Current Status of Research on Multi-axis FDM Additive Manufacturing for Mechanical Property Enhancement

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Abstract. Recent advancements in multi-axis printing and composite materials have shown promise in addressing these issues, but systematic studies on the synergistic effects of material enhancement and chunking optimization remain scarce. Therefore, this research aims to bridge this gap by integrating high-performance composites with advanced multi-axis chunking strategies to achieve superior mechanical performance and functional versatility. This paper investigates how to improve the mechanical properties by both material preference and chunking optimization in multi-axis FDM technology. In terms of materials, high-performance composites such as nano-reinforced plastics and bio-based materials are used, combined with a melt blending process to enhance strength. In the printing technology, the multi-axis chunking strategy dynamically adjusts the deposition direction, optimizes the path planning and support structure, enhances the interlayer bonding and reduces the anisotropy. Process parameter adjustment in the fiber orientation of the enhancement of the planning path, multi-material interface, combined with optimization to break through the single material performance limitations. Future research directions include intelligent material design, multi-material synergistic printing and sustainable development paths to promote the application of high-performance additive manufacturing in aerospace, medical and other fields.

Keywords: 3d printing, Multiple axis, Additive manufacturing

1 Introduction

Fused deposition molding (FDM) technology has become one of the mainstream processes in the field of additive manufacturing due to its low cost, operational flexibility, and wide material applicability, and is widely used in aerospace, medical implants, and the manufacture of complex structural parts. However, traditional FDM technology is limited by the uniaxial printing path and homogeneous material properties, and the parts are often faced with problems such as significant anisotropy and weak interlayer bonding, which makes it difficult to meet the mechanical properties of high-load scenarios.

To solve these problems, research in recent years has focused on two core directions: one is to optimize the intrinsic properties of materials through the development of high-

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performance composites; the other is to improve the structural design based on the chunking strategy of multi-axis printing and path planning technology, which synergistically promote the development of FDM technology towards functionalization and high performance.

In terms of material preference, early FDM mainly relied on single polymers such as ABS and PLA, whose tensile strengths were generally below 60 MPa, making it difficult to adapt to engineering needs. After 2010, nano-reinforced composites became a research hotspot, for example, Yufeng Guo developed PLA/nano-TiO_2 composites by the melt blending method, and the tensile strength was increased to 82 MPa. PEBA elastomers from Scultpeo extend the boundaries of material toughness through thermoplastic modification. In addition, bio-based materials (e.g., polycaprolactone) and green photosensitive resins are attracting attention because of their environmentally friendly properties, but their mechanical properties rely on multilayer stacking or fiber reinforcement to achieve breakthroughs. However, material compositing also faces challenges such as escalating costs and narrow process windows, such as carbon fiber reinforced geopolymers that require precise regulation of fiber doping to balance printability and strength.

At the process optimization level, multi-axis printing technology can significantly improve part anisotropy by dynamically adjusting the deposition direction and chunking strategyFor example, the model segmentation algorithm proposed by Yisong Gao achieves multi-directional path planning for complex parts, reduces the support structure and improves the strength of inter-layer bonding; and the STL layering algorithm improved by Hongshou Chen optimizes the printing efficiency through parameterized allocation. However, existing chunking methods still rely on hardware multi-degree-of-freedom collaboration and have high algorithmic complexity, which restricts their popularity in industrial scenarios.

In this paper, we systematically review the research progress of multi-axis FDM technology for mechanical property enhancement. On the one hand, we analyze the role of material selection on mechanical property enhancement, covering different types of materials such as high-performance engineering plastics, nano-composites, biobased and green materials, etc. On the other hand, we explore the regulation of mechanical properties by chunking optimization technology, including core algorithms of multi-axis chunking strategy, path planning and optimization of the support structure, etc. We will also review the progress of multi-axis FDM technology for mechanical property enhancement. On the other hand, we explore the regulation of mechanical properties by block optimization technology, including the core algorithm of multi-axis block strategy, path planning and support structure optimization. The research results show that the mechanical properties of FDM parts can be effectively enhanced through the synergistic effect of material selection and chunking optimization. For example, optimized materials and processes can increase the tensile strength of manufactured parts by 30-50% and significantly reduce anisotropic defects. At the same time, this paper also discusses future trends such as intelligent material design, multi-material collaborative printing and sustainable development paths to provide theoretical references and technical paths for high-performance additive manufacturing.

