DUAL MATERIAL SYSTEM FOR POLYMER LARGE SCALE ADDITIVE MANUFACTURING

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ABSTRACT

Big Area Additive Manufacturing (BAAM) technology allows for manufacturing of large-scale objects with a potential to reduce energy embedded in products, reduce or eliminate energy necessary for transportation of goods along with reducing the lead time and cost in some cases. Over the last few years, Oak Ridge National Laboratory (ORNL) has been focusing on large-scale printing of single material systems, typically un-reinforced or short fiber reinforced polymers, in order to address needs in stiffness-limited applications. This paper describes the development of a multi-material large-scale AM system through a collaboration with Cincinnati Inc. and Performance Feed Screw Inc. Modifications to the Big Area Additive Manufacturing (BAAM) system includes a new extruder design to accommodate a dual feed system, an expanded two-dryer system with a capacity of 273 kg/dryer, and a system that is capable of mixing pelletized materials up to 60Kg/hr. This article highlights the advantages and limitations of the multi-material system as well as potential applications.

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1. INTRODUCTION

Additive Manufacturing (AM) or Rapid Prototyping (RP), utilizes metals, ceramics, and composites to produce 3D structures at a low cost and lead time. RP can be achieved through methods such as Fused Filament Fabrication (FFF), Digital Light Processing (DLP), Stereolithography (SLA), etc. to produce small-, mid- and large-scale structures using polymer materials and their reinforced composites [1,2]. Small-scale FFF printing is a standard system commonly used for small prototypes, flexible sensors, and metal printing [2-4]. The process involves heating a filament through a nozzle and depositing layers that range between 0.1 mm - 0.8 mm (0.004 inch - 0.028 inch) in height with nozzle diameters ranging from 0.2 mm - 1.2 mm (0.008 inch - 0.0472inch) with a build volume up to a 28317 cm^3 (1ft^3). Structures fabricated using FFF technique have low volumetric flowrates around 16387mm^3/hour (1$inch^3$/hour) resulting in long build times [5]. Several small-scale systems have recently used multiple extruders in order to print dual materials. Multi-material printing allows users to tune the color, cost, weight, and the mechanical properties throughout the structure [6,7]. Studies have shown that by using multi-materials within a structure, new mechanical responses can be achieved such as increased mechanical properties, soft and rigid robotic structures, impact resistant structures, etc. [6,7]. Other applications include embedded sensors, custom mechanical responses, and changing the color of the part [3,6].

In order to create large articles at a low cost and short time, large scale systems were introduced to print with nozzles ranging from 2.5 mm - 12.7 mm (0.1 inch - 0.5 inch) and a layer height range of 1.27 mm - 8.89 mm (0.05 inch - 0.35 inch). The Big Area Additive Manufacturing (BAAM) system designed by the collaborative efforts of Oak Ridge National Laboratory (ORNL) and Cincinnati Inc., is a large thermoplastic extrusion deposition system with a build volume of 1.5 m × 3.6 m × 2.4 m (5 ft × 12 ft × 8 ft) and a deposition rate up to 45 kg/hr (100 lb/hr) [8]. The BAAM system has been used to manufacture parts such as large-scale prototypes, molds and dies and large lightweight optimized core structures [9-11]. Large-scale AM is currently limited to printing structures with a single material which limits the ability to optimize structure weight, functionality, cost, and layer time.

High performance feedstock materials, such as Polyethersulfone (PESU) and Polyphenylsulfone (PPSU), have been used for 3D printing of high temperature molds and dies [11]. AM compression molds are currently printed completely solid, as the pressures in the compression molding process can exceed 10.3 MPa- 13.8 MPa (1500 psi-2000 psi). The infill material is typically less critical for the integrity of the structure during the printing process, but necessary to prevent deformation during the compression process. Infill in compression molding prevents distortion during the compression process by filling the structure with a packing material to prevent the load bearing perimeters from deforming. Traditionally, a single material is utilized in these infill patterns, where it drives the cost and weight of the manufactured parts up. Cost and weight of structures can be minimized by utilizing recycled materials or foams for the infill. The mechanical and thermal properties of the AM structure are highly dependent on the material, processing conditions, and infill pattern density and direction [5,12-14]. Incorporating multi material printing to the process will allow for tailoring of these mechanical and thermal properties [6,14].

