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State-of-the-Art in Topology Optimization for Additive Manufacturing – Focus on Precision

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Abstract

The past decade has seen rapid advances in both Additive Manufacturing (AM) technologies and computational design methods for AM, most notably Topology Optimization (TO). The design freedom offered by AM and the systematic form-follows-function process of TO constitute a synergetic combination that enables generation of designs with unprecedented performance. In this contribution, next to a general introduction to TO-for-AM, recent developments in this field are considered, with special attention to various aspects of precision. This includes geometric precision in terms of design resolution and AM-induced distortion reduction, precision regarding material properties of printed parts, feasibility of surface inspection/measurement, and AM-enabled precision positioning applications.

Keywords: Additive Manufacturing, Computational Design, Topology Optimization, Distortion, Overheating, Material microstructure, Inspection

1. Introduction

Advances in additive manufacturing (AM), and in particular metal additive manufacturing, have enabled a steep increase in the use of printed parts in a wide range of industrial applications over the past decade [1,2]. Next to improved part performance through the design freedom offered by AM, and cost savings and reliability improvements through consolidation of assemblies, an upcoming driver for this development is also the potential advantages AM offers in terms of sustainability [3].

To realize and extend these AM benefits, next to capable AM technologies specific design procedures for AM are essential. The vast design space offered by AM challenges the imagination of human designers. For this reason, the use of computational design methods has been linked to Design-for-AM approaches from an early stage. Specifically Topology Optimization (TO) is a popular approach to generate designs for AM, as it offers a similarly large design freedom and does not require designers to propose an initial design concept. For a general discussion of TO techniques, the reader is referred to e.g. Sigmund and Maute [4].

The past years have seen intensive research efforts to incorporate relevant AM aspects into TO formulations. This contribution firstly aims to give a high-level overview of these developments, pointing the reader to more in-depth reviews than the present format allows for. Secondly, the focus is placed on recent TO-for-AM developments specifically connected to advancing particular aspects of precision. Four aspects are considered: 1) geometrical precision in terms of design resolution and AM distortion reduction, 2) developments aimed at obtaining precise material properties under the influence of the AM process, 3) guaranteeing the necessary access for inspection of the printed part, and 4) precision positioning application potential that can be unlocked by TO and AM. To not overextend this paper, the aim is not to cite and discuss each and every study within the scope, but to point out typical examples of current developments. Illustrations were taken from the author's own work for ease of availability.

2. Topology optimization for AM: General overview

Of the many TO-for-AM approaches that have been proposed in the literature, a useful categorization is to distinguish those based on enforcement of certain geometric design rules, and approaches where a physical manufacturing process simulation is integrated in the TO process. The latter can control more detailed physical effects, but their computational cost is also significantly higher than the former methods due to the included process simulation. This section presents a high-level overview of developments in these categories.

2.1. Design rule-based approaches

For most AM processes, geometric design rules have been determined by printing of test specimens and process characterization. These rules prescribe e.g. minimal wall thicknesses, hole diameters, and critical overhang angles of unsupported downfacing surfaces. These rules aim to serve as safe bounds, which when respected should guarantee the quality of the printed part.

Minimum feature size control has been part of TO methods well before the rise of AM. For this reason, the main focus in TO research for AM has initially been on formulation of effective methods for overhang angle control. Ideally these should add little computational overhead and should not negatively impact the convergence behaviour of the TO process. Various successful methods have been developed in the past years, and a representative example of self-supporting structures with controlled overhang angles generated by TO is shown in Fig. 1. A detailed discussion of the numerous proposed methods is outside the scope of this paper, and can be found in dedicated review papers [5,6]. What can be concluded is that overhang angle control meanwhile has become a mature part of the TO toolset. Commercial software packages have also integrated these methods in their TO modules, allowing designers to generate TO designs compatible with geometric AM design rules.