2 Research on the improvement of mechanical properties by material optimization

2.1 The compatibility of Ultem 9085 with the aerospace field

Ultem 9085 is a high-performance thermoplastic material. It has demonstrated remarkable adaptability in the aerospace field. Ultem 9085 has four major characteristics: high-temperature resistance, processing flexibility, lightweight, and safety and reliability, which have become the core advantages for adapting to aerospace. Xu Chang and his teammates set three variables, namely width, Angle, and number of turns, to conduct the mechanical property experiments of Ultem 9085. When the values were set at 0.016 min, 45/90° and 2 turns respectively, the mechanical properties of Ultem 9085 performed better than before [1]. The material in this state is very suitable for 3D printing applications. What's more, aircraft interiors and components require durability and comply with strict safety standards [2]. The Ultem9085 has a long-term operating temperature of -40°C to 170°C, which can last for thousands of hours without degradation of performance. Nowadays, the sensor housing near the automotive turbocharger still needs to withstand the high temperature of the engine compartment. After replacing the metal with 3D-printed Ultem 9085, the weight is reduced by 50% while no additional heat insulation coating is required. After long-term exposure to high temperatures, the material not only becomes brittle or degrades, but also maintains its rigidity and strength at high temperatures, enhancing the mechanical properties under high-temperature conditions. In addition, Ultem9085 also features high rigidity. It is equipped with the special chemical bonds in its molecular structure form a tight arrangement of molecular chains, endowing the material with an extremely high elastic modulus.

2.2 Toughness Enhancement Mechanism of Thermoplastic Elastomers

Plastic elastomer (TPE) is a kind of polymer material, which possesses the properties of both plastics and rubber. TPE can be plasticized and formed at high temperatures and retain its elasticity after cooling. Common Tpes include TPU, TPE-S, TPV, etc., and PEBA is also one of them, composed of hard segment polyamide and soft segment polyether, formed through block copolymerization. It is well known that the GMA group has a good effectiveness of PEBA as a toughening agent for PMMA. However, due to the requirement of using a large amount of PEBA, the challenges related to refractive index mismatch and compatibility have not yet been explored. However, if PEBA can be dispersed in PMMA in the form of nano-F fibrils and E-GMA can be selectively located in the interface, it is possible to overcome these challenges. In current research, there are already simple methods to utilize PEBA to enhance tensile toughness and impact strength without affecting the inherent tensile strength, stiffness, transparency, glass transition temperature and scratch resistance of PMMA, significantly improving the mechanical properties of the material [3]. PEBA fills the performance gap between traditional rubber and rigid plastic through its dual characteristics of "elastomer + engineering plastic". In the field of sports, many well-known brands use PEBA as the midsole of sneakers to enhance the storage of elastic potential energy and achieve high-energy rebound. Many snowboards also use PEBA as the elastic component of the snowboard holder because of its lightweight nature which bears extremely strong mechanical performance and load-bearing capacity, that it ideal for use in many extreme sports and racing car fluid mechanics structures.

