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Reviewed Paper

Characterizing Material Transition for Functionally Graded Material Using Big Area Additive Manufacturing

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Abstract

This study examines functionally graded materials (FGM) on a polymer based large scale additive manufacturing system. FGM utilizes a less expensive material with sub-optimal mechanical properties for the majority of the part, and uses more expensive higher performance material in selected areas. This process aims to optimize cost with weight and mechanical performance. FGM is already used a variety of industries, but is not common place in additive manufacturing, specifically large scale additive manufacturing like Cincinnati Incorporated's Big Area Additive Manufacturing (BAAM). BAAM can use a variety of plastic injection molding and extrusion style polymer pellets, which allows it to use both commodity materials and high performance engineering polymers. This study is an initial assessment of FGM using glass fiber reinforced ABS and carbon fiber reinforced ABS, and characterizes the performance of a density gradient shape function to characterize the blending of materials.

I. Background

Big Area Additive Manufacturing (BAAM) is a large scale 3-D printing system that is significantly larger and faster than most filament-based polymer extrusion systems. BAAM has a build area of approximately 2.5 meters by 6 meters with 2 meters of vertical travel. A high throughput, single screw extruder is mounted to the gantry that deposits beads of material ranging from 2.5 mm to 9 mm in diameter at a rate of 40 kg per hour. In addition, BAAM uses injection molding grade thermoplastic pellets instead of wound filaments. The most commonly used pellets are carbon fiber reinforced acrylonitrile butadiene styrene (CF-ABS), which range in price from $10 per kg to $20 per kg based on fiber loading and manufacturer. Glass fiber reinforced ABS (GF-ABS) has inferior mechanical and thermal properties, but costs around $2-$4 per kg. [1]

Figure 1. Big Area Additive Manufacturing system front view [2]

One particular benefit of additive manufacturing is the ability to tailor mechanical and thermal properties to a specific application. The local properties of a component can change based on internal structures, infill designs, and even material selection. This study is an initial examination of creating tailored properties using functionally graded materials with BAAM. Functionally Graded Materials (FGM) allows the use of a less expensive material with sub-optimal mechanical properties for the majority of the part, and a higher performance material in selected areas. This process aims to optimize cost with weight and mechanical performance. One basic example of an FGM application is a simply supported fiber-reinforced-composite beam that transitions from pure fiberglass at one end, to pure carbon fiber at the center, and back to pure fiberglass at the other end. In this example, the desire is to minimize deflection at the center of the beam by replacing the cheaper glass fiber reinforced material with a stiffer carbon fiber reinforced material. [3]

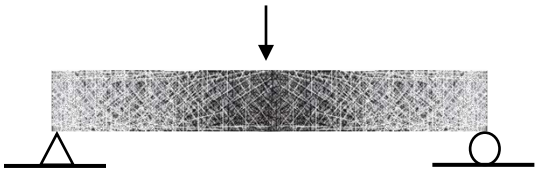

Figure 2. Illustration of a fiber-reinforced-composite simply supported beam that transitions from fiberglass to carbon fiber to fiberglass again, where white lines represent fiberglass and blacklines represent carbon fibers . [4]

The same principle of a simply supported beam with FGM can be applied to BAAM to optimize weight and cost of a printed part. A beam made entirely of GF-ABS material is five times cheaper than a CF-ABS beam, but weighs more, is more prone to warping, and will deflect more under load. A FGM beam aims to optimize the cost, weight, thermal, and mechanical properties.

The goal of this experiment is an initial assessment of the ability to transition materials using BAAM to create FGM structures. Since BAAM utilizes a discrete pelletized feedstock, it is possible to vary the composition of the extruded material by selectively mixing the pellets in

the feedstock section of the BAAM system. In addition, BAAM uses a single screw extruder, and sudden change in the feedstock materials will mix in the extruder to produce an output that gradually transitions between the two end states In the case of this study, the feedstock material is changed from glass filled ABS to carbon filled ABS during the extrusion process, and a characteristic shape function was defined to depict the transition between the materials. The shape function establishes the lag time between the input of the pellets and the output of the extruder. The shape function illustrated in Figure 3 estimates the fiber content of the extruded polymer at any given time, with the first vertical dashed line representing the lag time, or time required for the change in material to start occurring. The second dashed line represents the saturation time, which is the time required to reach a steady state value following the transition.

