2023 NDIA MICHIGAN CHAPTER
GROUND VEHICLE SYSTEMS ENGINEERING
AND TECHNOLOGY SYMPOSIUM
<ADVANCED MATERIALS AND MANUFACTURING> TECHNICAL SESSION
AUGUST 15-17, 2023 - NOVI, MICHIGAN

Thermally Annealed, High Strength 3D Printed Thermoplastic Battery Bracket for M998

E. D. Wetzel[1], R. Dunn[1], L. J. Holmes[2], Casey Shearrow[2], K. Hart[3], J. Park[4], and M. Ludkey[5]

[1]DEVCOM Army Research Lab, Aberdeen Proving Ground, MD
[2]U. of Harrisburg, Harrisburg, PA
[3]Prepared for Flight, LLC, Severn, MD
[4]U. of Massachusetts - Lowell, Lowell, MA
[5]DEVCOM Ground Vehicle Systems Center, Warren, MI

ABSTRACT

A 3D printed battery bracket is strengthened via post-print thermal annealing, demonstrating a transitionable approach for additive manufacturing of robust, high performance thermoplastic components.

Citation: E. D. Wetzel, R. Dunn, L. J. Holmes, K. Hart, J. Park, and M. Ludkey, "Thermally Annealed, High Strength 3D Printed Thermoplastic Battery Bracket for M998," In *Proceedings of the Ground Vehicle Systems Engineering and Technology Symposium* (GVSETS), NDIA, Novi, MI, Aug. 16-18, 2022.

1. INTRODUCTION

Army materiel is subject to challenging load and environmental conditions, leading to damage and failure that necessitates replacement or repair of components. One concept to simplify logistics and reduce downtime is to use 3D printing technologies for expeditionary manufacturing at the point of need. Fused filament fabrication (FFF) is the most commonly implemented 3D printing technology, in which a thermoplastic filament is heated and deposited by a computer-controlled motion control system to build a 3D solid. This method has significant advantages for expeditionary manufacturing, including robust and low cost hardware, simple operation, and long-shelf life feedstocks. The major shortcoming of FFF is that the parts are mechanically weak, particularly between build layers, making them unsuited for load bearing applications [1].

To overcome these challenges, post-annealing of FFF parts can be undertaken [2]. Heating a printed FFF part above its softening temperature, typically the glass transition temperature of the polymer, allows internal interfaces to flow and heal. Annealing can result in mechanical properties comparable to injection molded thermoplastics. To eliminate slump and creep during annealing, and thereby preserve part geometry, two techniques have been demonstrated by Army researchers: the use of a high temperature support shell [3]; and building the parts out of a filament that includes both a low temperature, annealable phase, and a higher temperature phase to stabilize the part during annealing [4,5]. In the shell technique, the part is annealed in the shell and then the shell is dissolved. In the dual material (DM) approach, an internal support skeleton resists deformation during annealing.

The objective of the present study is to demonstrate the practical implementation of thermal annealing for an Army-relevant component. The component chosen is a battery bracket for an M998 High Mobility Multipurpose Wheeled Vehicle (HMMWV). Figures 1a and 1b show the a metal battery bracket on the M998, and Fig. 1c shows an alternate fielded part made using injection-molded, chopped glass reinforced polypropylene. Using the injection-molded bracket as a model, in this study we use FFF to build and test battery brackets and battery bracket test specimens using acrylonitrile butadiene styrene (ABS). Components are evaluated as-printed, as after thermal annealing.

2. EXPERIMENTAL

2.1. Materials and print conditions

Three filaments were used in the present study: Stratasys (Eden Prairie, MN) red M30 ABS filament, Infinite Material Solutions (Prescott, WI) Aquasys 120 HTPVA filament, and a DM filament comprising a polycarbonate (PC) core and an ABS shell. The DM filament was produced by the authors using a filament pilot line from Fibre Extrusion Technology (FET; Leeds, UK) and a specialized die designed to achieve a star-shaped PC core [5]. The DM filament was fabricated using 3DXTech (Grand Rapids, MI) 3DMAX PC and Sabic (Houston, TX) CYCOLAC MG94 ABS.