2. DUAL MATERIAL SYSTEM DESIGN

2.1 Design Considerations

There are several approaches for designing a dual material system for large scale AM systems. However, there are several constraints and considerations that must be accounted for in a successful design. The primary considerations can be summarized as:

- Gantry system weight capacity: The BAAM gantry weight capacity was set to a limit of weight of 135 kg (300 lb). This limitation prevents excess inertia during gantry travel. Inertia concerns stem from rapid directional changes during sharp turns which could cause the extruder to shift or move under its own inertia. The standard deposition speed during printing is 0.28 m/second (11inches/second). The weight limitation prevents the addition of a second extruder to the gantry since the current extruder weights approximately 90 kg (200 lb).

- Space limitation: Additional capabilities typically occupy additional space. Since the maximum build volume of the printer needs to remain the same, the optimal design should occupy the minimal volume. Therefore, the new device should either be compact or added above the extrusion deposition line where build volume is not affected. Adding a second extruder would require a large space either on the same gantry or by adding a second gantry system to printer.

- Material switching and purging: Material that dwells in the extruder for prolonged periods of time can lead to problems such as polymer degradation and oxidation. As an example, it has been observed that foam materials tend to degrade when held at temperature for a prolonged time, which could lead to decreased mechanical performance and poor print quality (color changes and expansion decreases). In the case of adding a second extruder, material would need to reside in the extruder for the duration of the printing period of the first extruder. In this case, it would likely be necessary to purge the entire volume of the extruder in order to maintain consistent material properties. This would result in a significant amount of wasted material and excessive layer times. An ideal system would be capable of switching materials quickly with minimal dwell time in the extruder.

- Material type and processing conditions: The compatibility of the feedstock materials being used will be dictated by their chemical composition and processing conditions. A dual extruder system would allow for a wide variety of materials to be printed since they would not be directly blended or required to flow through the same extruder. If the materials were combined near the nozzle exit, a co-axial extrusion system could be used to create a core-shell structure where material A is extruded as an inner core while Material B coats the circumferential of Material A [15]. Although this system could deposit two materials at the same time and switch quickly, the material combinations would be limited to those with compatible chemistries that would enable bonding.

- Deposition rate: BAAM currently extrudes at 45 kg/hr (100 lb/hr) when depositing carbon fiber reinforced acrylonitrile butadiene styrene (CF/ABS). In order to maintain high deposition rates, the dryers and blenders must be able to process materials at a rate greater than the maximum deposition rate.

2.2 Design and Fabrication

In order to successfully develop a dual material system for the BAAM system, several modifications have been made. First, in order to comply with the weight constrains, a dual hopper with a sliding mechanism was designed, see Figure 1. In this system, the feedstock materials can be switched from Material A to Material B at the entrance of the extruder. This allowed for multi-material extrusion through a standard single screw extruder and avoided the need for an additional extruder (i.e. extra 90 kg). To reduce weight, all tubes and pivot brackets were fabricated using aluminum, and high strength steel was used in high stress locations. A sliding mechanism was attached at the entrance of the extruder to allow for material valves to open and close when switching material. The sliding mechanism consists of three primary components: the pivot mechanism, the piston, and maintenance/alignment features (Figure 1).

