Additive Manufacturing Utilizing a Novel In-Line Mixing System for Multi-Scale Design of Ceramic Composites

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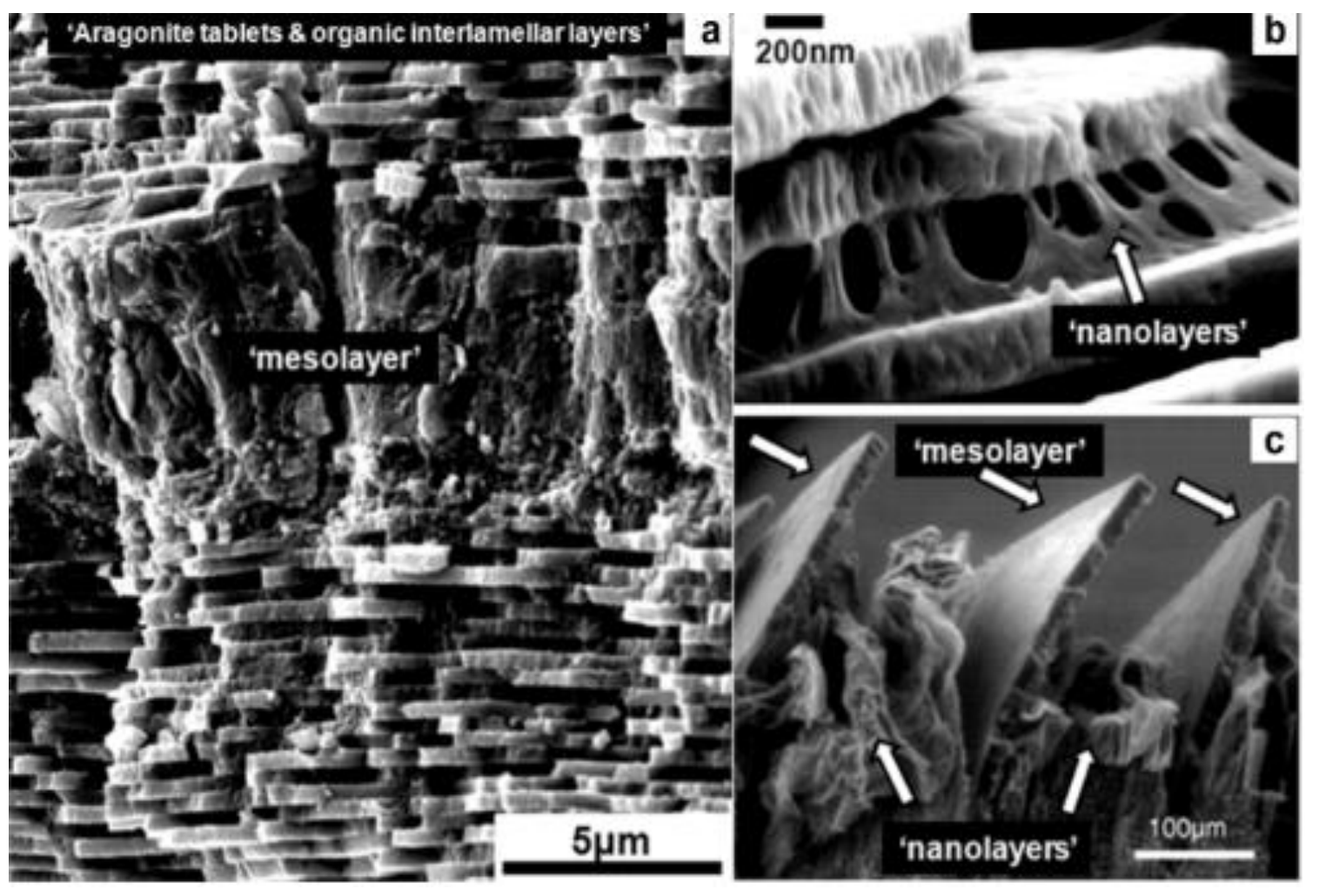
Motivation and Objectives

Novel additive manufacturing (AM) techniques are enabling a new generation of design where properties can be varied at each point in 3D space; limited only by the resolution of the process. These functionally graded materials (FGM) contain heterogeneity in both composition and geometry, with function no longer restricted to intrinsic properties [1]. Instead, structural organization and composition variation can be tailored to produce FGM with properties exceeding those of their constituent materials.
Herein, we describe the design of an AM system capable of producing functionally graded carbides. The objectives of this study are:

- Develop an AM system for use with ceramic inks and with multi-material and in-line mixing capabilities.
- Optimize componentry and processing parameters to increase resolution in terms of both geometry and composition variation.
- Explore process boundaries to identify best use cases for this AM technique.

Biological materials are a central inspiration for developing new processing techniques that enable heterogeneity in both composition and geometry. Natural composites use hierarchical structuring and composition gradients to improve properties over those of their base materials. For example, the abalone shell is a natural composite of calcium carbonate tiles and organic interlayers in a 'brick and mortar' microstructure, with additional higher-scale organic mesolayers [5]. Structural organization at multiple length-scales leads to an 8-fold [6] increase in fracture toughness over that of pure calcium carbonate.