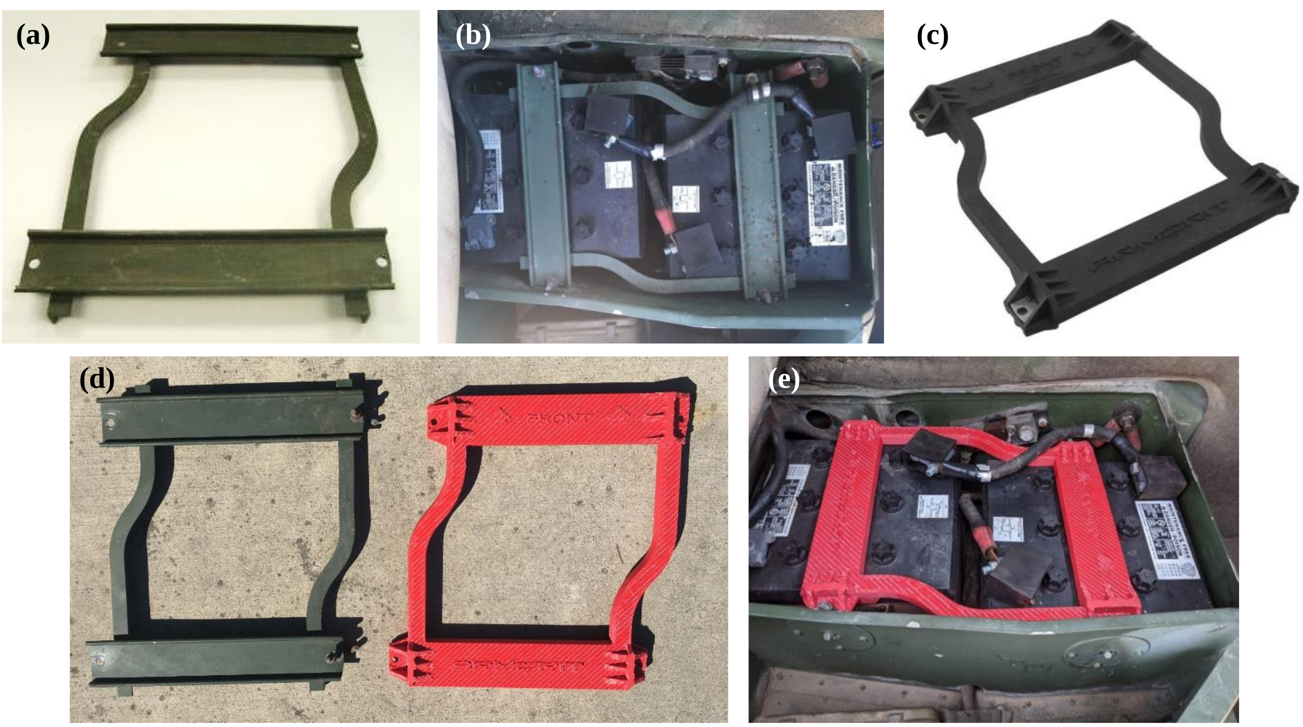

Figure 1: (a) Standard aluminum battery bracket, and (b) installed bracket on M998. (c) Aftermarket injection-molded polypropylene bracket. (d) Comparison of standard bracket and 3D printed bracket, and (e) 3D printed bracket installed on M998.