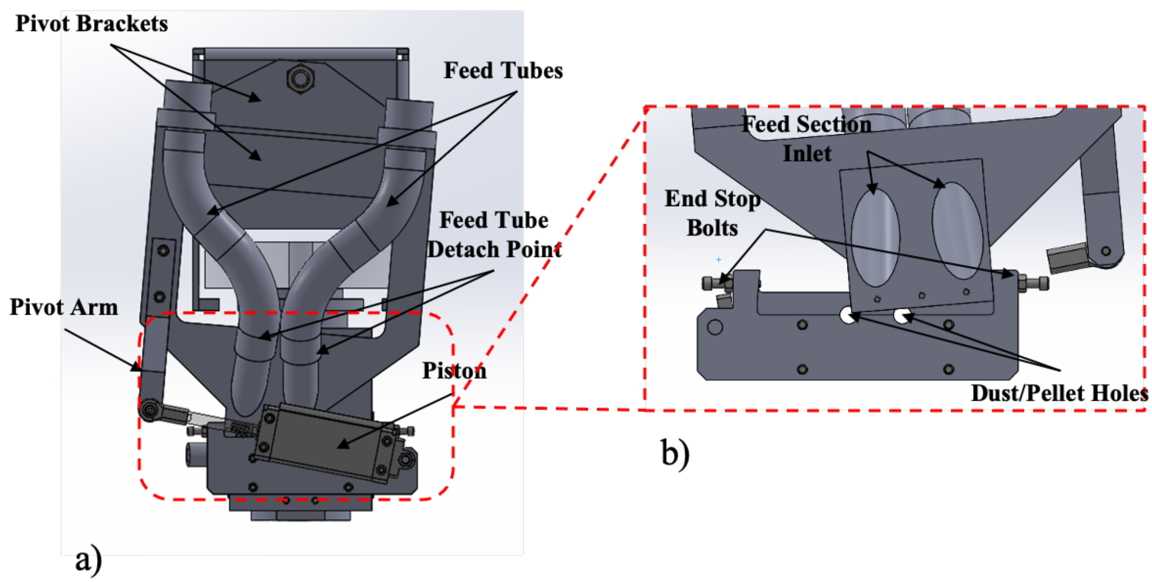

Figure 1. Design for dual material switching mechanism integrated to the BAAM system; a) CAD drawing showing the dual hopper/feeding tubes, sliding mechanism, and controlling piton, and b) Cross section at the extruder entrance showing alignment and dust removal features

Switching material during a build involves pushing or sliding a metal plate to open or close a feed line as seen in Figure 1. The sliding mechanism consists of a pneumatic driven piston that controls a pivot arm that is attached to the feed tubes. The pivot arm transfers the force from the piston to slide the feed line between the two hoppers (Figure 1). A thin profile flexible mount piston that requires 0.689 MPa (100 psi) driving pressure to deliver a force of 547 N (123lb) was used. The piston force must be sufficient to either move aside or shear through pellets that may be blocking the flow path to prevent jamming of the feed tubes. Gravity fed pellets are desired to be as close to a vertical path as possible to prevent bridging in the feed tubes. Small changes in the hopper angle are desired to minimize bridging in the feed tubes because the feed angle changes while switching. To reduce the angular change of the hoppers, the radius from pivot point to the feed entrance was increased. As sliding occurs, pellets blocking the motion must either move into the extruder or shear at the interface of the sliding metal. These locations were fabricated using hardened steel to prevent wear. The piston motion could be adjusted by tuning the location of the end stop bolts (Figure 1b) to align the interface between the feed tube and extruder entrance.