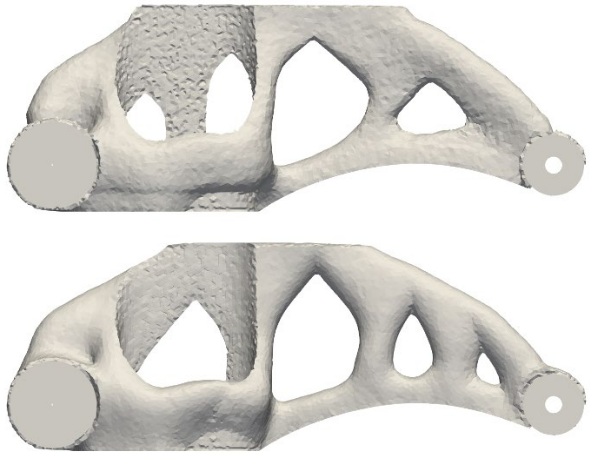

Figure 1. Brake lever design generated by TO with AM overhang control for two different critical overhang angles [7]. Printing direction is upward.

2.2. Process simulation-based approaches

Various AM process-induced effects on part precision or material quality cannot be fully captured by design rules alone. This includes part distortion, residual stress, support failure, local overheating and e.g. process-induced material anisotropy. After the incorporation of design rules in AM, focus of TO-for-AM methods has shifted to addressing these aspects. An overview is provided the review paper by Bayat et al. [6], and an example regarding control of overheating is shown in Fig. 2.

Instead of relying on purely geometric criteria, these approaches require evaluation of physical quantities such as temperature, stress and distortion that arise due to the AM process. AM process simulations can provide this information, however for use in the iterative, gradient-based TO process it is required that the employed models are both computationally efficient and differentiable [6]. At the same time, the AM simulations must provide sufficiently accurate predictions to guide the TO process to correct design solutions. These requirements have not traditionally been the focus of the AM simulation community, but are essential for simulation-based computational design. The question of finding adequate trade-offs between efficiency and accuracy has motivated, and will continue to drive, research into simplified yet acceptably accurate AM process models suited for design optimization [e.g. 8,9].

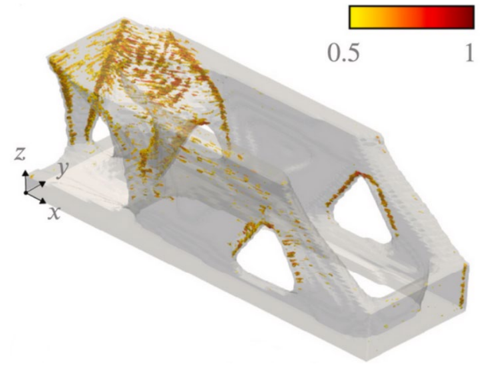

Figure 2. Bracket geometry generated through TO with overheating constraints, with overlaid normalized temperature data obtained during a powder bed fusion metal printing process [8]. The hotspots remain well below the critical value of 1.

3. Topology optimization for AM: Precision aspects

Following the preceding general overview, this section presents specific recent developments within the TO-for-AM research field, focused on four different aspects of precision.

3.1. Geometric precision

Accurate part geometries ensure that the intended performance is reached. In the context of TO for AM, this aspect is recognized at different levels: design, production and post-processing.

Firstly, at the TO stage, the design resolution defines the precision with which the optimized geometry can be captured, and the optimal performance that can be attained. Within TO in general, continued efforts are made to leverage the power of parallel computing architectures. Use of GPU computing is also on the rise. Specifically for TO-for-AM, a large-scale TO implementation including overhang control was recently demonstrated by Delissen et al. [10]. For a part with outer dimensions of 427×430×49 mm, using a finite element model of 27 million degrees of freedom a design resolution of 1 mm was obtained. Note that while this is presently impressive from a computational point of view, 1 mm still is relatively coarse compared to the typical resolution offered by AM processes. In this regard, there still exists room for improvement to fully exploit the AM design freedom.

Secondly, during production, AM-process induced distortions affect geometric precision. This can lead to parts that are out of spec, or in the worst case catastrophic build failures due to recoater collisions. Avoiding or at least lowering the risk of such occurrences through TO has been the focus of various studies. Typically simplified inherent strain models are applied to arrive at an acceptable computational effort [9], and an overview can be found in [6]. Recent developments to mention are the TO of support structures for metal AM distortion control including the full elastoplastic material behaviour, which is more realistic but also more demanding in terms of simulation and sensitivity analysis [11]. To reduce the computation time, GPU computing was used in this study, yet still significant simplifications in e.g. layer thickness were required. Next to increasing the fidelity of the employed AM process models, Komini et al. [12] propose an approach to account for the uncertainty introduced by approximate process modelling and lack of data, by setting up a stochastic TO-for-AM formulation to control part distortion. Also this approach presents computational challenges, but the presented 2D results show a strongly decreased distortion mean and variation of the obtained design, compared to the deterministic TO result. An example is shown in Fig. 3.