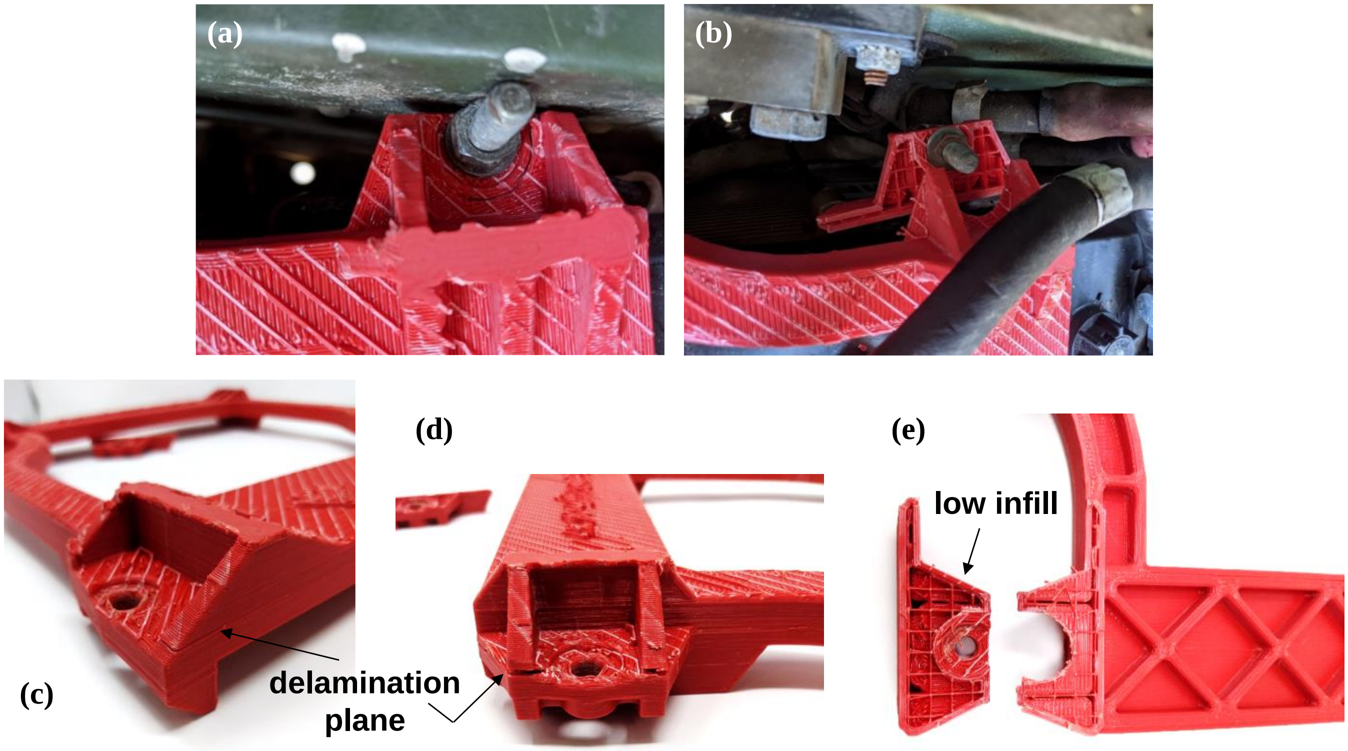

Figure 2: (a,b) Failure of as-printed ABS bracket during M998 installation. (c, d) Delamination failure mode for as-printed bracket. (c) Low infill as a contributor to poor interlayer strength.

Three printers were used to produce comparative bracket quarter-sections: a Prusament (Prague, Czech Republic) Prusa MK3, AON3D (Montreal, Quebec, Canada) M2, and Stratasys Fortus 450MC Gen 2 CF. Full size brackets for fit tests were printed on the AON3D printer. For the Prusa and AON3D prints, a nozzle temperature setpoint of 240°C was used for the ABS and HTPVA filaments; nozzle diameter was 0.5 mm; layer height was 0.22 mm; bed temperature was 90°C; and chambers were unheated during printing. For the Stratasys prints, a nozzle temperature setpoint of 315°C was used for the ABS and DM filaments; nozzle diameter was 0.2 mm; layer height was 0.1 mm; and chamber temperature was 92°C.

A digital model for the bracket was generated by 3D scanning an OEM injection molded bracket, and then converting the surface model to a solid model in Solidworks (Dassault Systems, Waltham, MA). A first generation bracket was printed using this model and default slicer settings, resulting in a sparse infill. Quarter section specimens were modeled as a sub-volume of the first generation bracket model, with some geometric modifications made to improve flange robustness. This model was sliced using Simplify3D 3.0.2 (Cincinnati, OH), with two perimeter shells and a 95% infill. For shell prints, the shell was added in Solidworks and then sliced as a two-line thick perimeter shell against the part surface, with a 25% rectilinear infill surrounding the shell to create a prismatic support box. A final full battery bracket model was generated based on the improved quarter section design.

