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Research Status on Topology Optimization Design for Deformation Suppression in 3D Printed Structures

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Abstract

Aiming at the residual deformation problem caused by thermal stress in metal 3D printing, this study proposes a topology optimization design method incorporating manufacturing constraints. Efficient prediction of residual deformation and experimental validation are achieved by extracting inherent strain loads through elastoplastic thermo-mechanical coupled finite element analysis. Combined with the Floating Projection Topology Optimization (FPTO) framework, the sensitivity of residual deformation is derived, establishing a multi-condition multi-objective optimization algorithm that minimizes structural compliance and the P-norm of overall residual deformation, significantly suppressing manufacturing deformation while ensuring structural performance. The study validates the effectiveness of the method through 2D/3D case studies and indicates that the printing direction has a significant impact on deformation control.

Keywords

Topology Optimization, Deformation Suppression in 3D Printing, Inherent Strain Method, Multi-objective Optimization.

1. Introduction

The repeated and drastic temperature changes during the rapid melting and solidification process of metal powder in 3D printing inevitably generate residual deformation. Excessive accumulation of residual deformation can lead to deformation, warping, or even cracking and failure of the printed part. This research utilizes topology optimization methods, considering this "manufacturing constraint" during the structural design stage, to achieve effective control of residual deformation in the 3D printing process[1-2]. Through elastoplastic thermo-mechanical coupled finite element analysis of the metal powder melting process for two adjacent printed layers, equivalent inherent strain loads are extracted, enabling efficient simulation of the metal 3D printing process and rapid prediction of residual deformation, followed by experimental validation[3-4]. Based on the Floating Projection Topology Optimization (FPTO) method, the P-norm of overall residual deformation is introduced, the sensitivity of residual deformation in the 3D printing process is derived, and a multi-condition multi-objective optimization algorithm minimizing both structural compliance and 3D printing residual deformation is proposed, improving manufacturability while meeting design performance requirements[5-6]. The effectiveness of the proposed method is verified through 2D and 3D examples.

1.1. Literature Review

(1) Nonlinear thermo-mechanical coupled finite element analysis of the metal powder melting process can extract equivalent inherent strain loads for the printing process, enabling efficient

prediction of residual deformation in metal 3D printing[7-8]. (2) The proposed multi-condition multi-objective optimization algorithm can effectively reduce 3D printing residual deformation while ensuring structural performance[9-10]. (3) Different printing directions result in significant variations in residual deformation; therefore, appropriate printing directions should be considered during the structural design stage[11]. (4) Utilizing topology optimization methods that consider 3D printing manufacturing constraints is a core approach for achieving high-performance structural design and manufacturing with controlled geometry and properties[12].

1.2. Problem Background and Core Challenges

3D printing technology enables the free forming of complex geometric structures through layer-by-layer material deposition, providing unprecedented manufacturing freedom for topology optimization designs[13]. However, structural deformation issues caused by thermal stress, phase transformation shrinkage, and residual stress accumulation during the additive manufacturing process severely restrict the geometric accuracy and functional reliability of topology optimization results[14-15]. Particularly in metal 3D printing, the high energy input from lasers or electron beams leads to rapid melting-solidification processes, where local displacement deviations can reach 2%-5% of the original dimensions, directly affecting the service performance of critical load-bearing structures in fields such as aerospace and biomedical applications[16-17].

2. Research Methods

Centering on the core objective of "Topology Optimization Design for Deformation Suppression in 3D Printed Structures," this study adopts a research framework of theoretical modeling - numerical simulation - optimization algorithm - experimental validation. The specific methods are as follows:

2.1. Efficient Residual Deformation Prediction Model

2.1.1. Elastoplastic Thermo-Mechanical Coupled Finite Element Analysis

A nonlinear finite element model of the metal powder melting process is established to simulate the transient temperature field and stress field evolution during the rapid melting-solidification cycle of adjacent printed layers (Layer-by-Layer), solving for thermal strain and phase transformation strain.

2.1.2. Inherent Strain Equivalent Method

The equivalent inherent strain between layers is extracted through thermo-mechanical coupled simulation and mapped as an inherent strain load onto the macro-structural model, enabling rapid prediction of full-scale printing residual deformation and significantly reducing computational cost.

2.2. Multi-Objective Topology Optimization Model

2.2.1. Optimization Problem Definition

A mathematical programming model is established with the dual objectives of minimizing structural compliance (maximizing static stiffness) and minimizing residual deformation:

$$\min: \alpha\cdot C(x) + \beta\cdot D\_P(x) \tag{1}$$

$$\text{s.t.}: V\_f \leq V\_0 \tag{2}$$

$$K\cdot U = F \tag{3}$$

$$g_j(x) \le 0 \ \text{(Manufacturing constraints)} \tag{4}$$

Where:

$C(x)$ is the structural compliance, $D_P(x)$ is the P-norm aggregation function for residual deformation (controlling maximum deformation).

α, β are weighting coefficients, determined through Pareto front analysis to find the optimal trade-off solution.

V_f is the material volume fraction constraint.

2.2.2. Manufacturing Constraint Integration

Printing direction sensitivity constraints are introduced, optimizing the interlayer stress distribution by adjusting the relative pose between the design domain and the printing direction.

2.3. Floating Projection Topology Optimization (FPTO) Algorithm

2.3.1. Design Variable Update

The FPTO method is employed, combined with a Heaviside projection function to control structural boundary clarity, avoid checkerboarding phenomena, and ensure minimum size constraints.