Thirdly, after printing a part, post-processing is typically required to reach the required surface finish and precision of interfaces. Subtractive processes such as wire EDM, and also conventional milling and drilling, form part of these finishing operations. The cost linked to post-processing may even exceed that of the AM phase for complex parts, which underlines the relevance of also considering the post-processing phase and its impact on precision in the TO design process. One early example is the consideration of drilling forces on a printed part, to ensure geometric accuracy of the drilled hole by sufficiently stiff support structures [13]. Especially for slender structures, consideration of post-processing forces and the order of operations must be considered carefully. By extension, hybrid manufacturing (integrated additive and subtractive processes) present additional design challenges [6].

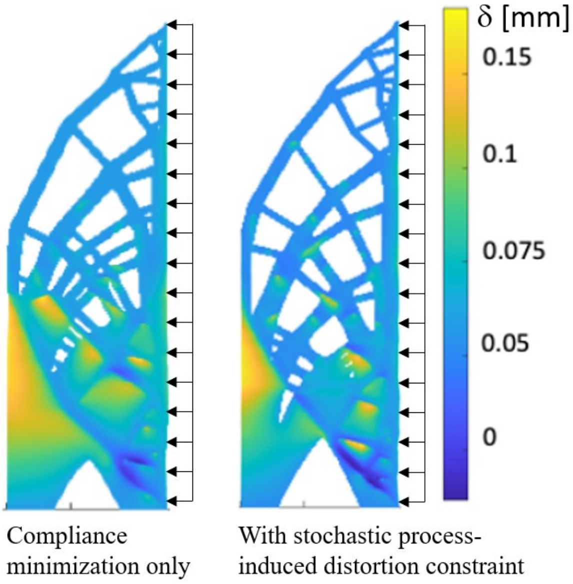

Figure 3. 2D structures and associated process-induced distortion δ obtained by conventional compliance minimization (left) and TO with AM distortion constraints considering uncertainty in the inherent strain process model (right) [12]. The print direction is upward. Only the loaded right edge is included in the distortion constraint. The targeted distortion was on average reduced by 37%, and its variance by over a factor 10.

3.2. Material property control

Aside from geometry, another aspect that requires precise control is the material behaviour of the produced part. During AM processes, the deposited material experiences large fluctuations in temperature and stress state. This can strongly affect the local microstructure development, such as phase composition, grain size and morphology, and texture in metal alloys. Combined, this results in certain local material properties, determined based on the local thermomechanical history, which depends on both part geometry and process conditions.

In order to control the resulting properties, Mishra et al. present a new TO-for-AM approach that includes the full thermal history of the AM process [14]. Using an adequate model of the relation between thermal process history, microstructure development and material properties, the resulting local material properties can be predicted and even optimized. Significant differences in e.g. hardness and yield strength of printed HSLA steel were demonstrated, controlled by TO-generated changes in part geometry. The computational effort required for this TO process with a full transient AM simulation in its inner loop was reported to be significant, and a challenge for future research is to reduce this to practical levels. The prospect of precise control of local material properties, enabled by AM and computational design, offers great opportunities to improve part performance in many applications.

3.3. Access for inspection/measurement

Precision is directly linked to inspection. Measurement and verification of e.g. geometric precision or surface conditions is essential in the qualification process of AM parts. Given the geometric complexity that AM allows, it is not a trivial question whether such inspections are possible. Access for instruments, or at least a direct line of sight, are typically required yet far from guaranteed for AM parts, in contrast to e.g. milled parts. Therefore, taking this access into consideration during the TO process instead of considering it as an afterthought is important to guarantee that a part can be inspected. The recent TO study by Allaire et al. [15] addresses this question motivated by the need to access support material for removal after printing, but similar access measures could be applied for ensuring inspection is possible. Similarly, TO approaches developed for multi-axis machining (e.g. [16]) could be utilized to ensure tool access for all part surfaces, where also the size and shape of the tool can be considered.