Stratasys prints required specialized software and hardware setups. Stratasys OpenAM software was used to create a custom printing profile for the DM material via modification of the ABS-G material profile. The extrusion multiplier was

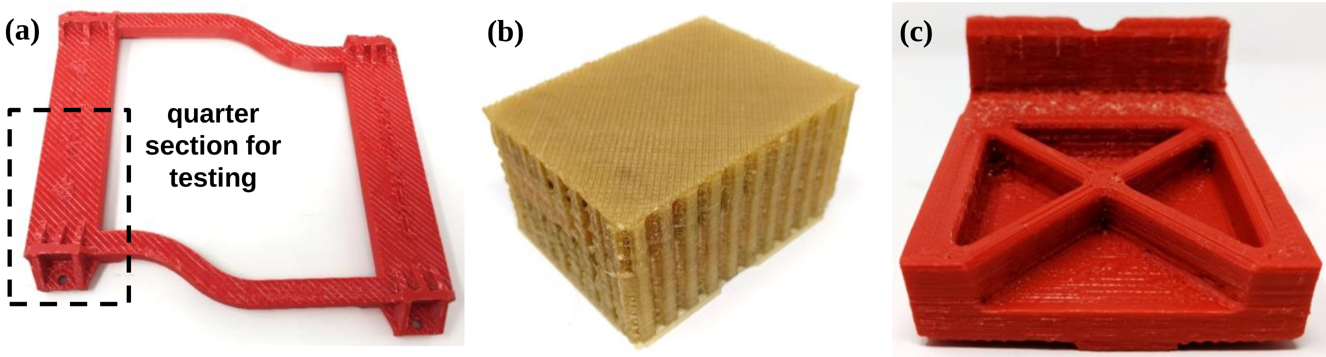

Figure 3: (a) Quarter section area used for load frame testing. (b) ABS quarter section printed in a dissolvable support shell (amber colored material). (c) ABS quarter section after annealing and support shell removal.

manually adjusted to a value of 1.15 to achieve full density parts. The DM filament as an elliptical cross-section shape with a typical major diameter of 1.75 mm and minor diameter of 1.55 mm, compared to the Stratasys proprietary material size of 1.78 mm. This size difference required multiple modifications to the standard filament handling path. The material block that normally feeds materials from the cannister to the print head was bypassed and instead DM filament was fed directly to the print head from a secondary spool. A 1 m length of filament was inserted into the conventional material block and feedpath to provide positive filament detection for the filament path sensors. Finally, a Generic-ABS cannister chip was connected to the printing block via jumper wires to provide a validated material profile.

2.2. Annealing and shell dissolution

For quarter-section testing, eight processing conditions were evaluated. Three ABS sample sets were printed in the Prusa, AON3D, and Stratasys printers without dissolvable shells, and then tested as-printed. Three ABS sample sets were printed in the AON3D printer with a dissolvable shell. For two of these sample sets, after printing the print chamber temperature was raised to 130°C and held for 18 h or 72 h, respectively. For the third AON3D sample set, the specimens were removed from the printer and annealed in an oven at 135°C for 72 h. Two sample sets were printed in the Stratasys printer using DM filament, with one tested as-printed and the other tested after annealing in an oven at 135°C for 72 h.

For shelled prints, after annealing the shells were dissolved by sonicating in warm water (30°C) for 18 h. Some mechanical brushing was used to remove residual shell material.

2.3. Quarter-section testing

Quarter sections were tested using an MTS (Eden Prairie, MN) Synergie Load Frame, with a 5 kN load cell and a displacement rate of 2 mm/min. The quarter section test is configured to simulate the combination of tension, compression, and bending experienced by a bracket flange as the battery hardware is tightened and the bracket bears down on the battery. Three specimens for each of five printing and annealing conditions for ABS in the Prusa and AON3D were characterized; for Stratasys prints, one specimen of ABS and as-printed DM were compared with two specimens of annealed DM.