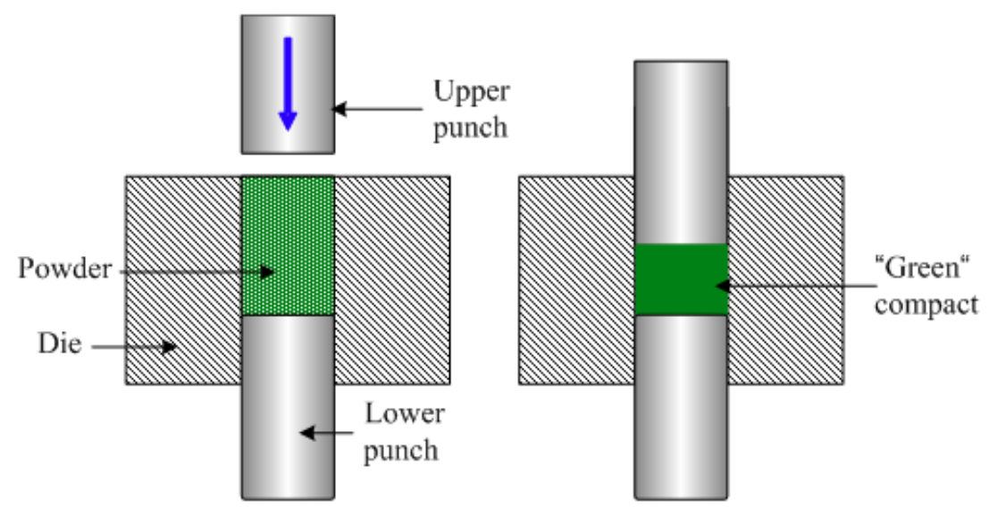


Background

Technical ceramics have exception wear, corrosion, and temperature resistance and are important in a number of industries. A significant challenge in the application of technical ceramics is their defect-dominated mechanical properties [3]. For this reason, extrinsic toughening mechanisms (such as those utilized by the abalone shell) must be explored to fully realize the exceptional properties of technical ceramics. Thus, a fabrication method is required that can produce complex, three-dimensional parts with material heterogeneity and organization at multiple scales.

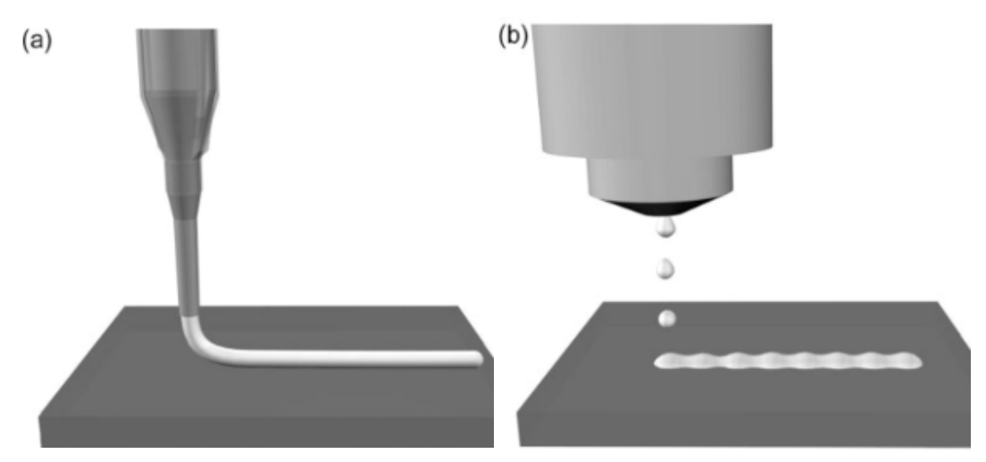
Traditional processing/forming technologies used for ceramic materials limit 3D design space and do not support composition variation. A common forming technique is pressing, where powder is compacted in a die with a specific two-dimensional profile [3].

- Produces extruded profiles
- No composition variation
- Stochastic mixing used for multi-materials

