Characterizing Process-Induced Defects in Metal and Ceramic Fused Filament Fabrication for Accessible Aerospace Components

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Overview

Metal and Ceramic Fused Filament Fabrication (3F) offers a cost-effective pathway for aerospace-grade components using desktop printers and kilns, but also introduces inter-layer lack-of-fusion (LOF) defects whose locations are governed by slicing architecture. NASA-STD-6030 provides no defect acceptance criteria for metal or ceramic material extrusion (MEX). This fellowship investigates whether wall count can predict LOF defect distribution and effects across five sintered materials (copper, SS 316L, Inconel 718, borosilicate, and zirconium silicate), producing a characterization dataset and printing deposition model.

Background

Motivation

To create practical design guidelines for M/C3F components and develop LOF application-specific flaw tolerance requirements. M/C3F enables aerospace fabrication without powder handling, clean-room requirements, but reliability is poorly understood. NASA's STMD and IMQCAM identify "effect of defects" characterization as a critical AM qualification need and this work addresses that gap for the accessible, low-cost process methodology that NASA does not yet cover. Focused on charactering tensile stress, hardness, and coefficient of thermal expansion of one build orientation with

Prior Work (Completed)

A prior copper M3F shrinkage study (Russ, Bradley, Powell, Calhoun, 2025) found using gradient boosting achieved R^2=0.672, outperforming spline regression (R^2=0.35). At 85% filling, horizontal shrinkage (~9–11%) fell below the 15-20% typical for metal FFF, while Z-axis shrinkage (~14%), which indicates lower than average densification of typical literature values though on par with [1], like to processing in an unregulated air atmosphere. Gradient boosting predicted these results with R^2=0.672, identified non-prismatic were harder to predict than prismatic ones and that measurement size was a dominant factor.

[FIGURE 1: XGBoost feature importance — Fig. 13 Set B, prior shrinkage paper]

Ideal Equipment Setup and Characterization Motivation

[FIGURE 2: Schematic of Printer Set-up with thermal sensing]

IR Camera for how long the interface stays above the binder glass transition temperature (T_g), which correlates green-part inter-layer bond quality. This thermal history data is for the green parts; microscopic cross-sections, push-rod dilatometry, and Vickers hardness will map the post-sinter outputs. Together corollate between deposition conditions and final defect state. A custom furnace inside a vacuum oven enables post-sinter thermal characterization up to 700°C.

LOF and Other Defects Visualized

[FIGURE 3: Schematic of intra and inter layer defects]

Methods

Materials

Copper, SS 316L, Inconel 718, Borosilicate, Zirconium Silicate Filamet™ (Virtual Foundry)

Independent Variables

Wall count: **3, 4, 5**
Directly specifiable and measurable on sintered cross-sections across any printer platform. All other parameters held constant.

Characterization (planned)

Optical cross-section and SEM/EDS
Vickers hardness map
ASTM E8 Fig 19 for metals (Figure 6)
ASTM C1161 Standard B for ceramics
Archimedes density (sintered) in 99% isopropyl alcohol
Calculated density (green) using scale
DSC/TGA
DIY Slot-in Furnace with dilatometry

[FIGURE 4: Debind/sinter schedule subplots — all 5 materials]

[FIGURE 5: Crucible + sample positioning diagram]

Results

Preliminary (Completed)

Calculated binder volume fraction ~54.6% that the void volume sintering could potentially consolidate. Preliminary sintered copper samples produced; full characterization in progress.

[PHOTO 2: Sintered Samples Dimensioned] & [FIGURE 6: ASTM E8 Fig. 19 dog bone dimensions]

Literature Review and Modeling

ANSYS Mechanical thermal models of the sintering process for 3, 4, and 5 wall count conditions are in development to predict how wall architecture influences thermal gradients during densification, and therefore where LOF defects are expected to concentrate. These models will be validated against measured cross-section data and litature review.

[FIGURE 7: ANSYS Mechanical — thermal model, 3/4/5 wall panels]

Conclusion/ Future Direction

Using measurable printer-agnostic slicing parameters for green parts to model LOF defect characterization data for metal and ceramic M3F to predict defect location and assess failure risk given material specific fracture mechanics to give mechanical properties while also potential modeling thermal and electrical antitropy. Results will directly support accessible aerospace hardware qualification for student programs.

Equipment (In Progress)

- Custom slot-in furnace in vacuum oven + IR camera + DAQ — thermal testing to 1000°C, ZnSe viewport
- Vacuum oven door CAD with viewport mount — designed

[PHOTO 3: Custom furnace — in construction] & [FIGURE 7: Plot of Vacuum Oven Door CAD]

Future Work

- MIM baseline comparison for defect population benchmarking
- Literature parameter normalization study — standardizing published M3F data to geometric ratios
- Complete Github of all project research uploaded.

[FIGURE 8: Plots of normalized debind/sinter schedule, filament density, and x, y, and z shrinkage of copper at 100% infill]

References

[1] Montes-Ramirez et al. (2024). Shrinkage and Deformation Compensation in MF3 Sintered Copper. J. Manufacturing Processes, 121, 9–19. https://doi.org/10.1016/j.jmapro.2024.04.069
[2] NASA-STD-6030 (2021). Additive Manufacturing Requirements for Spaceflight Systems. https://standards.nasa.gov/standard/nasa/nasa-std-6030
[3] Virtual Foundry TDS Copper (2024). https://thevirtualfoundry.com/debind-sinter/
[4] Build plans, references, & protocols: Github repository link needed

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