2.3 Modification strategies of nanocomposites

Dispersion and strengthening effects of nanoparticles (TiO_2, Carbon fibers). Nanoparticles can enhance the mechanical properties of materials in 3d printing. TiO_2 nanoparticles are prone to agglomeration due to their high specific surface area, and their uniformity in polymer matrices (such as PLA, nylon) needs to be improved through surface modification (such as silane coupling agents) or ultrasonic treatment. For carbon fibers, the shear mixing process needs to be optimized to avoid fiber breakage and interface weakening in order to maintain the stability of their mechanical properties. Well-dispersed nanoparticles significantly enhance the mechanical properties of materials through interfacial reinforcement mechanisms: TiO_2 can increase the hardness and wear resistance of composite materials, while endowing them with antibacterial or photocatalytic functions; Carbon fiber enhances tensile strength and stiffness through the load transfer effect and improves thermal stability. In addition, nanoparticles can regulate the rheological properties of 3D printed melts and affect the interlayer bonding quality. In fields such as aerospace and biomedicine, the customized performance of such nanocomposites provides a new approach for the manufacturing of lightweight and multi-functional components. The moderate dispersion of TiO2 makes the mechanical and thermal properties as well as the wear resistance of epoxy resin excellent. The organic combination of TiO2 and carbon fiber realizes the strengthening and improvement of the mechanical properties of the material [4].

The influence of melt blending process on interlayer bonding force. Melt blending significantly affects the interlayer bonding force of 3D printing by high-temperature mixing reinforcing fillers (such as carbon fibers, nanoparticles) with matrix materials (such as PLA, ABS). The addition of fillers may change the rheological properties of the melt, however the moderate addition of surface-modified fillers (such as glass fibers treated with silane coupling agents) can enhance interfacial compatibility, strengthen bonding through mechanical interlocking or chemical bonds, and thereby improve the mechanical properties of the material. Thus, the structural stability and mechanical properties of the material have been significantly improved after the fusion of PLA and carbon fiber.

2.4 Innovative exploration of bio-based and green materials

Medical applications and strength optimization of polycaprolactone (PCL). Polycaprolactone (PCL), as a biodegradable polyester, is widely used in bone repair scaffolds, drug sustained-release carriers and soft tissue engineering (such as cartilage repair) due to its excellent biocompatibility, controllable degradability (degradation cycle 2-3 years) and flexibility. However, its mechanical strength is relatively low and requires blending modification and structural design optimization. Weng Fangqing and her teamates' research is to enhance the strength of PCL by combining crab shells with PCL, thereby improving its mechanical properties. According to the data of the two groups of experimental samples studied, the crab shell powder particles are irregularly distributed in the PCL matrix. In the data,without the addition of the compatibilizer PCLPU, there are obvious numerous grooves and cracks at the junction of crab shell powder and PCL, with a clear boundary between the two phases. This is because the main component of crab shells, calcium carbonate, is hydrophilic, while PCL is hydrophobic. The interaction force between them is weak and the interfacial compatibility is poor. In the sample PCP15 obtained after adding the compatibilizer, the binding site of crab shell powder and PCL can be clearly observed,and the cracks and gullies have nearly disappeared, thus forming a relatively complete compatible system. By comparing the data of PC and PCP15, it can be known that with the addition of the compatibilizer PCLPU, the interaction force and compatibility of the crab shell powder-PCL composite material can be significantly improved and optimized, greatly enhancing the mechanical properties [5-7].

The mechanical properties of recyclable photosensitive resin are balanced. Recyclable photosensitive resins in 3D printing balance mechanical properties and recyclability. Their balancing strategy focuses on the design of dynamic chemical bonds and the regulation of reinforcing phases. By introducing dynamic covalent bonds (such as disulfide bonds, imine bonds) or non-covalent interactions (hydrogen bonds, coordination bonds), the resin forms a reversible cross-linked network after light curing, maintaining a high degree of cross-linking. It can also be depolymerized under specific conditions (such as heat and pH) to achieve recovery. Meanwhile, adding nano-fillers (such as cellulose nanocrystals and silica) can enhance the modulus and creep resistance, and reduce structural damage during the recycling process. Bio-based polymer materials take the abundant and recyclable resources from nature as synthetic raw materials, and have advantages such as low cost, energy conservation and emission reduction, and promoting the carbon cycle that traditional petroleum-based polymer materials do not possess [8]. Recyclable photosensitive resins can be made from bio-based polymer materials, which are cost-effective and energy-saving without affecting the mechanical properties of the materials. Using polycaprolactone (PCL) derived from biological resources as the monomer, polycaprolactone diol was prepared by ring-opening polymerization. Using it as the raw material, UV-curable polyurethane acrylate with shape memory performance was synthesized. Zhu G et al. [9] synthesized bio-based UV-curable oligomers (GMAESO) using gallic acid, methacrylic anhydride (MAAH), and epoxy-modified soybean oil (ESO) as raw materials, and prepared a series of UV-curable materials by mixing them with hydroxyethyl methacrylate (HEMA) as a diluent [10]. Optimizing the balanced toughness and rigidity of the resin monomer structure, the correlation network has greatly improved the load-bearing capacity and mechanical performances.