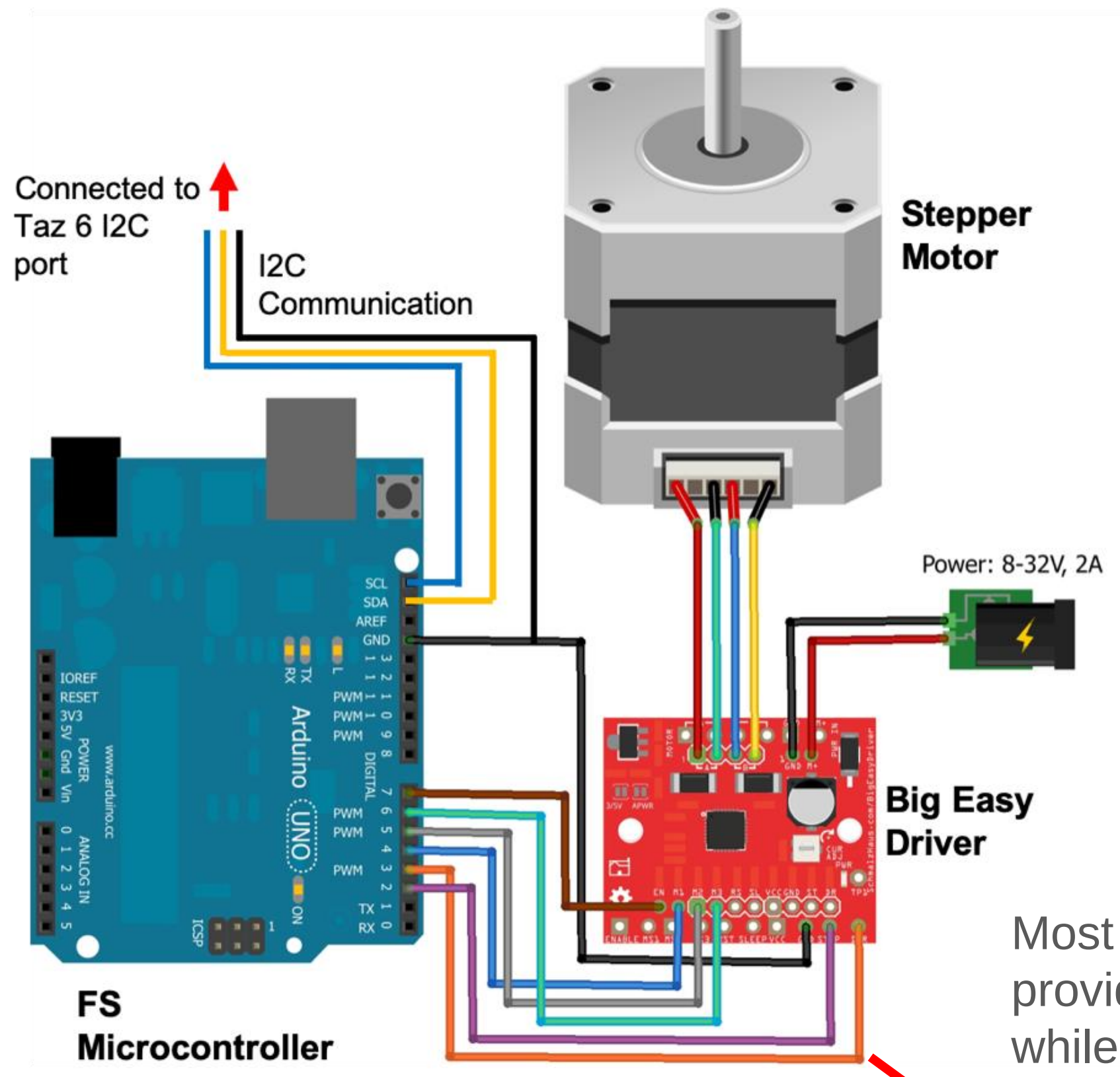


Direct ink writing (DIW) is a type of additive manufacturing (AM) in the material extrusion category [7]. DIW was selected to produce ceramic composites in this study due to the following advantages:

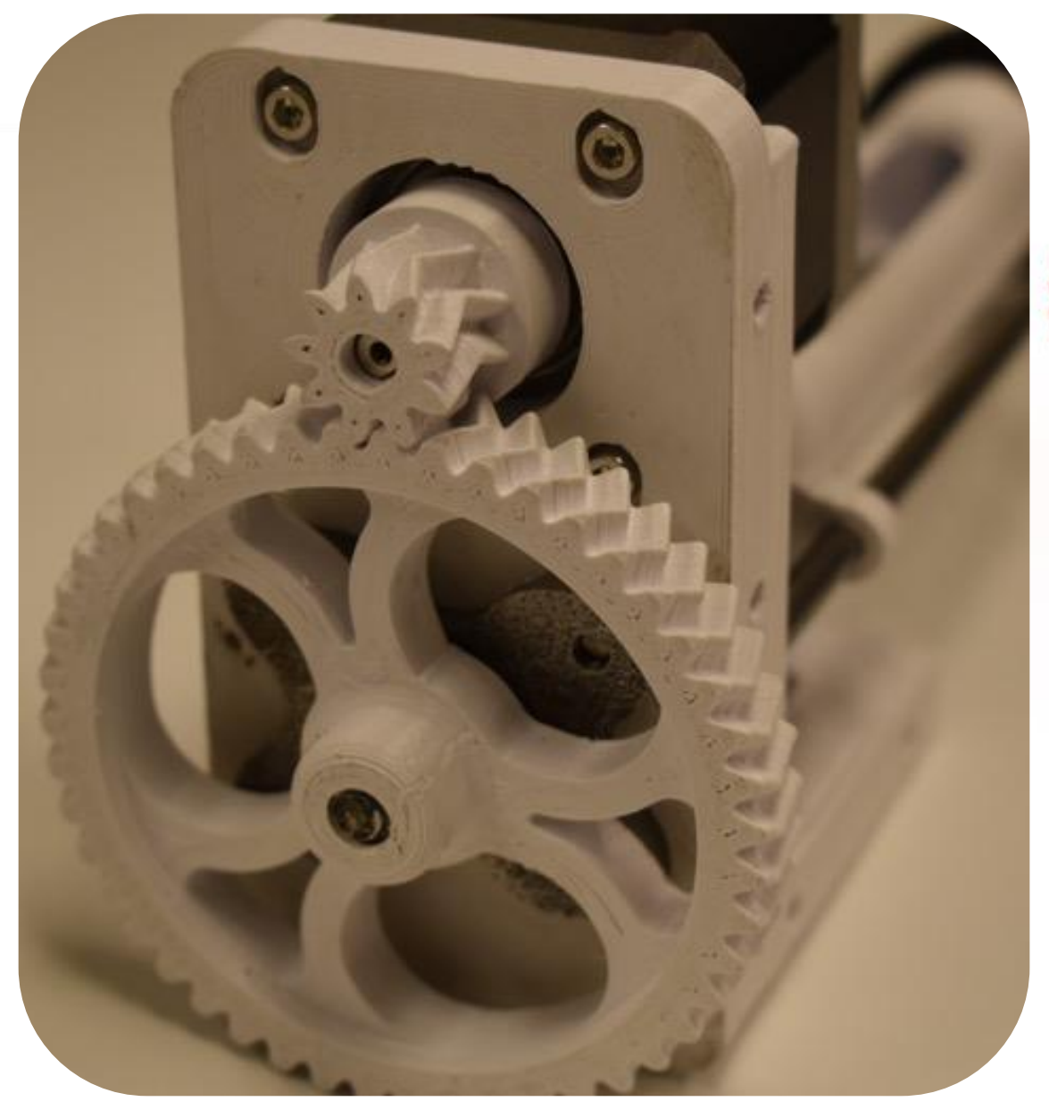
- Produces dense ceramics
- Supports multi-material printing
- Inexpensive, low-complexity equipment