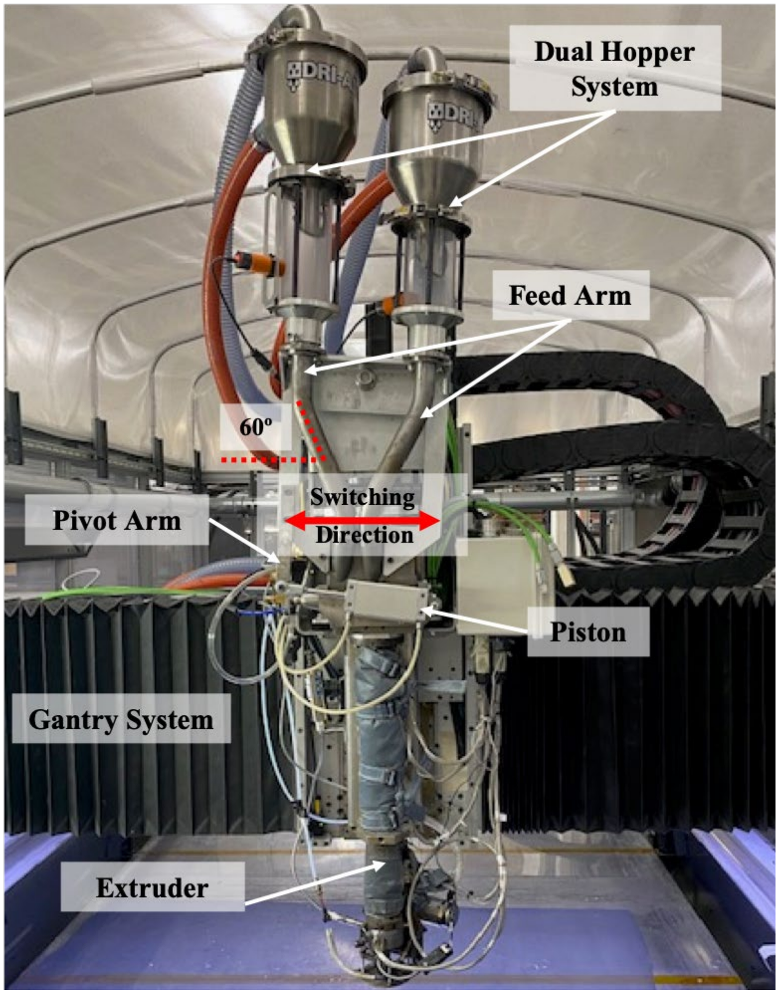

Figure 2. BAAM extruder equipped with dual hopper system

One of the common issues in working with a pelletized feedstock is the containment of the materials in the feed lines. CF dust and pellets are often found around the system throughout the build time, which can result in defects in the part. Also, dust and pellets can block the motion of the switching mechanism and jam the feed lines. To mitigate these issues, two holes were added to the sliding locations to allow for the excess dust and pellets (i.e. occurs during the switching process) to exit the system without damaging any of the system components, see Figure 1b. Applying the dual feed system design to the current BAAM extruder results in system capable of feeding from two separate dyers or blenders, enabling the deposition of functionally graded material or multi-material extrusion (Figure 2)

The BAAM system was fitted with two 272kg (600lb) dryers (DRI-AIR model RH600), used for drying the feedstock materials before the deposition process, as seen in Figure 3. A blender (Maguire model WSB-100 Series) with a precision mixer that is capable of mixing four different materials up to 59 kg/ hr (130lb/hr) was added to the system, see Figure 3. The blender is used for precision mixing of additives, expandable foaming spheres, chemical foaming agents, and various other functional materials. The mixer is equipped with four hoppers such that any ratio between various materials can be accomplished during a single build. After mixing, the material is shuttled to the dual hopper system integrated to the BAMM extruder.

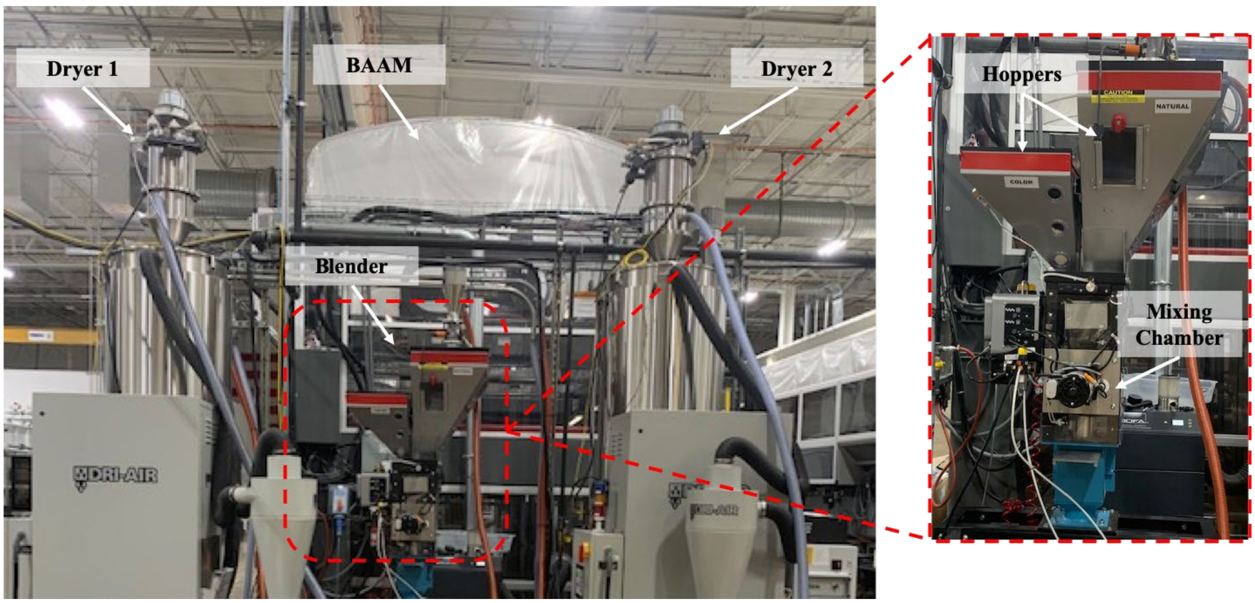

Figure 3. BAAM equipped with dual dryer and blender with zoom out of blender showing hoppers and mixing chamber