3 Mechanical property regulation of block optimization technology

3.1 Core algorithm of multi-axis blocking strategy

Volume decomposition and orientation adaptive deposition are efficient 3D printing strategies for complex structures. Volume decomposition divides the overall model into multiple sub-volume units (such as based on stress distribution or geometric features), and shortens the printing time through parallel path planning (with an efficiency improvement of 20%-40%). Directional adaptive deposition dynamically adjusts the deposition direction according to the local geometric curvature and mechanical bearing requirements. By adopting topological optimization and path coupling algorithms, the material is deposited along the principal stress direction, significantly enhancing the interlaminar bonding strength (increasing the tensile strength by 30%-50%) and reducing anisotropic defects. The advantage of top-up optimization lies in that, under the same quality, through the improvement of code and algorithm, adaptive deposition and volume decomposition exhibit stronger mechanical properties and can withstand more forces.

3.2 Path planning and support structure optimization

Improvement of the stl hierarchical algorithm. Aiming at the problems of the traditional 3D printing adaptive layering algorithm, such as complex calculation process, inability to eliminate the influence of the step effect, inability to retain the model characteristics, and easy loss of characteristics[11, 12], the STL model triangular surface normal vector adaptive layering algorithm has more refined layering in the areas with obvious contour changes in the STL model [13]. Han Xingguo et al. proposed a cross-sectional contour generation algorithm for parts with complex curved surfaces. The simulation test results show that the metal blades produced by the model processed according to this algorithm have higher accuracy [14]. The adaptive layering of the STL model is realized by using the embedded function speed in the matlab software [15]. The adaptive layering algorithm that retains the feature details of the STL model can significantly improve the mechanical properties of the printed parts through adaptive layer thickness adjustment, path optimization and parametric design of the filling structure: the interlayer bonding strength is greatly increased, the tensile/compressive strength is optimized, and the anisotropic defects are reduced. The algorithm combines real-time thermodynamic simulation to dynamically adjust the printing speed and temperature, further reducing porosity and enhancing fatigue life. In the medical industry, minimally invasive surgery customizes the direction of 3D printed fiber deposition based on the microstructure of patients' bones, simulating the anisotropy of natural bones, thereby enhancing mechanical properties in all directions.

Design under multi-degree-of-freedom collaboration. Fused Deposition Modeling (FDM) is a free-form process that allows for expansion to more than three axes by adjusting kinematics, print heads, and trajectory planning [16,17]. The main advantage of multi-directional slicing is that it reduces supporting materials by tilting the building platform to avoid overhanging structures [18]. The seven-axis FDM machine tool developed by the University of Stuttgart has a very good directional planning path, achieving online tensile strength while ensuring that the parts are unsupported. The method of simultaneously using the inclined and rotating tables can be transferred to the laser metal deposition [19]. Another research work provides a three-dimensional path generation for the strength optimization of the bending layer from the traditional three-axis system to the FDM process [20]. Under the continuous multi-axis printing configuration, there is also a lattice-filled structure generation method for automatically generating filled structures and the accompanying multi-axis printing paths of any free-shaped parts. This method can print the boundary surfaces of filled structures and parts without support, and a series of IGDS-GDFs will naturally decompose the entire structure [21]. The directional filling strategy (along the path of the principal stress distribution) enhances the density of the bearing area, and the tensile strength increases by 20%-40%. Adaptive lattice design (porosity gradientization) reduces weight and maintains compressive stiffness. This method is needed in the design of satellite supports in the aerospace field. It synchronously controls the layer thickness and thermal field, reduces interlayer defects, supports precision instruments with the minimum weight, and simultaneously meets the requirements of high strength and fatigue resistance. It achieves the synergy of lightweight and high strength and toughness, significantly improving mechanical properties.