3. RESULTS

3.1. Shell-annealing

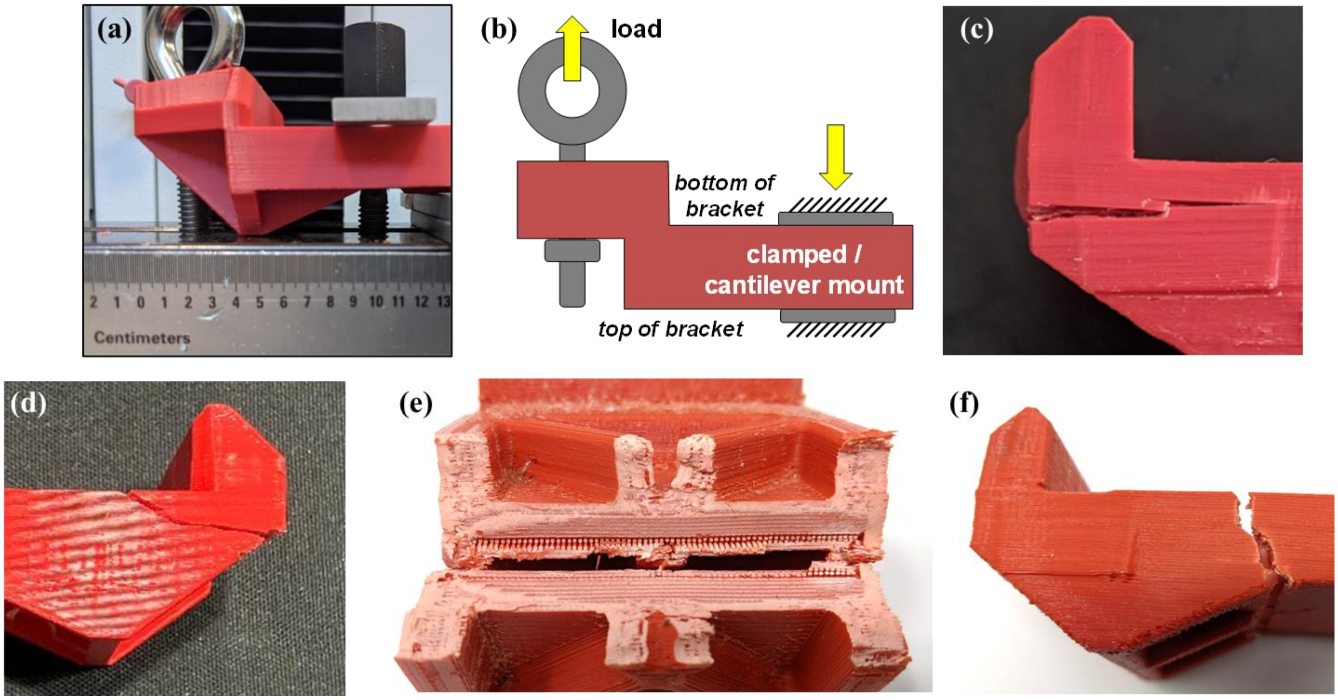

Figure 4: (a,b) Photo and schematic of load frame testing of quarter section. (a) As-printed AON3D and (b) as-printed Stratasys, and (e, f) annealed AON3D specimens after failure. The as-printed samples show significant delamination, whereas the annealed samples fail through layers.

Figures 1d-1e show the first generation, as-printed ABS bracket. The fit and form of the printed part are excellent, and it could be effectively installed in the battery bay. Tightening the hold-down hardware for the bracket, however, leads to bracket failure (Figure 2). The failure mode is primarily delamination between z-direction print layers. It is also evident that low infill in this initial design (Fig. 2e) contributes to the low part strength.

Figure 3 shows a bracket quarter section as-printed with a dissolvable HTPVA shell (Fig. 3b), and after shell removal (Fig. 3c). Print quality is excellent, although the surface finish is rough compared to a non-shelled part. Figure 4 shows the quarter section test, and failure behaviors of the test sections. The AON3D as-printed specimen fails via delamination (Fig. 4c), in a manner consistent with observations during M998 mounting. The Stratasys as-printed specimen fails with a mixture of delamination and in-plane tension. The annealed specimen, exhibits failure through many layers with little delamination (Figs. 4d and 4e). The fracture surface of the annealed specimen is rough and whitened, suggestive of plastic failure and material ductility. Figure 5 summarizes the average peak loads for the quarter section experiments. Specimens annealed for 18 h exhibited failure loads 93% higher than the as-printed quarter sections. Specimens annealed for 72 h were nearly 3× stronger than the as-printed specimens.