3.4. Application example: precision positioning

To conclude this section, after discussing precision aspects of geometric design, distortion during printing, material properties, post-processing and inspection, it is appropriate to finally consider an application where the combination of TO and AM enables new levels of performance in a motion system for precision positioning. In the recent study by Delissen et al. [10], mentioned already in Section 3.1 regarding its groundbreaking TO-for-AM design resolution, a motion platform is considered for a case study to determine the potential of AM for demanding high-precision applications in the semiconductor industry. Objective of the study was to maximize the first three structural eigenfrequencies of the platform, under a mass constraint and with various actuator masses (permanent magnets) with predetermined locations. Next to a geometric design rule (overhang control), also the milling of pockets for the actuators and assembly of the complete system is considered in the simulation model used in the TO process. As mentioned above, the part measured 427×430×49 mm, and an optimized geometry at 1 mm resolution was obtained in one day of computation.

The obtained design was printed in aluminium (Fig. 4) and its dynamic performance was determined experimentally. The measured eigenfrequencies matched the finite element results within 1%. Compared to a conventional design created by a human designer, at least 15% higher performance was obtained by systematically exploiting AM design freedom using the developed TO-for-AM approach. This study illustrates the potential for performance increases in similar demanding, dynamic high-precision positioning applications. For further details, the interested reader is referred to the original publication [10].

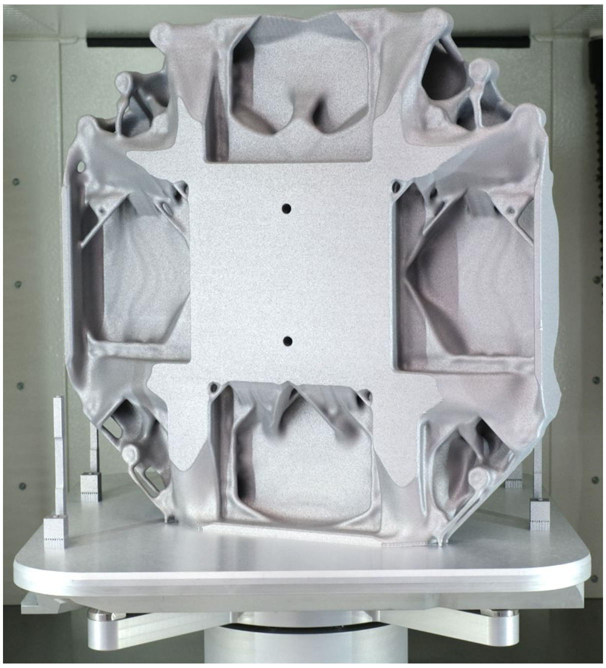

Figure 4. Topology optimized motion platform frame, produced by powder bed fusion in aluminium [10]. Relevant eigenfrequencies were improved by 15% or more compared to the benchmark design.

4. Summary and outlook

The field of topology optimization (TO) for additive manufacturing (AM) is in rapid development, and has advanced from the enforcement of basic design rules to the incorporation of complex physical effects that occur during the AM process. This paper has presented a high-level overview of these developments, followed by a discussion focused on recent contributions directly relevant to precision. These are found on multiple levels. At the geometry level, regarding design resolution, AM distortion control, post-processing operations. At the material level, through an upcoming capability to control local material properties based on the combined effect of part geometry and process history. At the inspection level, to verify part precision, access to every surface must be ensured. And finally, at the application level, where the right combination of TO and AM can significantly improve performance of precision systems such as motion platforms.

The computational effort involved in the more complex examples, particularly TO-for-AM approaches involving AM process simulations, makes that research into increased efficiency or adequate simplifications is a priority to enable their use for practical application. Potentially machine learning techniques can be employed to replace full physics simulations with reasonable approximations, at least for part of the TO process. Furthermore, the direct control of material properties and the consideration of uncertainties in AM process models form two of the most novel directions that can still be extended and refined significantly. Given the already demonstrated benefits, through continued exchanges between the precision, AM and TO research communities, further process can be expected in all discussed directions.

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