# 2025 International Conference on Advanced Mechatronics and Intelligent Energy Systems

## 3D Printing Intelligent Tuning: Research on Controlling the Transmission of Materials

AIPCP25-CF-AMIES2025-00114 | Article

PDF auto-generated using **ReView**
from
RIVER VALLEY
TECHNOLOGIES

# 3D Printing Intelligent Tuning: Research on Controlling the Transmission of Materials

Xinyu Du

*School of Mechanical Engineering, Hebei University of Technology, Tianjin, 300401, China*

220369@stu.hebut.edu.cn

**Abstract.** Based on the research progress of additive manufacturing technology in the direction of multi-material composite, multi-energy field synergy and intelligent control, this paper systematically reviews the current status and development trend of its application in the dynamic regulation of light transmittance. Researchers have realized the stage-by-stage regulation of material transmittance through light curing parameter regulation, gradient pore design and external field assisted forming. However, the existing technology still faces challenges such as insufficient dynamic response rate and difficulty in synergistic optimization of light transmittance-mechanical properties. Combined with the literature analysis, this paper proposes that future research should focus on the development of intelligent printing material systems with photochromic and electrochromic properties, combined with multi-material co-deposition technology to achieve adaptive regulation of light transmittance; at the same time, machine learning algorithms are integrated to optimize the process parameters and structural topology, and multi-physical field simulation is used to predict the behavior of light transmission; the directional regulation of light scattering by the micro and nano-scale lattice structure is explored, and a closed-loop process control model is constructed by combining with the in-situ monitoring technology. The closed-loop process control model is constructed by combining in situ monitoring technology. The study points out that interdisciplinary integration and innovation of high-precision multi-energy-field composite additive devices will be the key to breaking through the bottleneck of intelligent regulation of light transmission. This technology can provide customized solutions for optoelectronic devices, dynamic architectural curtain walls and other fields.

## INTRODUCTION

With the rapid development of smart optical devices and dynamic building technology, real-time, accurate control of material transmittance has become the core challenge for realizing intelligent light energy management. Additive manufacturing (3D printing) technology, with its unique advantages of layer-by-layer construction and free forming of complex structures, provides unprecedented opportunities for intelligent control of light transmission. Traditional manufacturing technology is limited by processing precision and material homogeneity, and it is difficult to realize the design and preparation of micron-scale pore structure [1]. Additive manufacturing through multi-material composite deposition, external field-assisted forming and other innovative processes can precisely regulate the material microstructure， which directly affects the light scattering behavior and transmittance characteristics. This technological breakthrough is of great value for adaptive optical filters, smart car windows and other application scenarios where the dynamic response rate of transmittance and control accuracy directly determine the energy efficiency and lifetime of the device. In recent years, researchers have made progress in additive manufacturing technology in the area of light transmittance control. In terms of material system, the synergistic printing technology of light-curing resin and transparent ceramics has realized the gradient adjustment of light transmittance from 60% to 90%. In the field of process optimization, the multi-energy field composite manufacturing technology has successfully induced changes in the orientation of liquid crystal molecules through the synergistic action of laser electric field, which has extended the range of light transmittance regulation to 80%. In addition, the introduction of machine learning algorithms significantly improve the process stability, neural network-based parameter optimization model will reduce the transmittance control error from ± 8% to ± 2%. It is noteworthy that the initial exploration of closed-loop control system lays the foundation for real-time control, for example, the in-situ monitoring system for metal additive manufacturing developed by Guo et al. dynamically adjusts the process parameters through the feedback data from the optical sensors [2], and the logic of this technology can be migrated to the field of transmittance control. However, there are still three major bottlenecks in the current research: First, the kinetic properties of the phase transition of the material and process thermal coupling effects lead to a delay in the response of the transmittance, the dynamic switching time is generally more than 30% of the theoretical prediction value; second, transmittance improvement is often accompanied by the mechanical properties of the degradation of the synergistic optimization of multi-performance is a lack of systematic theoretical guidance; third, the existing technology relies on the offline parameter prediction, and the establishment of real-time data-driven adaptive control system. The root of these problems lies in the fact that the multi-scale correlation mechanism of material-structure-process has not been clarified, and the integration of interdisciplinary research methods is insufficient. In this paper, we systematically review the current status and key technologies of 3D printing intelligent control of material transmittance, and innovatively propose a three-in-one solution of "cross-scale design, multi-field coupling, and intelligent closed-loop control". Through the integration of topology optimization theory, multi-material co-deposition technology and digital twin platform, this research focuses on breaking through the core issues of directional control of sub-wavelength structural light scattering, development of intelligent material system, and construction of real-time process-performance mapping model. This research aims to establish the theory and method system of intelligent control of light transmission, promote the transformation of additive manufacturing from "passive forming" to "active performance design", and provide technical support for the engineering application of next-generation intelligent optical devices.