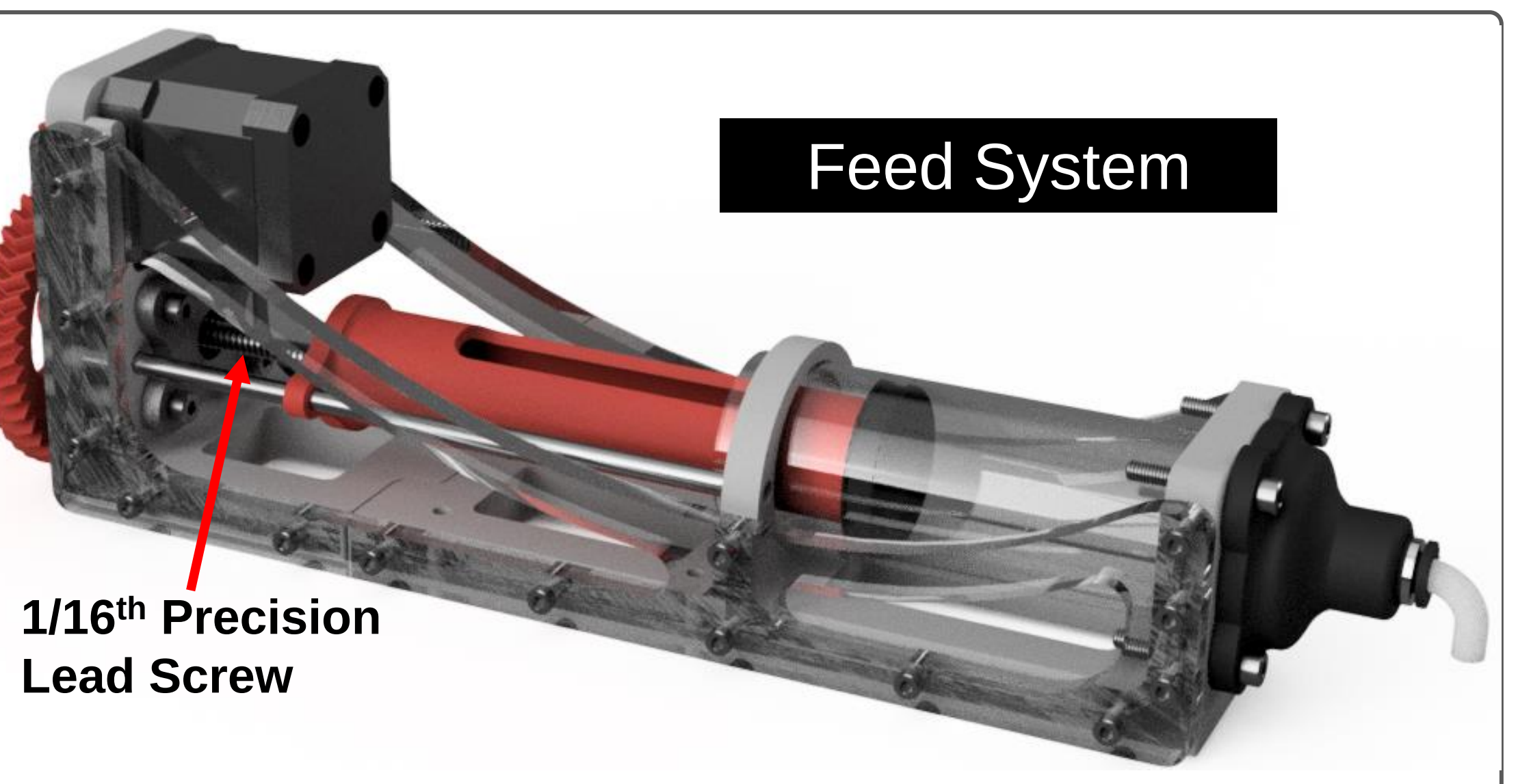
Feed System Controller



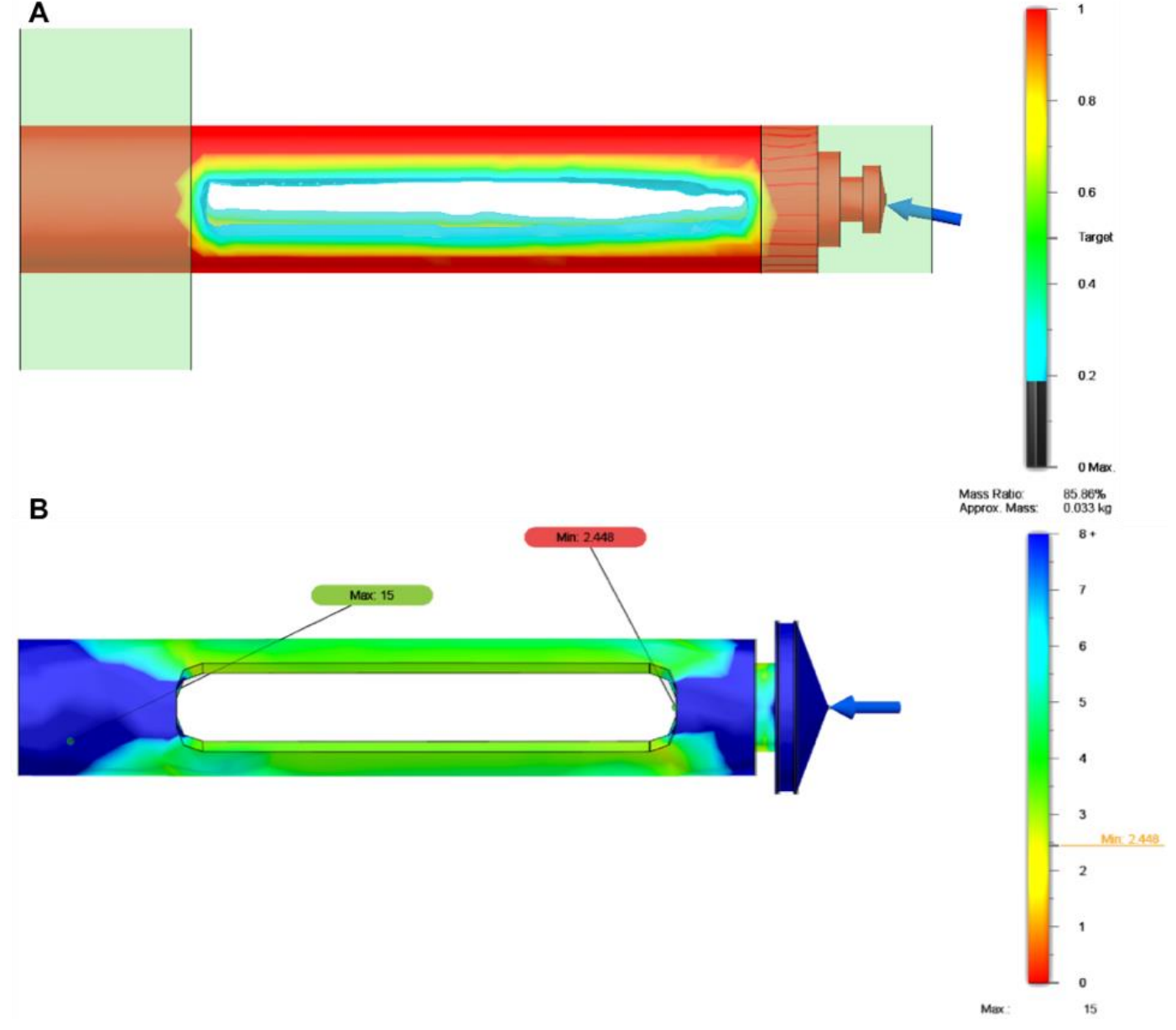
47:9 Gear Ratio



Feed System



Topology Optimization of Plunger



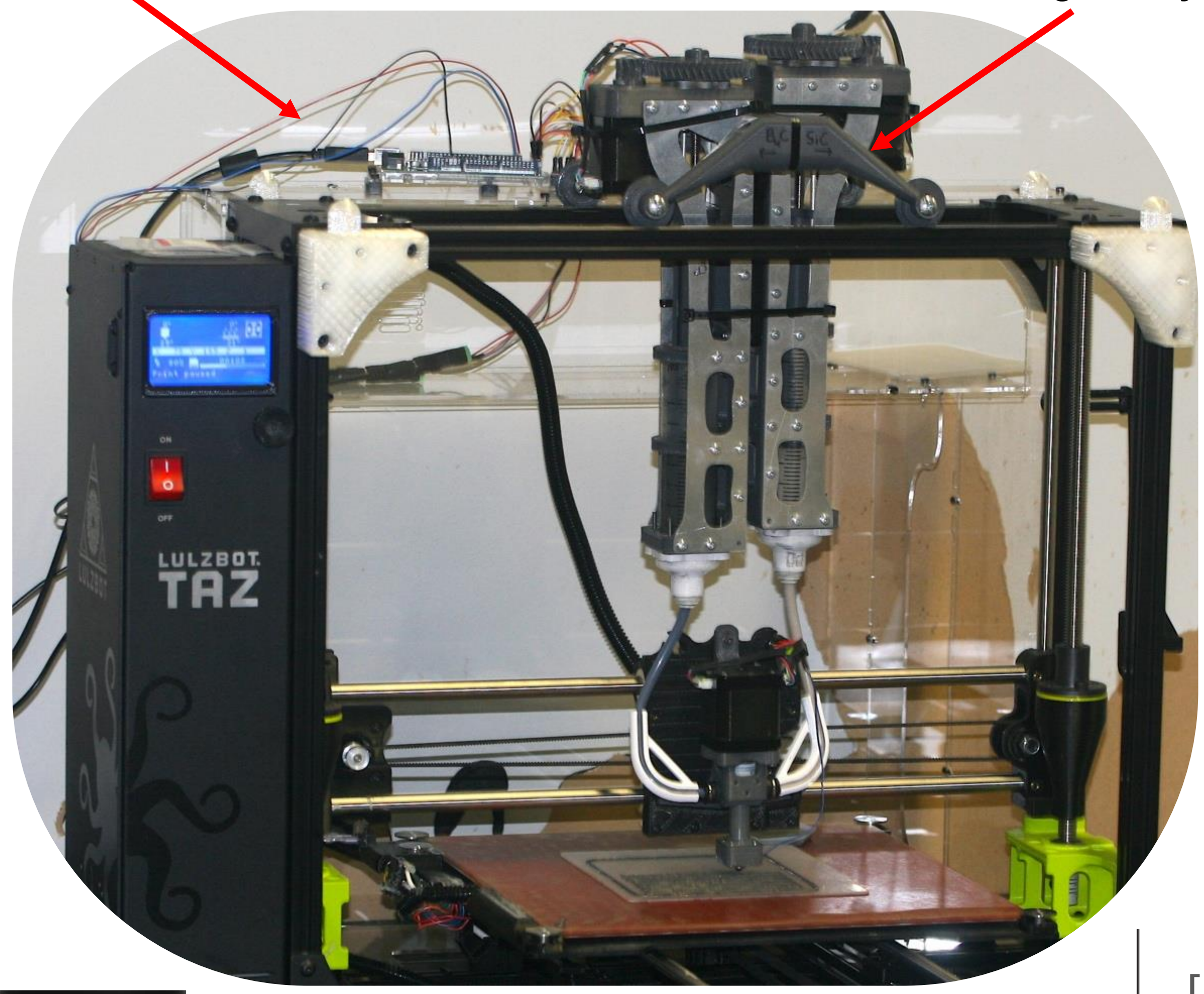
System Design

Most components were 3D printed using the Lulzbot Taz 6's provided FDM tool-head. Auger printed with PC-ABS material, while parts not in contact with ceramic material were printed with ABS