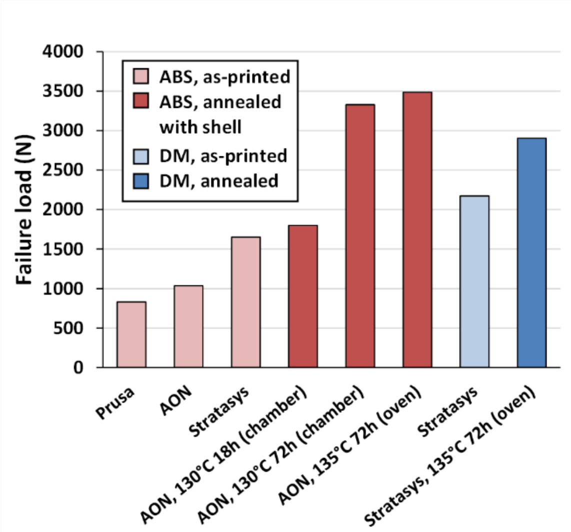

Figure 5: Quarter-section failure load for different print and annealing conditions.

resulting in multiple spools of filament for evaluation (Fig. 6e). The cross-section of filament (Fig. 6f) has a star-shaped core of PC in an ABS body, with a consistently elliptical cross-sectional shape. This ovality results from turning the vertically-extruded filament stream into a horizontally oriented water bath (Fig. 6c).

Quarter sections were successfully printed using DM filament in the Stratasys printer (Fig. 7a), and annealed without measurable deformation (Fig. 7b). Quarter section testing resulted in failure loads of 2173 and 2905 N for as-printed and annealed test specimens, both values considerably higher than as-printed ABS quarter sections. Both conditions resulted in a mixture of tensile and delamination failures. For the annealed DM specimens, failure was observed around the loading lug due to tilting of the loading bolt within the mounting hole at high loads. It is