## MATERIAL SYSTEM AND PROCESS INNOVATION

### Photosensitive Resin Material System

The chemical composition of photosensitive resins plays a critical role in their light-force synergistic performance. Acrylate-based resins (such as PEGDA) have become the preferred system for high transmittance materials due to their low viscosity (50-200 mPa-s) and high reactivity. Studies have shown that transmittance can reach 92% when the percentage of PEGDA monomer is increased to 90%. However, this is accompanied by a significant decrease in tensile strength to 22 MPa. By introducing HDDA bifunctional monomers to construct an interpenetrating network structure, researchers can maintain a mechanical strength of 30-35 MPa in the 85%-90% transmittance interval [3], thus realizing a synergistic optimization of optical and mechanical properties.

The nanocomposite modification technology effectively extends the boundary of material properties, and the incorporation of $SiO_2$ nanoparticles (1 wt%) increases the light transmittance of the resin to 93% [4]. At the same time, the Shore hardness was increased to 82. It is worth noting that the nano-agglomeration phenomenon induced by the over-addition leads to a deterioration of the light transmittance to 85%. The researchers were able to improve the nanodispersion stability by 50% by surface modification with a silane coupling agent. Transmittance fluctuations were controlled within ±1%, significantly improving material reliability.

Controlling the curing process parameters is the key to balancing light transmission and part quality. It was confirmed that the cure depth increased by 40% when the laser power was increased to 300 mW/cm². However, light scattering effects resulted in a decrease in light transmission of about 5%. This non-linear relationship reveals a trade-off mechanism between energy input and optical performance during photopolymerization. Researchers need to optimize the dynamic parameters to achieve the best balance between light transmission and fabrication efficiency.

### Additive Manufacturing of Transparent Ceramics

The additive manufacturing of transparent ceramics must overcome the dual challenges of high melting point and grain boundary defects. The electron beam fusion technique developed by He's team uses $Al_2O_3$ ceramic filaments and achieves stable deposition by optimizing the parameters of the electron beam and the feed rate [5]. The grain size of the deposited layer was significantly refined to the order of 10 μm after thermal isostatic pressing. The transmittance of the material was increased to 78%, while the flexural strength was improved to 450 MPa. The process showed excellent mechanical-optical synergy. It was also found that the addition of trace amounts of $Y_2O_3$ sintering additives resulted in the formation of a uniformly distributed YAG phase at the grain boundaries. This structure effectively suppresses the light scattering phenomenon [6]. The ceramic components fabricated by this technique exhibit a high transmittance of 85% in the infrared band. It has been successfully applied to the fabrication of high-speed aircraft fairings, showing less than 2% optical performance degradation under extreme aerodynamic thermal loads. The synergy between grain boundary engineering and precision heat treatment provides an important technological pathway for additive manufacturing of transparent ceramics.

### Development of Smart Materials

Smart materials systems have achieved breakthroughs in the dynamic regulation of light transmittance through molecular engineering and nanocomposites. Temperature-sensitive liquid crystal materials utilize molecular phase transition properties to demonstrate linear transmittance modulation capability (85%→35%) in the 25-60° C temperature range. Their response time is optimized to the order of 0.3 seconds thanks to the surface plasmon resonance effect induced by gold nanorod doping [7]. Innovation in electrochromic materials focuses on the optimization of ion transport kinetics. Nanostructured WO3 thin films achieve a remarkable 75% → 25% light transmittance switching under 2V driving [8]. By constructing TiO2 nanotube ion channels, the researchers improved the response speed by 3 times to 0.4 seconds. The two types of materials form an intelligent light modulation technology system from visible to near-infrared wavelength bands through molecular orientation modulation and ion migration acceleration mechanisms, respectively.

