Probing Operation Limits of Advective Assembly in Additive Manufacturing using Digital Twins

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Multi-material additive manufacturing (MMAM) builds composite architectures to produce objects with enhanced functionality and mechanical properties. These structures can be reliably assembled using successive layer deposition, however, layer-by-layer MMAM suffers from long print times as well as poor interfacial adhesion between layers. To address these challenges, the Bayles Group uses principles of advective assembly to engineer the next generation of MMAM printing nozzles. Advective assembly (AA) is a new processing technique[1] that structures composites by flowing disparate inks through a series of addition, rotation, and splitting elements which sculpt laminar streamlines (Figure 1a). By incorporating AA elements into a single nozzle, operators structure multi-material filaments before they arrive at the print bed. The modular combination of the flow elements allows operators to create voxelated, designer architectures provided that the flow remains stable.

Here, we use computational fluid dynamics to systematically investigate how ink rheology affects flow stability. Often, 3D printing inks are shear thinning and viscoelastic due to their polymeric nature. When these fluids are used, the successive geometric operations result in complex flow patterns and stress gradients compromising architecture fidelity.[2] To combat this, AA makes use of viscoplastic materials where past particle image velocimetry experiments[1] have shown that viscoplastic, shear thinning microgel inks assemble with high fidelity. We hypothesize that the reliable assembly is due to the yield stress of the granular ink which limits deformation of the architecture to regions near the wall. To systematically probe these hypotheses and operational limits, we build digital twins of advective assembly nozzles in ANSYS Fluent 2023 R1 (Figure 1b). We investigate operational regimes for different Newtonian and Non-Newtonian fluids over a range of inlet velocities, yield stresses, power law indices, and viscosities. The effect of these parameters on the outlet structure (Figure 1c) is reported via a computational framework which compares the simulated output to a model first-order prediction. These differences are calculated through matrix comparison metrics such as the Jaccard index, matrix norm, and a modified Frobenius norm. Overarchingly, quantitative identification of stability limits is critical for the operation and optimization of advective assemblers in MMAM (Figure 1d).

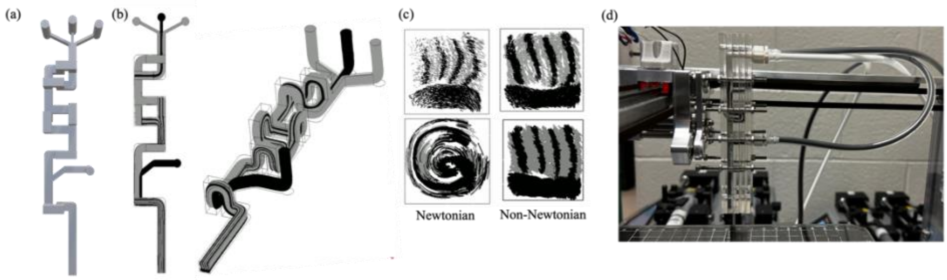

Figure 1: (a) Assembler internal geometry used in ANSYS Fluent. (b) Orthographic projections of the completed flow solution from ANSYS Fluent. (c) Outlet cross-sections for Newtonian and Non-Newtonian fluids through the geometry. Inlet velocity increases from top to bottom. (d) Constructed assembler nozzle attached to a commercial E3D toolchanger 3D printer.

[1] A. V. Bayles, *et al*., *ACS Appl. Mater. Interfaces*. **38**, 21 (2022).
[2] P. D. Anderson, *et al*., *Applied Rheology*. **16**, 198 (2006).