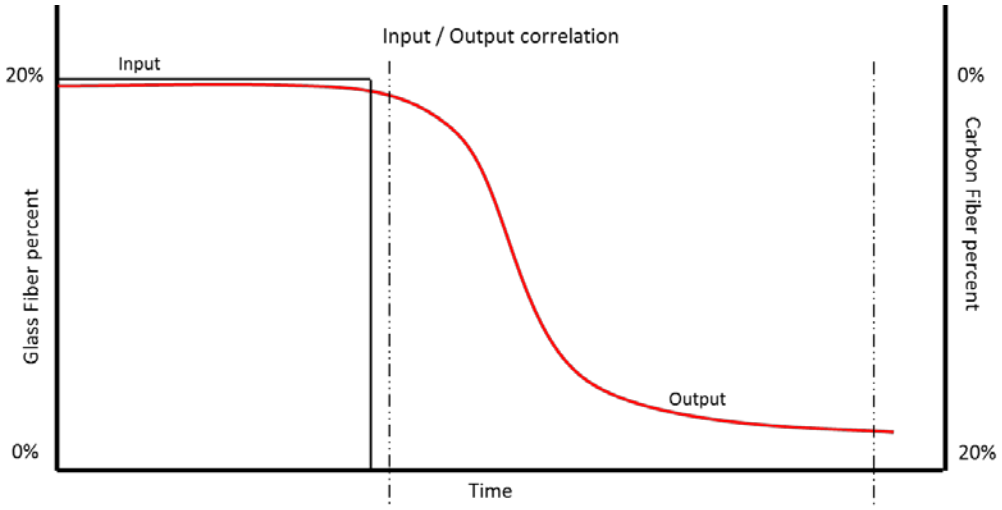

Figure 3. Characteristic shape function that defines the transition in material.

A. Materials

The pellet feedstock materials utilized for this study were 20% by weight Glass Fiber-ABS (GF-ABS) and 20% by weight Carbon Fiber-ABS (CF-ABS) were supplied by Techmer Engineered Solutions. The materials were dried at 65ºC for four hours.

B. Extrusion system

The Cincinnati Incorporated BAAM system utilizes a custom, single screw extruder with five heating zones and a single feed hopper (Fig. 4). The barrel is approximately 24-inch-long with a screw specially designed for processing fiber filled ABS. The screw has a maximum speed of 400 RPM, which correlates to a mass throughput of ~40 kg per hour.

For this experiment, pelletized GF-ABS material was directly added to the hopper and extruded at a screw speed of 100 RPM (10 kg/h). At this speed, the extruder has a residence time of 24 seconds, which is a measure of the amount of time required for a pellet to travel through the extruder. A sampling rate of 8 seconds was selected to capture three data points during a given pellet's residence time in the extruder. In order to minimize unintentional mixing of pellets of different composition within the hopper, the transition between materials occurred in a "starve feeding" condition, in which all of the pellets of a given composition were completely consumed within the hopper (partially exposing the extrusion screw intake region) before a charge of pellets of a different composition were introduced. This approach insured that

materials mixed in the extruder rather than inside the hopper. In this case, the starting material was GF-ABS with a red dye to visually distinguish it from the 500 mL charge of black CF-ABS. Figure 5 illustrates the transition in the extruded material from completely red GF-ABS (far left), to a mixed GF/CF-ABS (middle), to a saturated (predominantly black) CF-ABS on the far right. The transition represented in Figure 5 occurred over a period of 80 seconds, with 8 second intervals between samples.