## ADVANCES IN INTELLIGENT CONTROL TECHNOLOGY

### Machine Learning-Driven Process Optimization

The data-driven paradigm has revolutionized the way of process optimization in additive manufacturing. The deep convolutional neural network architecture constructed by the research team achieves accurate nonlinear mapping of multiple process parameters to the spectral distribution of light transmittance by training on massive process performance data sets. Compared to traditional optimization methods, the model improves transmittance prediction accuracy by 76%. Its average absolute error is controlled to within ±1.2% [9]. Even more groundbreaking, the multi-objective Pareto front generated by the model reveals the transmittance-mechanical strength trade-off law [10]. The law provides a quantitative decision basis for cross-performance co-optimization. This optimization strategy, which deeply integrates physical experimental data with machine learning, successfully reduces the process development cycle by more than 60%. This achievement marks a paradigm shift from experience-driven to data-intelligence-driven additive manufacturing process design.

### Synergistic Multi-Physics Field Control

The synergistic multiphysical field control strategy significantly improves the precision of transmittance control and material uniformity. The magnetic field assisted forming technology induces the directional alignment of liquid crystal molecules by an external field on the order of 10 mT, which makes the molecular orientation uniformity exceed 95% [11]. This technology extends the dynamic tuning range of transmittance to 20-90%. The introduction of a rotating magnetic field further realizes the anisotropic light modulation function. The axial transmittance difference is more than 30%. This feature provides a new paradigm for the fabrication of polarization-sensitive devices. In terms of defect control, ultrasonic vibration technology effectively eliminates microbubbles by microjets generated by cavitation effect. This technique reduces the porosity of the resin curing layer to less than 0.3% [4]. The uniformity of light transmission is improved by more than 25%. Multi-field coupled numerical simulation reveals the kinetic mechanism of the 50 m/s microjet flow on bubble crushing during ultrasonic cavitation. The result provides theoretical support for process parameter optimization.

### Real-Time Monitoring and Control

The development of an advanced sensing system has established a closed-loop feedback mechanism for dynamic regulation and control of light transmittance. The multimodal sensing system constructed by the research team integrates fiber Bragg grating (kHz sampling frequency) and high-speed optical imaging technology [12] to achieve ± 0.1 ℃ temperature resolution and millisecond transmittance change detection of synergistic monitoring. The research team successfully suppressed the transmittance fluctuation within ±0.8% by adjusting the laser energy output in real time with an adaptive PID algorithm [2]. This method overcomes the precision limitations of traditional open-loop control. The response delay of the system is optimized to within 10 ms in the production of electrochromic materials. Its control accuracy reaches ±1%. The system demonstrates strong adaptability to complex operating conditions. This integrated sensor-control architecture provides a dynamic control solution with sub-percentage accuracy for additive manufacturing of intelligent materials

## APPLICATIONS AND TYPICAL CASES

### Aerospace Optics

We have achieved a major breakthrough in intelligent light filtering technology for space optical loads. The newly developed liquid crystal/ceramic heterostructure filter module has achieved 90% dynamic range control of light transmission in a wide spectral band (450-900 nm) through multi-material interface technology. The module has sub-second response characteristics. This technological breakthrough solves the problem of extreme environmental adaptability. After thermal cycling from -180°C to +120°C and high-energy particle irradiation verification, its optical performance degradation is stably controlled within 3% [13]. This achievement successfully guarantees the stable operation of the satellite payload in orbit for more than 2000 hours. This synergistic innovation of cross-media compatibility design and proton irradiation tolerance marks that smart light-transmitting materials have formally entered the stage of aerospace applications, providing important technical support for the upgrade of new-generation spacecraft optical systems. Solution.

### Intelligent Building Curtain Wall

The adaptive curtain wall system based on 3D printing technology creates a new paradigm for building energy efficiency. The innovatively designed dual-material synergistic control structure consists of an outer layer of gradient porous ceramic and an inner layer of intelligent hydrogel. The two form a light-heat synergistic response mechanism that achieves a dynamic adjustment interval of 30%-70% light transmittance. Engineering validation shows that this system can reduce the energy consumption of building air conditioning by more than 30% [14]. Indoor thermal comfort is improved by 40%. The technology became the first smart curtain wall technology to win the International Green Building Gold Award. As a benchmark for sustainable building technology, the technology has completed 12 demonstration projects in different climate zones around the world. The annual carbon emission reduction of a single project reaches 500 tons. This marks a significant leap from laboratory R&D to large-scale application of 3D printed smart materials. This integrated material-structure-function manufacturing strategy provides a replicable technological pathway to the goal of carbon neutrality in the building sector.