Base System

LulzBot Taz 6
Aleph Objects, Loveland, CO

Rolling Gantry

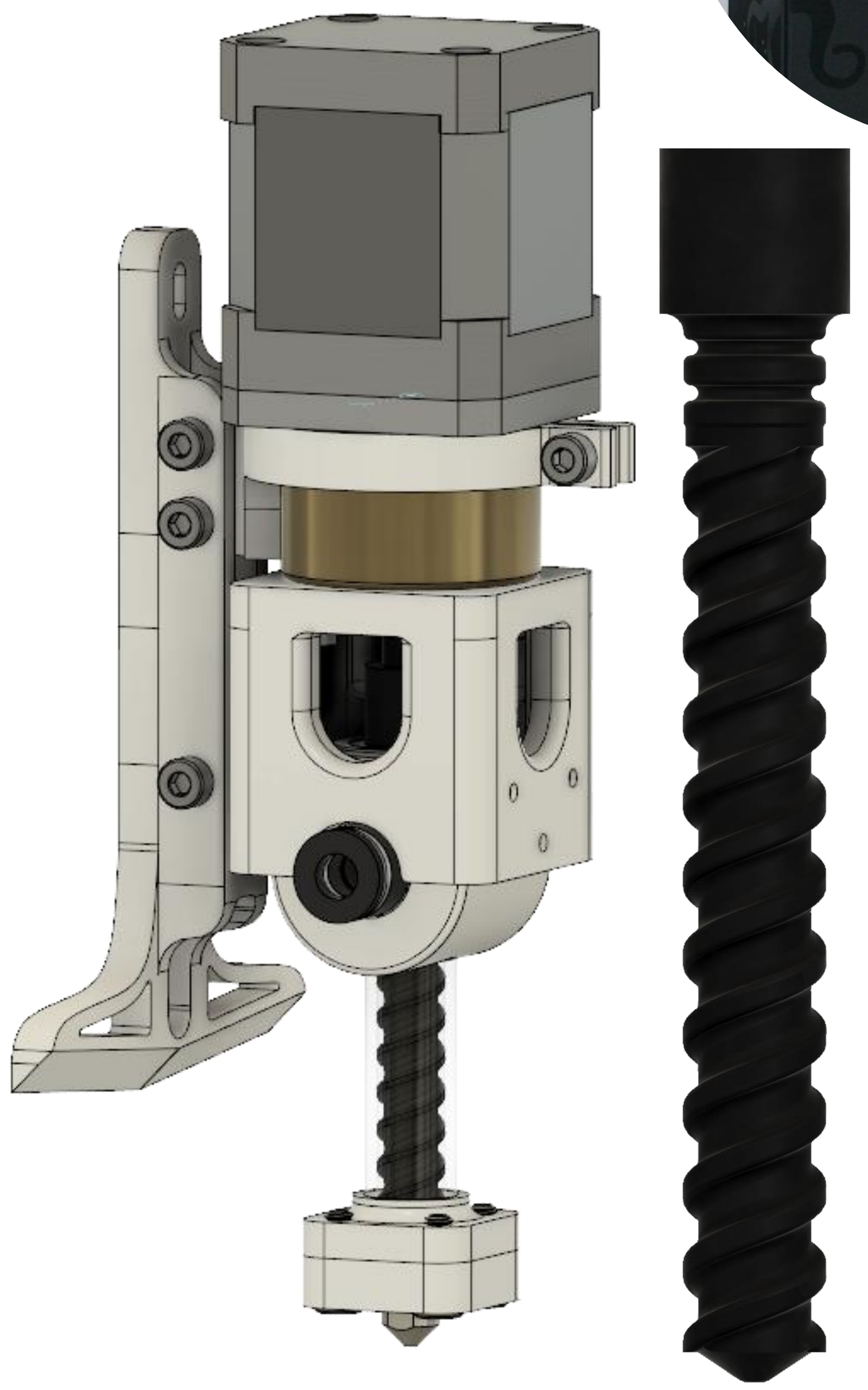


FEA Simulations

Simulations done in Autodesk's Fusion 360 software. Performed to validate design performance, with topology optimization to reduce material use and print time. Parameters:

- 100 psi on plunger gasket
- 30% weight reduction
- Maximize stiffness
- Preserve end geometry

