MULTI-AXIS ADDITIVE MANUFACTURING OF TOPOLOGY AND TOOLPATH OPTIMIZED COMPOSITE STRUCTURES

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Multi-axis additive manufacturing (AM) offers the opportunity for novel part fabrication methods by enabling the relative reorientation of the deposition tool and part during the printing process. Deposition paths can be placed outside of the XY-plane, allowing the toolpath to be customized for the manufacturing and application requirements of the part. Tool head orientations (i.e., build directions) can be continuously varied throughout the part to minimize support material requirements, improve surface finish, and deposit material conformally onto non-planar substrates. Critically, this ability synergizes with the inherent alignment of material anisotropy in the material extrusion (ME) process; the direction and placement of composite material can be tailored in full 3D to align with anticipated load paths. In this way, the relatively weak layer-interfaces are removed from the load paths, applying all of the load to the fiber, increasing mechanical properties.

Although conventional ME processes enable 3D geometric optimization, toolpath optimization was limited to the XY-plane; with multi-axis deposition, it is now possible to optimize both the geometry of the part and the toolpath used to fabricate it simultaneously and in full 3D. However, leveraging this capability requires advances in process planning. Existing toolpath planning methods largely limit deposition path planning and fabrication to curved surfaces to prevent collision concerns between the part and deposition tool (e.g., [1], [2]); complex end-use load cases may not be decomposable into stratified curved surfaces, leading to material being placed in sub-optimal orientations. Simultaneous control of part geometry and toolpath is also restricted, and this separation of part design and fabrication can result in sub-optimal mechanical performance and (in the worst case) an unrealizable combination of geometry and toolpath.

To enable the fabrication of structures optimized for arbitrary load cases, the authors have created the topology and toolpath optimization (TTO) workflow (Figure 1), which combines multi-axis AM, topology optimization (TO), and composite materials to enable concurrent optimization of part topology and printing toolpath. This integration of the design and manufacturing phases of part fabrication preferentially and specifically aligns the composite reinforcement to maximize part performance. The manufacturing-aware generative design technique also ensures that the geometry and toolpath are achievable (i.e., printable without collisions) on the specified multi-axis deposition platform.

TTO uses a custom TO algorithm to determine material distribution and orientation (in 3D) relative to the input load cases, aligns material depositions (i.e., the composite reinforcement) to those optimized directions [3], and orders the deposition paths for collision-free fabrication. Previous work from the authors compares the custom TO algorithm to existing algorithms that only optimize for material orientation in the XY-plane (e.g., [4]) for a variety of load cases [5].

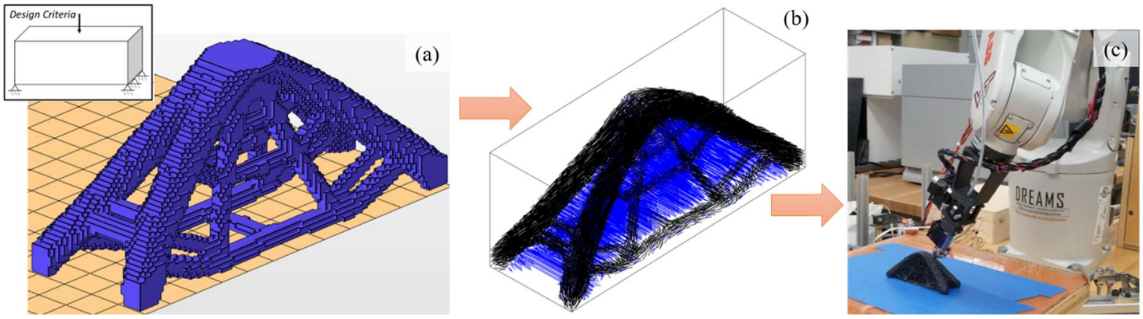

Figure 1. (a) Geometry optimized for the load case (inset), (b) deposition paths propagated aligned to the load paths (black) with appropriate support structure (blue), and (c) printing the structure on a multi-axis deposition

Results

The TTO workflow has been used to fabricate a variety of load cases. A structure experiencing multiple loading conditions (i.e., tensile and bending; Figure 2a) was optimized, and fabricated structures using both TTO and conventional toolpath planning methods were mechanically evaluated in the optimized-for loading conditions. Performance improved by 108.24% and 29.25% in tensile and bending, respectively, over the conventional toolpath planning strategies. The curved tensile bar load case (Figure 2b) was used to validate the TTO workflow in a multi-axis context. Here, the TO algorithm was allowed to vary material orientation and distribution in the light gray regions, but only orientation in the dark grey regions. This ensured grip regions were developed in the final design space for test fixturing. The white regions were forced cavities to promote the generation of non-planar features.

Deposition paths were propagated through the optimized design space, and collisions between each deposition path were determined based on the physical characteristics of the deposition platform. The deposition paths were then ordered for collision-free deposition such that the platform always had access to unprinted regions of the geometry. As a result, the multi-axis deposition paths were almost perfectly aligned with the underlying load paths acting on the structure; in contrast, the conventional toolpath planning methods were entirely unable to align the reinforcement with the Z-component of the load paths. This improved alignment in the TTO samples resulted in an 82.8% improvement in mechanical efficiency. Across a variety of loading conditions, this novel process planning strategy has been demonstrated to nearly double the mechanical performance of the printed structure with commodity, short-chopped carbon fiber thermoplastics; with a continuously reinforced or otherwise highly anisotropic material, this degree of improvement is expected to further increase.

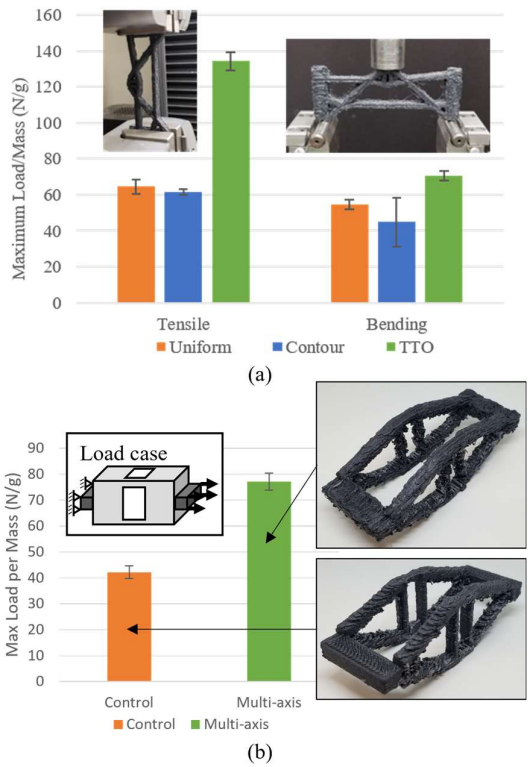

Figure 2. Example structures fabricated through TTO. (a) structure optimized for tensile and bending loads simultaneously and (b) curved tensile bar. Mechanical testing of both structures demonstrated significant performance improvement using TTO relative to conventional toolpath planning methods.

References

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