4 Improvement of process parameters for multi-axis FDM

4.1 Enhancement of fiber orientation

Continuous carbon fiber composites have the characteristics of continuity and directionality. To improve the printing quality and mechanical properties of 3D printed parts made of carbon fiber composites, Qiu Wen et al. developed a 3D printing path planning method for continuous carbon fiber composites based on principal stress trajectory lines [22]. By improving the traditional path planning algorithm, they elevated the printing quality of parts to enhance their mechanical properties. The traditional path planning method is based on the shape and contour of the parts for path planning, which fails to fully utilize the anisotropic characteristics of carbon fiber composite materials. Therefore, it is necessary to combine the actual operating conditions of the parts with the printed paths of carbon fiber composite materials, so as to give full play to the performance advantages of the materials. Based on these problems, the 3D printing path planning method of continuous carbon fiber (referred to as carbon fiber) composites based on the principal stress trajectory line is adopted. Finite element analysis is conducted according to the actual working conditions of the parts to obtain the principal stress trajectory line of the parts. The printing parameters of 3D printing of carbon fiber composites are constrained by the principal stress trajectory line to generate the continuous carbon fiber printing path. To achieve the transformation of the carbon fiber printing path from the external force to the stress distribution of the part during the usage process, improve the accuracy of the combination of the carbon fiber path and the stress distribution, and convert the dispersed stress field distribution into a concentrated carbon fiber printing path with certain regularity, so as to improve the mechanical properties of the part [23]. In the automotive field, racing car steering wheels are usually made of aluminium. However, traditional aluminium alloy steering wheels are heavy, and isotropic materials cannot specifically optimize mechanical properties. The racing wheel made of the composite material reinforced with carbon fiber orientation retains the excellent mechanical properties of anisotropy while reducing the weight of the racing wheel itself. The finite element analysis (FEA) determines the direction of the principal stress of the steering wheel during sharp turns and collisions, helping to save materials while ensuring the strength and stability of the mechanical properties of the principal stress part.

4.2 Mechanical optimization of multi-material interface bonding

YIN J et al. investigated the influence of the printing platform temperature on the 3D printing performance of thermoplastic polyurethane (TPU)/acrylonitrile butadiene-styrene copolymer (ABS) composites [24]. The experiments found that as the printing platform temperature increased from 30°C to 68°C, the interfacial bonding strength of the TPU/ABS composite material significantly increased by 0.8MPa. KISHOREV et al. increased the surface temperature of the printed layer by using infrared preheating technology to enhance the interlayer bonding strength of the printed parts [25]. The results showed that: When the surface temperature of the substrate is increased from below the glass transition temperature to close to or above it, the interlayer bonding strength of the 3D printed part is significantly increased [26]. Through the design of gradient transition structures (such as microscopic interlocking and chemical bonding) and interface treatment processes (plasma activation and blending modification), the bonding strength of the PLA/TPU rigid-flexible composite interface has been increased by 30%-50%, and the impact resistance and fatigue life have been significantly optimized. Rigid PLA and flexible TPU work in synergy to achieve a gradient distribution of tensile modulus, reduce stress concentration, and are suitable for components such as flexible electronic packaging and bionic joints that require rigid-flexible coupling functions, breaking through the limitations of the mechanical properties of a single material.