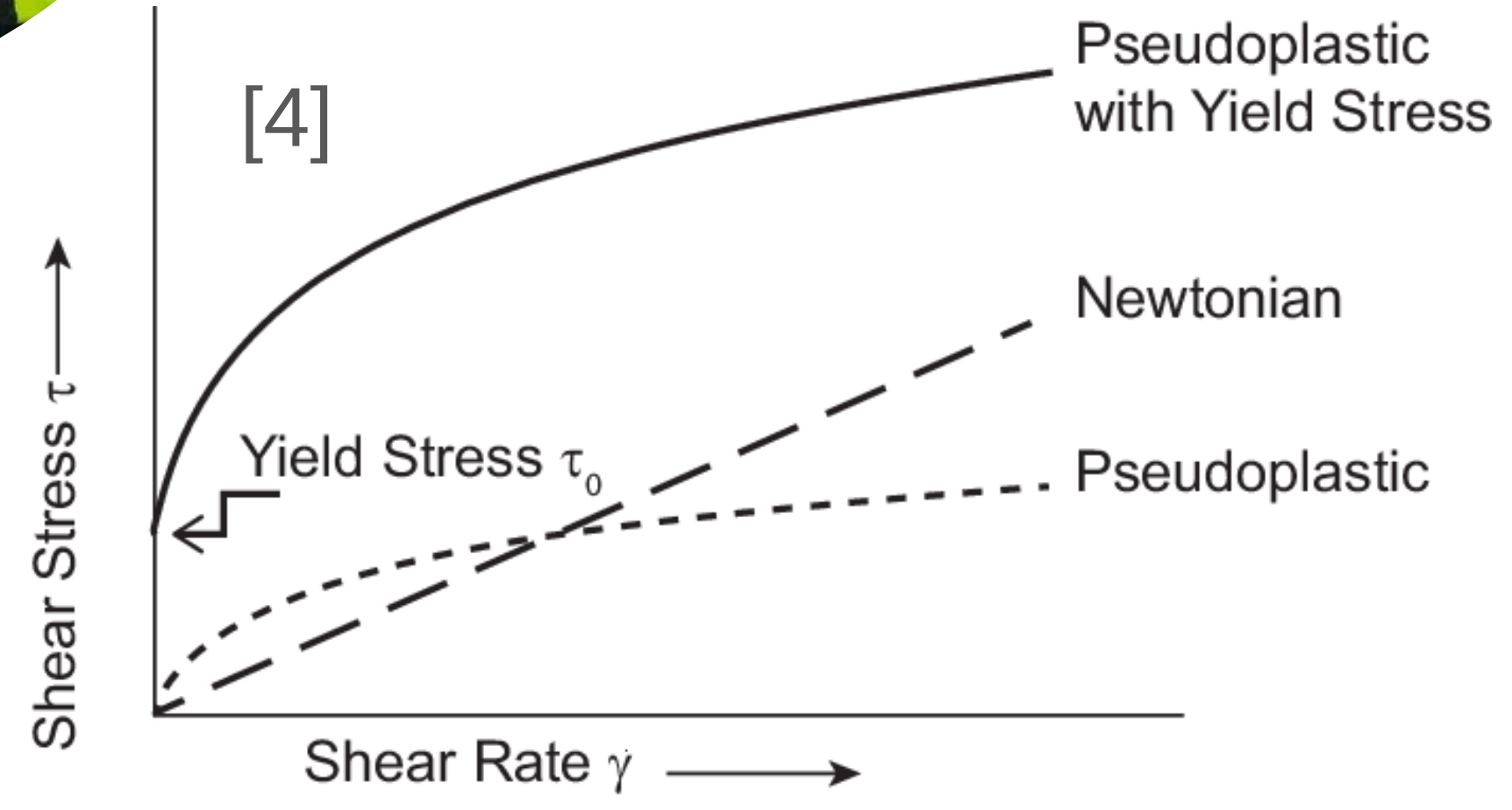
Print Head



Auger Design Parameters

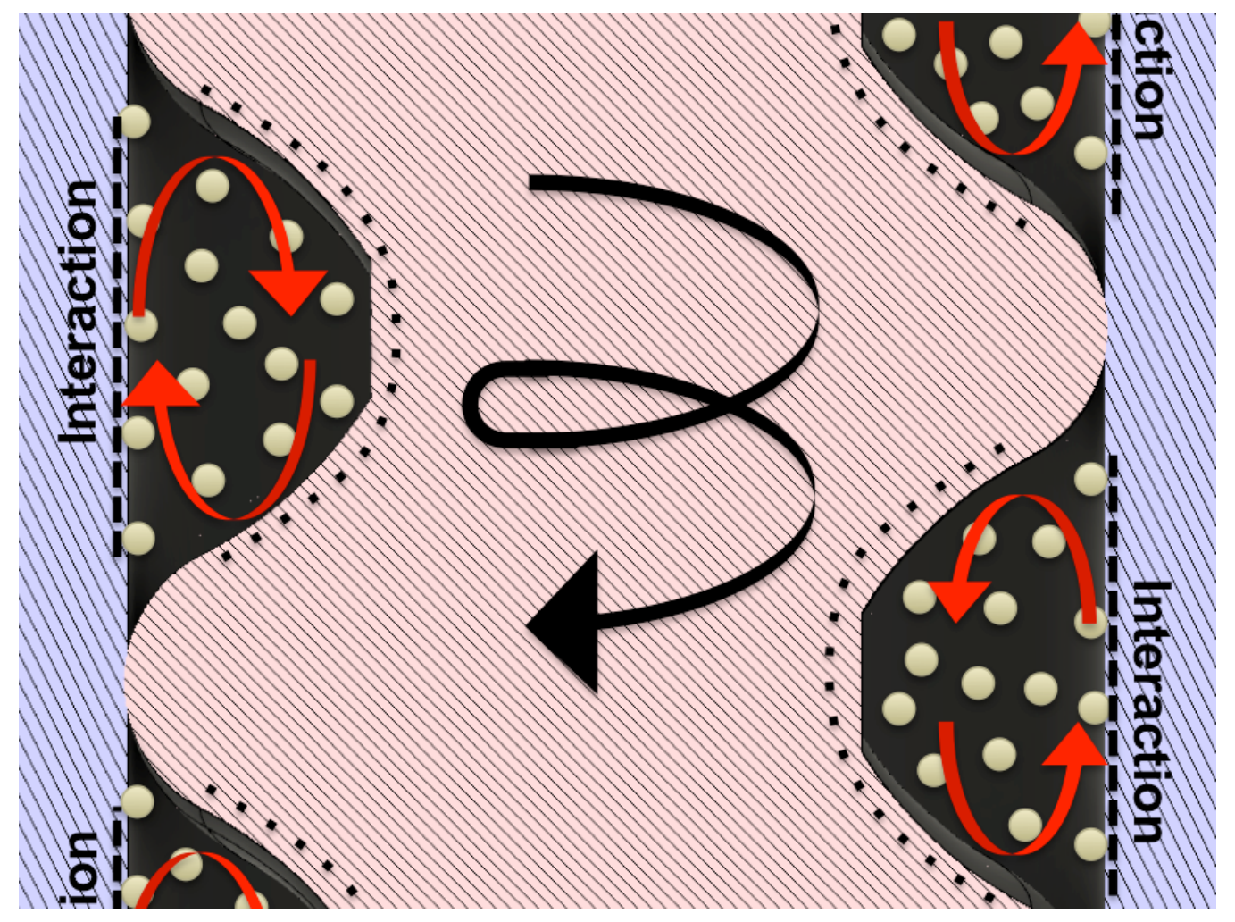
- Length
- Number of threads
- Pitch
- Mixing volume

Ceramic Ink Design



In-line Mixing

- Mixing
- Conveyance
- Residence time



Ink Optimization

For predictable mixing and conveyance, ceramic inks must have similar:

- Yield stress
- Flow curve

For successful densification, ceramic inks must have similar:

- Solids loading

Competing factors void filling vs. feature definition

Results

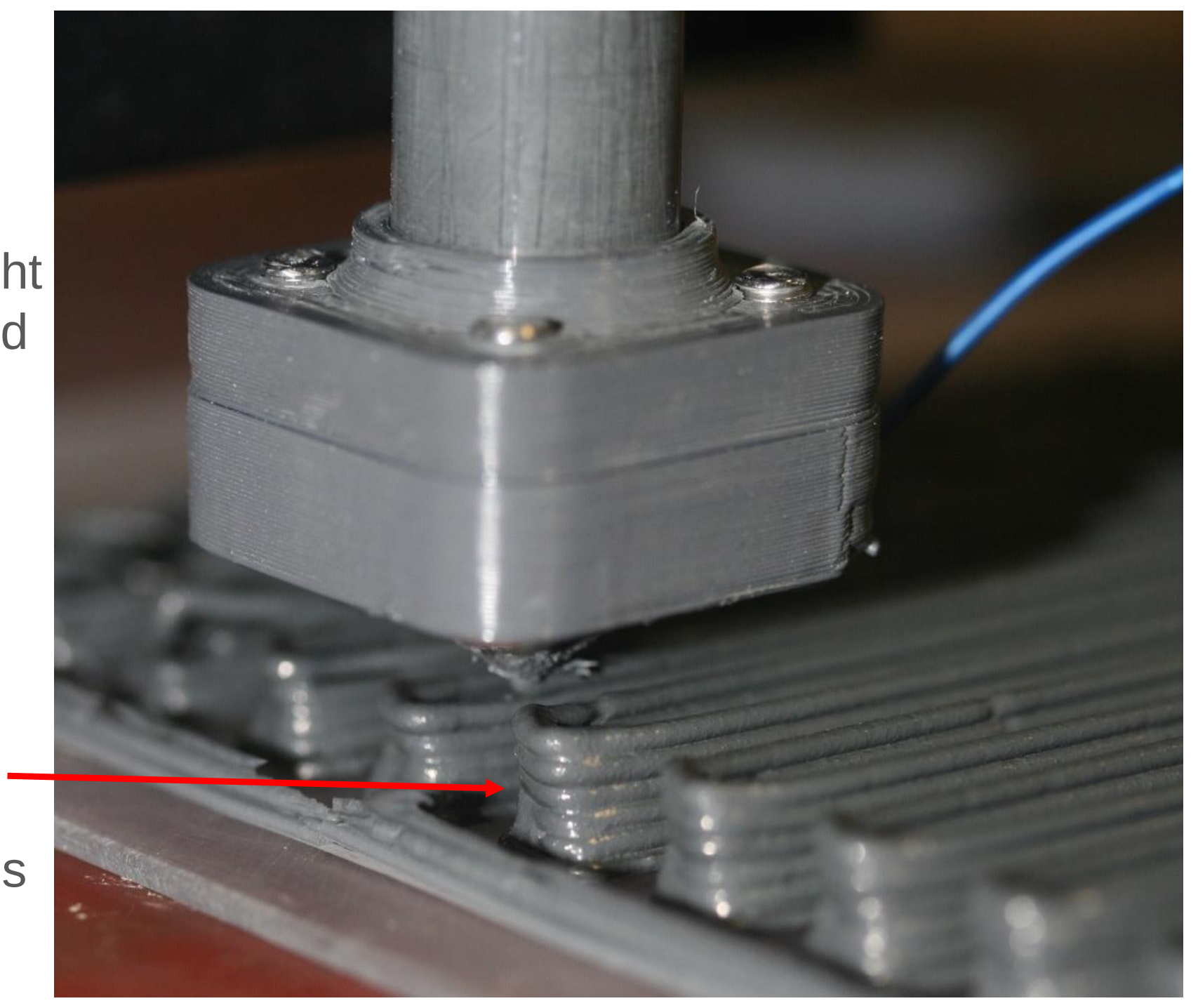
This study utilized boron carbide and silicon carbide due to their very high hardness, good mechanical properties, and low density [2]. Composite parts were formed via DIW using a custom-built system with multi-material and in-line mixing capabilities. B_4C and SiC were printed as aqueous ink formulations with high solids-loading and yield-pseudoplastic rheology.

Stacked B_4C Traces

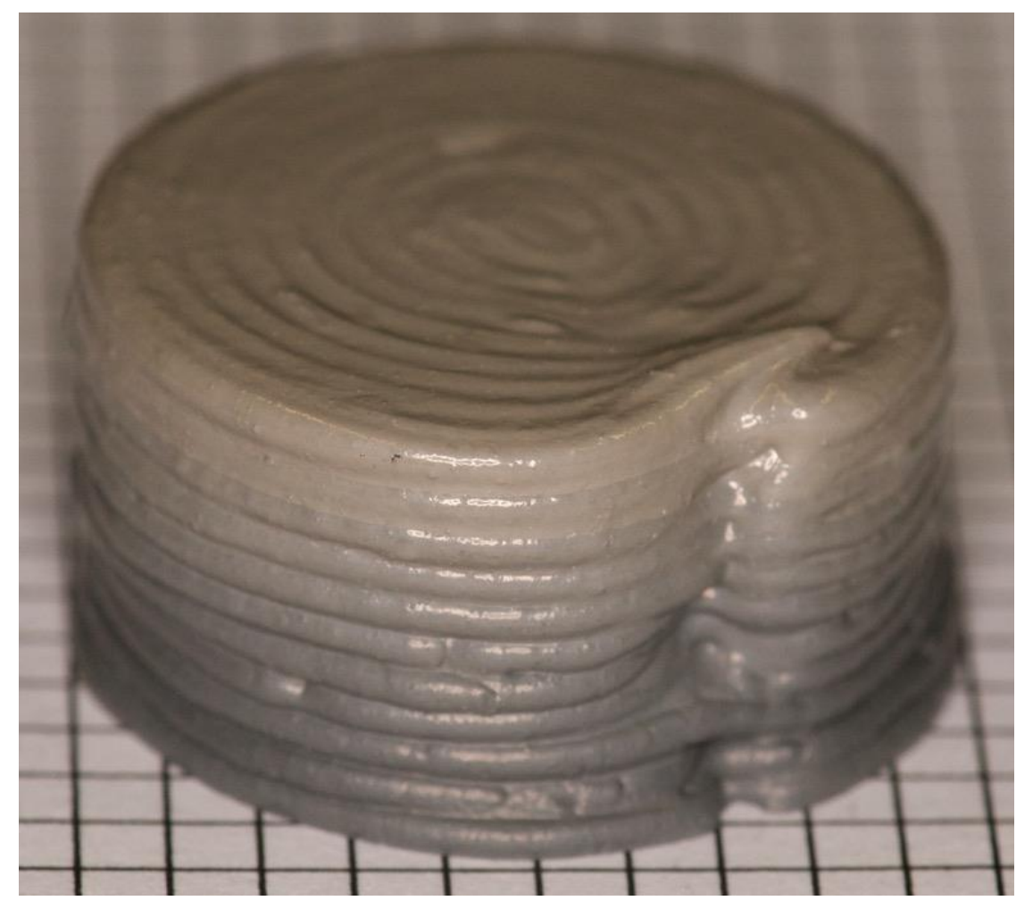
Print parameters:

- 1.2 mm nozzle
- 1.2 mm layer height
- 4 mm/s print speed

Six layers stacked without observable slumping indicates optimized yield stress



Gradient B_4C/SiC Composite



Layered B_4C/SiC Composite

Boron carbide (dark-gray) and silicon carbide (light-gray)

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