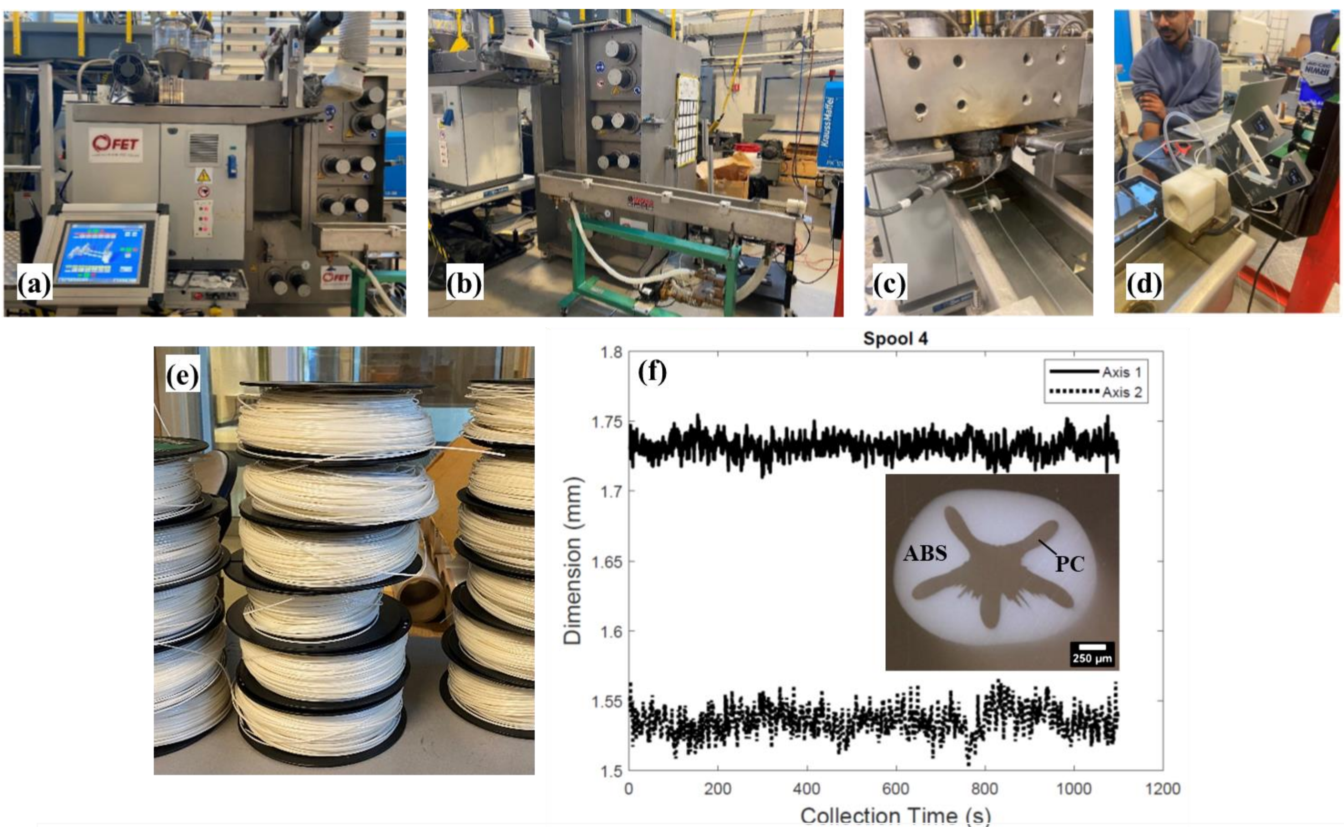

Figure 6: (a-d) Production of DM filament. DM filament (e) spools, (f) diameter data and cross-sectional micrograph.

3.2. Dual-material filament

Figures 6a-d show production of the DM filament on the FET extrusion system, likely that an improved test setup, with continuous vertical loading without tilt, would have reached even higher failure loads. It may also be possible to increase failure loads via improved part geometry. For example, moving the mounting hole locations inward by a few milimeters would increase the area and volume of material supporting the loading hole.

The annealed DM part achieves a load 17% lower than the best annealed shelled ABS. This difference is likely due to the fact that the shell-annealed part is fully dense with ABS, whereas the DM part contains both ABS and PC, as well as interfaces between ABS and PC phases that do not anneal.