3. DEMONSTRATION AND APPLICATION

Dual material deposition and blender capabilities with BAAM has allowed for the printing of structures that demonstrate properties which were unattainable with a single material system. Traditionally, structures that need rigid exteriors have been designed as thin-walled hollow structures, or alternatively a sparse infill has been used with the same material. Dual material printing enables solid or sparsely filled structures to achieve lower cost and weight requirements by strategically placing lightweight structural materials (e.g. foam) in areas where loading conditions are low (Figure 4b). For example, in molds, a high cost and heavy polymer such as PESU can be used on the exterior molding surface while a high temperature foam is used on the interior to reduce the weight and cost. Applications such as wings or turbine blades can be custom designed to use stiffer materials where loads are high and lighter weight materials where loads are low [9]. Dual material printing coupled with custom core structures allows for stiff and lightweight structures (Figure 4d).

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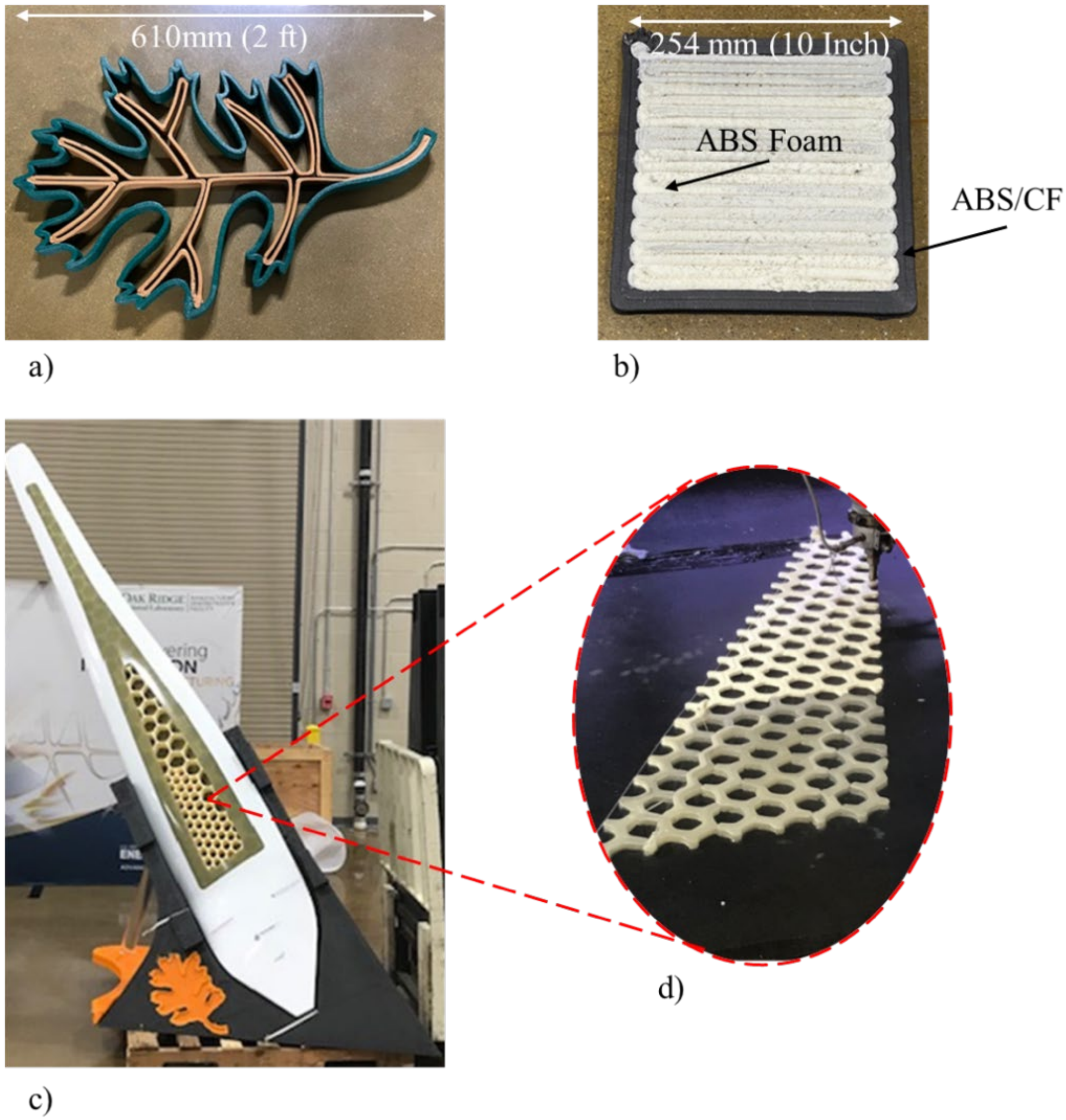