5 Current challenges and future trends

5.1 Intelligent development direction

Currently, machine learning (ML) in 3D printing materials and processes faces challenges such as data fragmentation, weak physical interpretability, and lack of cross-scale modeling, resulting in limited process prediction generalizability. In the future, it is necessary to build a multi-module fusion platform, develop multivariate hybrid models, explore the characteristics of things through machine learning, predict the performance, and derive the experimental data after a large number of experiments, and screen out the features that have the greatest impact on the experimental results, so as to greatly reduce the entire experimental duration [27]. Combining active learning and digital twins to achieve closed-loop optimization of materials-processes-performance, promoting high-throughput autonomous experimental systems (e.g., robotic printing-characterization integration), accelerating the discovery of new alloys/composites, and shortening the R&D cycle time by more than 50%.

Currently 3D printing digital twins rely on offline modeling and local sensing (temperature, deformation), but the lack of precision in real-time coupling of multi-physics fields and the lag in cross-scale data fusion result in delayed response to defect regulation. Future research could further explore the effectiveness of these two technologies in different industrial scenarios and how to further improve their overall economy and reliability for wider application promotion in industrial production [28]. In the future, it is necessary to integrate high frame rate vision-multispectral sensing, edge computing and physical augmentation AI to build a millisecond-level twin feedback system to realize real-time closed-loop control of molten pool morphology and residual stress (with accuracy upgraded to 95%+). Combined with quantum computing to optimize the process chain, it promotes in-situ manufacturing in space, zero-defect production of ultra-large component printing, and revolutionizes the paradigm of high-end equipment manufacturing.

5.2 Sustainable development pathways: biodegradable materials and the circular economy

3D printing of biodegradable materials is a development path that tends to promote the greening of the industry, but some innovative technologies still have the challenge of cost-performance imbalance. In the future, breakthroughs are needed in the design of high-performance bio-based materials, closed-loop recycling systems and distributed recycling and printing networks, combined with AI to optimize material-process matching, to promote zero-waste in the whole life cycle of medical implants, degradable packaging and so on. With Policy-Technology Synergy, 3D Printing May Become the Core Carrier of the Circular Economy, Realizing the Goal of Cutting Carbon Footprint by More Than 50%.

6 Conclusion

This paper provides a systematic review of multi-axis FDM additive manufacturing technologies for mechanical property enhancement, and reveals the core progress and technology paths of the current research from the two dimensions of material preference and chunking optimization. In the field of materials, high-performance engineering plastics have achieved a balance between high-temperature resistance and high strength through the optimization of process parameters; nanocomposites have enhanced tensile strength and improved interlayer bonding with the help of interfacial modification and melt blending process; and biobased materials have broken through the bottleneck of mechanical properties while maintaining biocompatibility through the modification of capacitance agents and structural design. At the process optimization level, the multi-axis chunking strategy improves the strength of interlayer bonding through volume decomposition and directional adaptive deposition; the improvement of the path planning algorithm significantly improves the printing accuracy and load-bearing capacity, and the multi-material interface bonding technology nearly doubles the interface strength through temperature regulation and gradient structure design.

The study shows that the synergy between material property optimization and multi-axis printing technology is the key to break through the mechanical property limitations of traditional FDM, which provides a feasible solution for aerospace lightweight components, personalized manufacturing of medical implants, and so on. The core significance lies in the construction of an integrated optimization system of “material-structure-performance” through interdisciplinary integration, which provides theoretical support for solving engineering needs under complex loading scenarios.

Looking forward to future technological advancement, multi-axis FDM technology needs to deepen breakthroughs in the following directions: first, the direction of intelligence, integrating machine learning and digital twins to realize closed-loop optimization of material-process-performance, shortening the R&D cycle and improving the reliability of production; second, the direction of multi-material synergistic printing, developing composite structures with gradient properties to meet the multifunctional needs in extreme environments; third, the path of sustainable development, promoting the large-scale application of bio-based materials and closed-loop recycling technology. The third is the sustainable development path, promoting the large-scale application of bio-based materials and closed-loop recycling technology. With the synergistic evolution of technology and industrial ecology, multi-axis FDM additive manufacturing is expected to become the core technology in high-end equipment manufacturing, biomedical and other fields, leading the paradigm change of personalized and green production of “manufacturing as design”.

Authors Contribution. All the authors contributed equally and their names were listed in alphabetical order.

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