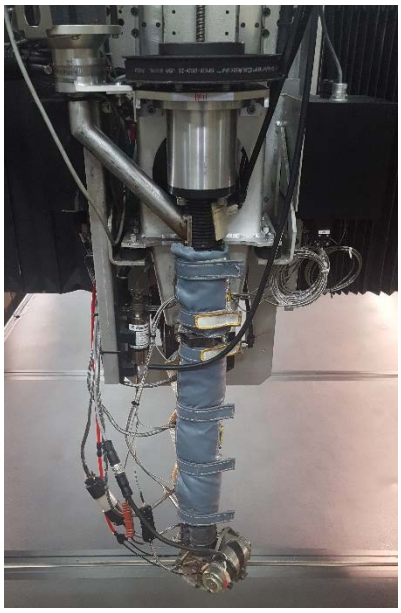

Figure 4. BAAM extruder.

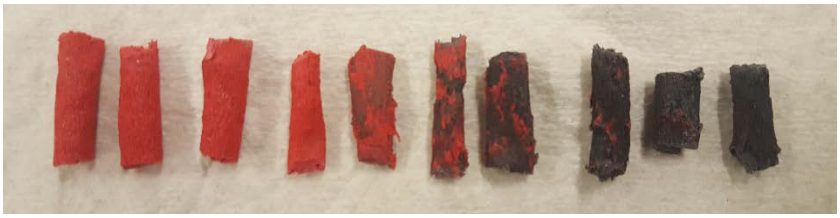

Figure 5. Extruded samples transitioning from glass fiber filled ABS (right) to carbon fiber filled ABS (left).

In order to quantify the transition between materials and generate a characteristic shape function, the fiber content in each of the samples was measured with Thermogravimetric Analysis (TGA). TGA measures the weight loss of a small sample of a material as it is heated. The samples in this study (Figures 5,6) were heated to 800ºC at a rate of 10ºC per minute in air.

Figure 6. (Right)Universal Analysis Q500 TGA system [4]. (Left) Samples in TGA pans

III. Results

The fiber content of each sample can be quantified through TGA by analyzing the weight loss characteristics of each sample. In each case, the ABS matrix completely burns off in two stages; first styrene acrylonitrile (SAN) around 350C, followed by polybutadiene (PB) around 550ºC. The remaining sample is the combined weight of the glass or carbon fibers, which should be roughly 20% based on the average feedstock designations. As the temperature increases above 600ºC, the carbon fibers begin to pyrolize in air, leaving the only the remnant ash and glass fibers behind. Figures 7 and 8 show TGA results for the GF-ABS and CF-ABS pelletized feedstock materials, respectively. As expected, the samples experienced around 80% weight loss after the ABS burned off at 550ºC. The glass fibers remained constant around 20.5% of the starting weight. The carbon fibers burned off past 550ºC, but the fibers left behind 4.725% weight in ash.