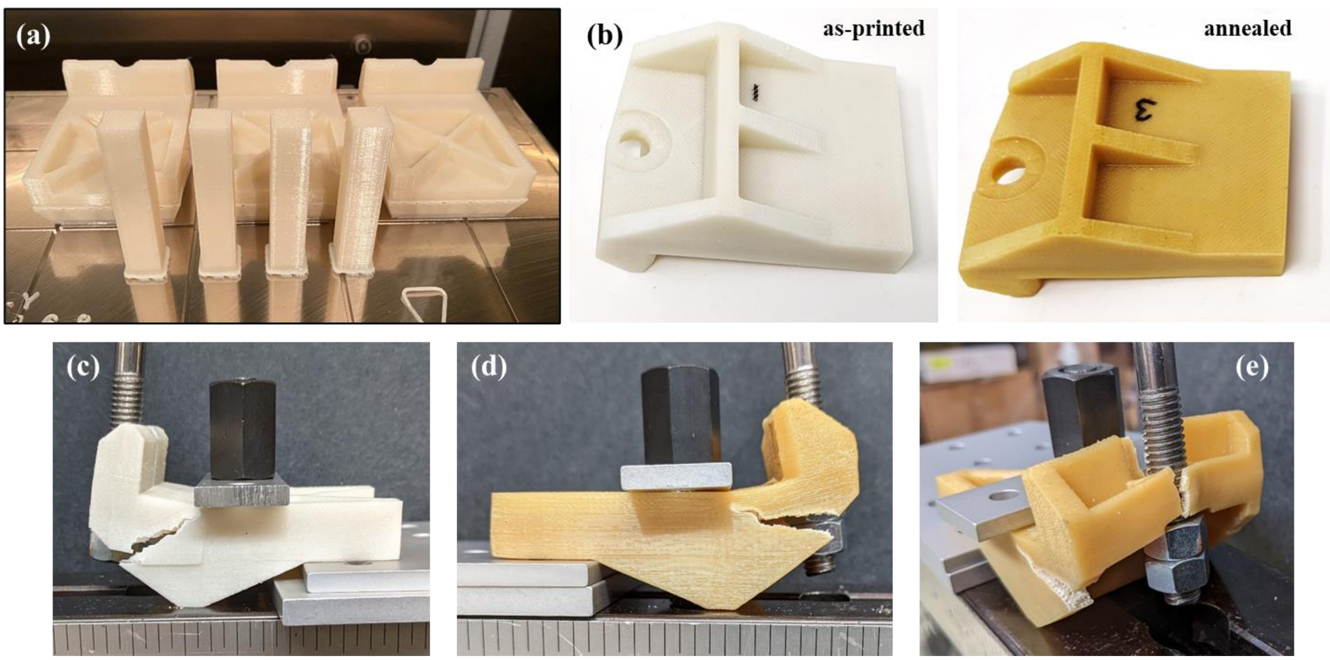

Figure 7: (a) Printed DM test specimens. (b) DM specimens after and before annealing. Images at failure for (a) as-printed and (b, c) annealed DM specimens.

4. OUTLOOK AND CONCLUSIONS

The present quarter-section data suggests that annealing is an effective strategy to dramatically increase the mechanical robustness of 3D printed parts. While shell annealing has proven to be an effective approach, it requires the use of a dual material printer, adds an extra shell removal step, and results in a rough surface finish. Parts printed using the DM filament, in contrast, can be annealed to high strength without requiring a dissolvable shell. The DM filament approach can be applied using a single material printer, and results in a high quality surface finish. The DM filament also allows for higher print nozzle temperatures, because of the stabilizing effect of the polycarbonate core. Full-size test brackets are being printed (Fig. 8) for testing of shell-supported, and DM filament test articles. These will be installed on M998s and characterized based on hold-down torque at failure. Best performing brackets will then be installed on M998s and field tested with the Maryland Army National Guard.

A version of the printed bracket is currently in the Army 3D printing parts database but its usage is restricted due to structural strength limitations inherent in FFF parts. After successfully demonstrating mechanical resiliency in our printed and annealed bracket, our plan is to expand consideration to other load bearing parts, conducting necessary proof testing to expand the range and quality of parts available for Army expeditionary manufacturing.

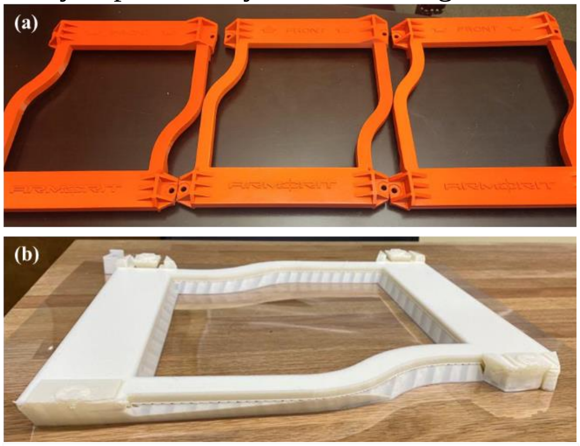

Figure 8: Full battery brackets printed using (a) ABS and (b) DM filament. The DM part failed mid-print, but is being re-printed for evaluation.

5. REFERENCES

[1] Hart, Kevin R., and Eric D. Wetzel. "Fracture behavior of additively manufactured acrylonitrile butadiene styrene (ABS) materials." Engineering Fracture Mechanics 177 (2017): 1-13.

[2] Hart, Kevin R., et al. "Increased fracture toughness of additively manufactured amorphous thermoplastics via thermal annealing." Polymer 144 (2018): 192-204.

[3] Dunn, R. M., K. R. Hart, and E. D. Wetzel. "Improving fracture strength of fused filament fabrication parts via thermal annealing in a printed support shell." Progress in Additive Manufacturing 4.3 (2019): 233-243.

[4] Hart, Kevin R., Ryan M. Dunn, and Eric D. Wetzel. "Tough, additively manufactured structures fabricated with dual-thermoplastic filaments." Advanced Engineering Materials 22.4 (2020): 1901184.

[5] Koker, Brian, et al. "Enhanced interlayer strength and thermal stability via dual material filament for material extrusion additive manufacturing." Additive Manufacturing 55 (2022): 102807.