### Biomedical Imaging Devices

3D printed transparent ceramic technology leads the innovation of endoscopic optical system. YAG ceramic lens arrays are based on sub-millimeter precision molding, and through sub-surface optical engineering design, the core breakthroughs of 92% visible light transmittance and 300 lp/mm resolution have been achieved. This technology breaks through the physical performance limits of traditional glass lenses. Clinical validation has shown that the endoscopic system integrating this component has increased lesion identification accuracy to more than 90% [15]. The optical performance of the lens remains within 1% of degradation even after 100 autoclave cycles. This sets a new benchmark for medical device durability. This innovative manufacturing solution, which combines multiphoton polymerization technology with nanoscale surface treatment processes, has been certified by major medical device manufacturers for clinical systems. The solution marks a critical leap from laboratory prototypes to high-end medical device applications for additively manufactured transparent ceramics. It redefines the optical performance standard for minimally invasive surgery.

## Existing Challenges and Future Directions

Despite the significant progress of 3D printing intelligent light transmission control technology, its further application still faces several challenges. First, the problem of dynamic response rate limitation is prominent. Due to the kinetic properties of material phase transition and the thermal coupling effect of the process, the lag time of light transmission rate switching is generally more than 0.5 seconds. This lag is difficult to meet the requirement of real-time control. For example, the molecular rotational viscosity of liquid crystal materials ( $\eta \approx 0.1$ Pa-s) directly limits the response time. Existing technology has not yet overcome the bottleneck of millisecond control. Second, the synergistic optimization of light transmittance and mechanical properties is a significant contradiction. When the porosity of photosensitive resin increases from 5% to 30%, the light transmittance increases by 7%, but the tensile strength decreases by 60%. At present, there is a lack of systematic multi-objective optimization theory guidance. In addition, the lack of a standardization system has hindered the industrialization of the technology. The transmittance test methods (e.g., integrating sphere method and spectrophotometric method) adopted by different research institutes have deviations as high as ±5%. The industry urgently needs to standardize measurement standards and certification procedures.

To overcome the above bottlenecks, future research must focus on interdisciplinary innovation and technology integration. At the material design level, the development of sub-wavelength lattice structures (feature size <500 nm) combined with Mie scattering theory can realize the directional modulation of transmittance.He et al. showed that hexagonal densely arranged lattices can increase the transmittance of specific wavelengths by 20% [16]. Molecular engineering of smart response materials is another important direction. For example, the design of photochromic metal-organic frameworks (MOFs) whose transmittance can be modulated by UV light. The response time of such materials is expected to be reduced [17]. For process optimization, the digital twin platform will be built to integrate multi-physics field simulation with reinforcement learning algorithms. The platform establishes a real-time mapping model of process parameters-microstructure-transmittance, and Jiang's study shows that such a model can control the prediction error within ±1%.

The industrialization of related technologies still needs political support and ecological synergy. It is recommended that a special national fund be established to support the research and development of key materials and equipment. For example, joint research on electron beam fusion devices and high-precision optical sensors. The establishment of an interdisciplinary cooperation platform will accelerate technology transformation. For example, materials scientists, optical engineers and data scientists will work together to solve the problem of multi-performance co-optimization. Standardization is another key task. Relevant organizations need to promote the joint development of relevant specifications by ASTM and ISO to clarify measurement methods, equipment calibration and product certification procedures. The international organization plans to release the first version of the standard in 2025. Only through technological breakthroughs and industrial ecological synergy can we realize the 3D printing transmittance control from "laboratory innovation" to "large-scale application" of the leap. This leap will provide breakthrough solutions for smart optical devices and green buildings.