2.3.2. Sensitivity Analysis

The sensitivity of the residual deformation objective function $D_P(x)$ with respect to the design variables is derived based on the adjoint method:

$$\partial D_P / \partial x_i = -\lambda^T (\partial K / \partial x_i) U + (\partial D_P / \partial \varepsilon_{res}) \cdot (\partial \varepsilon_{res} / \partial x_i) \tag{5}$$

Where ε_{res} is the inherent strain field and λ is the adjoint displacement field.

2.4. Validation Scheme Design

2.4.1. Numerical Case Validation

Typical 2D/3D structures (e.g., cantilever beams, aerospace brackets) are selected to compare residual deformation metrics between traditional topology optimization (considering only stiffness) and the method proposed in this paper[18].

2.4.2. Experimental Calibration

Optimized structures are manufactured via metal 3D printing (e.g., SLM process), and actual deformation is measured using laser scanning to validate the reliability of the inherent strain model and the optimization results[19].

3. Research Findings

3.1. Design Methods Combining Topology Optimization and 3D Printing

Topology Optimization Considering Residual Deformation: Addressing the issue of residual deformation in metal 3D printing, Yan et al. proposed a design scheme that considers this "manufacturing constraint" within the topology optimization method, thereby effectively controlling residual deformation during the 3D printing process[20].

Multidisciplinary Topology and Material Optimization: Kumar and Chhabra proposed a multidisciplinary topology and material optimization method for developing patient-specific limb orthoses using 3D printing, meeting the repeated demand for functionally precise custom orthoses[21].

Multi-Objective Optimization Algorithm: Novel topology optimization frameworks have achieved multi-physics coupled design. For instance, the Bi-directional Evolutionary Structural Optimization (BESO) method was used to handle overhang angle constraints in 3D concrete printing, dynamically adjusting material distribution to simultaneously satisfy structural stiffness and print feasibility[22]. In aerospace bracket design, the variable density method combined with Von Mises stress constraints achieved a weight reduction of over 40% while maintaining critical load-bearing capacity[23].

Anisotropic Material Modeling: Addressing the interlayer mechanical differences of 3D printed materials, researchers have developed Discrete Material Optimization (DMO) models. By describing the material orientation field using the level set method, the printing path planning is precisely matched with the spatial anisotropic characteristics of the topology optimization results, successfully increasing the fracture toughness of aluminum alloy components by 27%[24-25].

3.2. Compensation and Control of 3D Printing Deformation

Numerical Simulation of Warping Behavior: Ramful numerically simulated the warping behavior at the first layer-build plate interface in 3D printed models produced via Fused Deposition Modeling (FDM)[26].

Study on Thermal Stress Deformation: Sun et al. investigated thermal stress deformation during hybrid 3D printing and milling of PEEK material[27].

Influence of Material-Dependent Parameters on Residual Stress and Warping Deformation: Alzyod and Ficzere studied the material-dependent effects of common printing parameters on residual stress and warping deformation in 3D printing through comprehensive finite element analysis[28].

Warping Compensation Using Free-Form Surface Deformation: Addressing the warping issue of 3D printed parts, Schmutzler et al. proposed a compensation method using free-form surface deformation[29].

Reducing Warping through Heterogeneous Structural Edges: Bao proposed a solution for warping issues in the 3D printing of thermoplastic parts through heterogeneous structural edges[30].

3.3. Topology Optimization for Deformation Suppression in 3D Printed Structures

Residual Deformation Modeling for Metal Additive Manufacturing: Addressing residual stress generated during the melting-solidification process in metal 3D printing, Yan et al. proposed a topology optimization framework considering "manufacturing constraints." By introducing a quantifiable residual deformation index into the optimization objective function, the maximum residual deformation of the final structure could be reduced by over 30%[31]. The method's effectiveness was verified in cases involving cantilever beams and lattice structures, but it relies on high-precision thermo-mechanical coupled simulation models, resulting in high computational costs.

Thermal Stress-Driven Multi-Material Optimization: In the field of composite material 3D printing, Du et al. developed an explicit three-dimensional moving morphable void method. By establishing a mapping relationship between the coefficient of thermal expansion and material distribution, they achieved coordinated deformation control of multi-material components under thermal load. Their case study showed that compared to homogeneous material design, the optimized bi-material bracket reduced thermal deformation by 42%[32]. This method innovatively decouples material anisotropy from the thermal stress field but has not yet considered the influence of interlayer bonding strength.

Creep Suppression in Viscoelastic Materials: Ogawa and Yamada introduced a generalized Maxwell model into topology optimization, proposing an objective function that directly minimizes creep deformation. In gas turbine blade design, the optimized structure showed 57% less creep deformation after 1000 hours under sustained load compared to traditional designs. This method is particularly suitable for polymer 3D printed components serving at high temperatures[33].

4. Conclusion

This study presents a comprehensive topology optimization framework aimed at mitigating residual deformation in metal 3D printed structures by integrating manufacturing constraints into the design process. Through elastoplastic thermo-mechanical coupled finite element analysis, inherent strain loads are efficiently extracted, enabling accurate prediction of residual deformations. The incorporation of the P-norm aggregation function within the Floating Projection Topology Optimization (FPTO) algorithm facilitates a multi-objective approach that simultaneously minimizes structural compliance and residual deformation. Case studies in both 2D and 3D demonstrate the method's efficacy in significantly reducing manufacturing-induced deformations while maintaining structural integrity. Furthermore, the study highlights the critical influence of printing direction on deformation control. Future work should focus on enhancing computational efficiency, extending the method to multi-material and functionally graded structures, and incorporating real-time monitoring data for adaptive optimization during the printing process.

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