Figure 4. Applications for multi-Material structures showing variations in weight, cost, stiffness, and custom core designs; a) Multi material bio-derived leaf (Green: Bamboo/Polylactic Acid (PLA) and Brown: Wood flower/ PLA), b) Flat panel showing ABS foam used for lightweight structure by strategic placing of foam in infill pattern with a ridged CF/ABS exterior, c) Optimized PLA foam core structure for a turbine blade, and d) Zoom out for the functionally graded core during printing process

Reinforcing fibers such as CF, Bamboo Fiber (BF), and Glass Fiber (GF) are often added to base resins to provide higher stiffness and reduce warping of the printed parts. Fillers in polymers typically increase the cost and weight of the material and the impact on mechanical property performance depends on the type and amount of filler used. Dual Material printing enables placing materials with various fillers or neat resins throughout a part to tailor mechanical response in certain locations. Locations with high stiffness requirements can be printed with a CF filled material, and areas with low thermal properties and lower stiffness can be printed with a GF filled material. Similarly, Figure 4a shows how a fiber filled bio-derived material exterior and a low-cost bio filler interior are printed utilizing the dual hopper system. Utilizing the printing process and dual hopper system, structures with local reinforcement can be achieved as well [16].

Blended material compositions can also be altered during the build to define site-specific material properties. Modifying the material composition during printing creates some challenges as well. For example, printing with a combination of foaming and non-foaming materials can affect the geometry of the build (layer height, bead width) depending upon the local foaming conditions. Changes in bead and layer height must be accounted for in the toolpath such that material has enough space to deposit and does not overbuild and cause collisions. Currently, high expansion foams are extruded only on every other layer because the layer height for the foam is twice that of normal non-foamed materials. Blending four different materials can create structures where elasticity, strength, and weight are altered rapidly. For instance, building with a blend of thermoplastic polyurethane (TPU) and CF/ABS can result in highly stiff elastomers for high toughness applications. Recycled materials can also be blended with the virgin material to reduce waste in the AM and industry process to create a more eco-friendly printing environment.

As materials transition from one to another, a transition zone must be either purged (the process of clearing the printer's barrel for next transitioned material) or deposited into the structure before a virgin material can be deposited. If this material is purged, the layer time increases and allows the structure to cool. For many structures, an increase in layer time can lead to defects as well as poor layer-to-layer adhesion, causing delamination and failure. Similarly, in the case of foams, as material cools, the size of the layer height and bead width shrink, changing the proper spacing and placing defects throughout the structure. Rather than purging the transition material, it can be printed into a non-critical portion of the structure. Although this would remove defects from purging, it would modify the overall mechanical performance of the structure. Therefore, studies are currently being conducted to determine the impact of the material transition on the mechanical properties throughout the transition zone. For instance, it has been found that in the transition zone from CF ABS to neat ABS, a 96.68 cm^3 (5.9 in^3) volume of material is deposited, and mechanical properties may vary depending on filler content and base resin dominating in this zone [17]. Understanding how the transition occurs and the mechanical properties of the structure changes enables engineers to switch materials ahead of time such that the unstable mechanical properties appear in a non-critical section of the structure

4. CONCLUSION

BAAM extrusion-based printing can often manufacture large structures at a lower cost and faster rate than traditional manufacturing. However, the structures have been limited a single material, which limits the ability to have different local mechanical properties across the structure. Equipping the BAAM with a dual material system enables articles to be designed and printed with rigid and stiff exteriors with foam interiors, as well as different stiffness materials for custom impact and compression responses. Currently the dual hopper design is limited by temperature because both materials need to have similar processing conditions. The system also needs to account for a purge and/or transition zone to fully transition between materials. In future work, values for calculating the volume required to fully transition between materials will be determined and integrated into the slicing software such to minimize the waste during multi-material prints.

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