, microfluidic devices, micro-optics, and microelectronics more diverse and personalized. Future research will focus on the development of new photosensitive materials, the improvement of optical systems, the optimization of printing processes, and the control and optimization of the TPP printing process based on machine learning algorithms. The application of these technologies will further improve the manufacturing efficiency and product quality of TPP technology, promoting its application in more fields.

In summary, the contributions of TPP technology in the field of 3D printing are multifaceted, and its future research and application will focus more on interdisciplinary integration and technological innovation to achieve more precise, faster, and more widely used three-dimensional micro and nano manufacturing. With the continuous advancement of technology, TPP technology is expected to play a more important role in the field of high-precision manufacturing in the future.

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