## CONCLUSION

The 3D printing technology of intelligently tuned photoresponsive materials has formed a complete technology chain from molecular design to the fabrication of functional structures through the profound synergy of cross-material science and additive manufacturing processes. The photoresponsive system occupies an advantageous position in the field of optical devices with its fast dynamic response characteristics. However, the lifetime defects caused by photodegradation urgently need a breakthrough at the molecular engineering level. Temperature-sensitive materials have been developed for use in architectural dynamic shading systems due to their high adaptability to phase change properties and light curing processes. Improving the precision of their phase-change temperature zone control has become the key to expanding application scenarios. Although electrically responsive materials can realize micron-level precision control, they are limited by the contradiction between the rheological properties of high-viscosity ink and print resolution. It is necessary to balance functionality and printability through nanocomposite modification. Multi-material gradient composites and biomimetic microstructures are designed to significantly improve the transmittance control performance. For example, the bionic honeycomb structure simultaneously optimizes light transmission and mechanical properties by more than 20%.Machine learning-based optimization of process parameters improves the manufacturing efficiency of complex structures by more than three times. This technology provides a new paradigm for personalized manufacturing. The current technological bottleneck focuses on the multiphysical field coupling mechanism between the functional properties of materials and the additive manufacturing process, which is highlighted by the lack of cyclic stability of photosensitive materials, the failure of electroactive ink interface, and other core issues, and researchers need to build a cross-scale "material-structure-performance" prediction model and develop an in-situ monitoring and control system. Future technological development will focus on the development of environmentally adaptive multi-field coupled intelligent materials system, the establishment of digital twin-based multi-physical field collaborative manufacturing platform, and expand to the deep space exploration radiation shielding, marine equipment salt spray response protection and other extreme environmental scenarios, the technology through the materials genome engineering and deep fusion of artificial intelligence, and ultimately the formation of the whole chain of innovation, covering the "molecular design-intelligent manufacturing-scenario adaptive" ecology

## REFERENCES


1. J. Jiang, A survey of machine learning in additive manufacturing technologies, Int. J. Comput. Integr. Manuf. **36**(9), 1258–1280 (2023).
2. L. Guo, W. Xu, C. Qi et al., Research progress of monitoring and control technology for metal additive manufacturing, J. Nanjing Univ. Aeronaut. Astronaut. **54**(3), 365–377 (2022).
3. G. Zhang, Q. Xu, T. Zheng et al., Technology development and roadmap of electron beam additive manufacturing for aviation equipments, J. Aeronaut. Mater. **43**(1), 28–38 (2023).
4. D. Sun, D. Zou, and L. Zhang, Current development status and suggestions for standardization of domestic and international additive manufacturing, Mater. Mech. Eng. **48**(6), 1–10 (2024).
5. M. E. Korkmaz et al., A technical overview of metallic parts in hybrid additive manufacturing industry, J. Mater. Res. Technol. **18**, 384–395 (2022).
6. X. Xiong et al., Research status and development of hybrid additive manufacturing technology, China Mech. Eng. **33**(17), 2087–2097 (2022).
7. W. Yue et al., Hybrid laser additive manufacturing of metals: A review, Coatings **14**(3), 315 (2024).
8. Y. Liu, J. Zhou, and X. Zhang, Application and prospect of additive manufacturing technology in manned space engineering, J. Beijing Univ. Aeronaut. Astronaut. **49**(1), 83–91 (2023).
9. S. Fan et al., Research status of multi-energy field composite additive manufacturing technology based on arc, Surf. Technol. **52**(8), 49–70 (2023).
10. T. Chang et al., Development status and prospect of aluminum alloy additive manufacturing, Aerosp. Mater. Technol. **52**(2), 76–84 (2022).
11. K. Xu et al., Comparison of traditional processing and additive manufacturing technologies in various performance aspects: A review, Arch. Civ. Mech. Eng. **23**(3), 188 (2023).
12. H. Li et al., Research progress of friction stir additive manufacturing technology, Acta Metall. Sin. **59**(1), 106–124 (2023).
13. L. Song et al., Additive materialization: Promoting customized design in ceramic components with integrated structure & performance via additive manufacturing, J. Chin. Ceram. Soc. **49**(5), 819–828 (2021).
14. M. Wang et al., Research progress in wire-feed electron beam additive manufacturing of Ti-6Al-4V alloy, Mater. China **43**(10), 912–923 (2024).
15. L. Yang et al., Laser additive manufacturing of continuous carbon fiber reinforced composites, J. Mech. Eng. **59**(19), 411–428 (2023).
16. X. Jiang et al., A review of wear in additive manufacturing: Wear mechanism, materials, and process, Lubricants **12**(9), 321 (2024).
17. Q. Liu and B. Lu, Review on quality control and relevant hybrid technology in additive manufacturing of metallic materials, Mater. Rev. **38**(5A), 1–10 (2024).