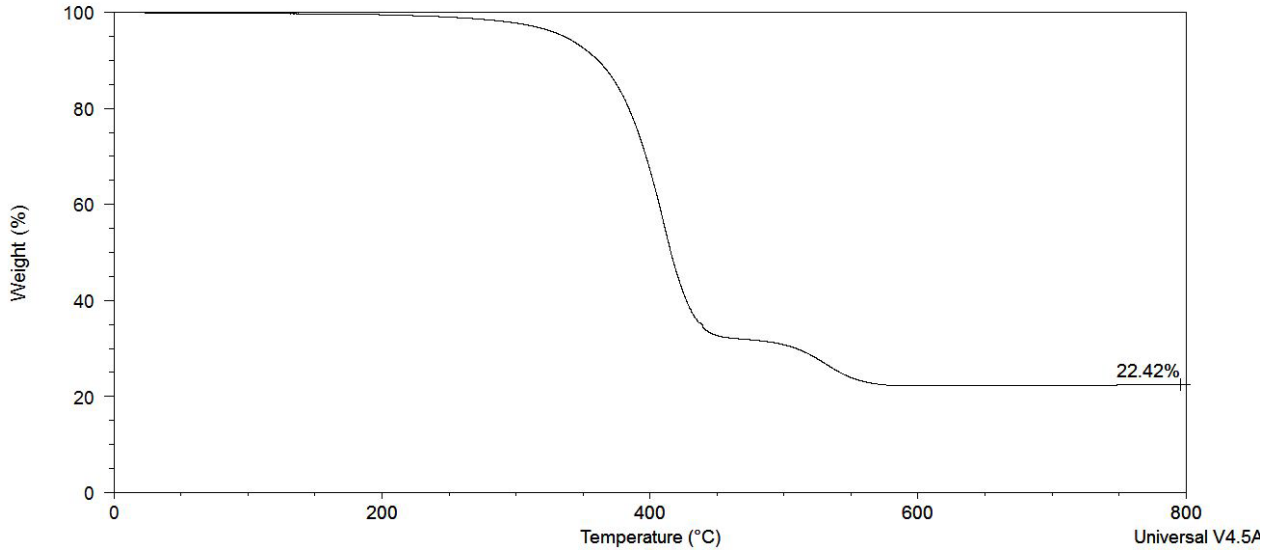

Figure 7. TGA of GF-ABS pellets. ABS is burned off around 550ºC and the fibers remain in the tray

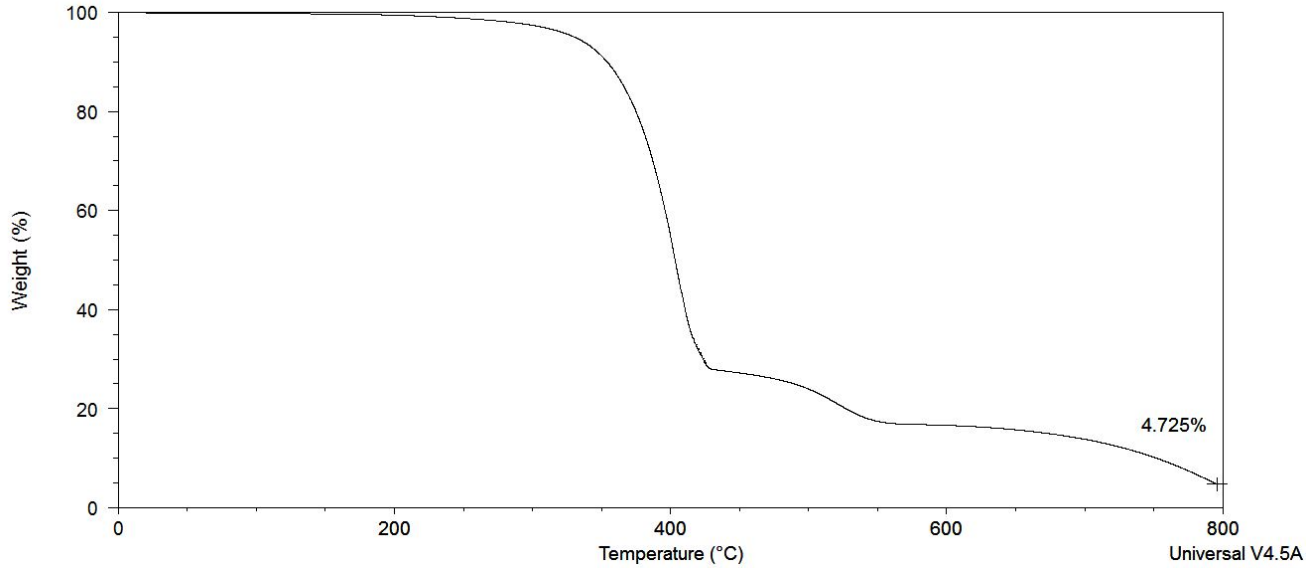

Figure 8. TGA of CF-ABS pellets. The carbon fibers burn off and leave residual ash at 800ºC.

The TGA plots for the extruded samples shown in Figure 5 are collected in Figures 9 and 10 below. The sample number in the legend corresponds to the time stamp and respective residual weight % listed in Table 1.

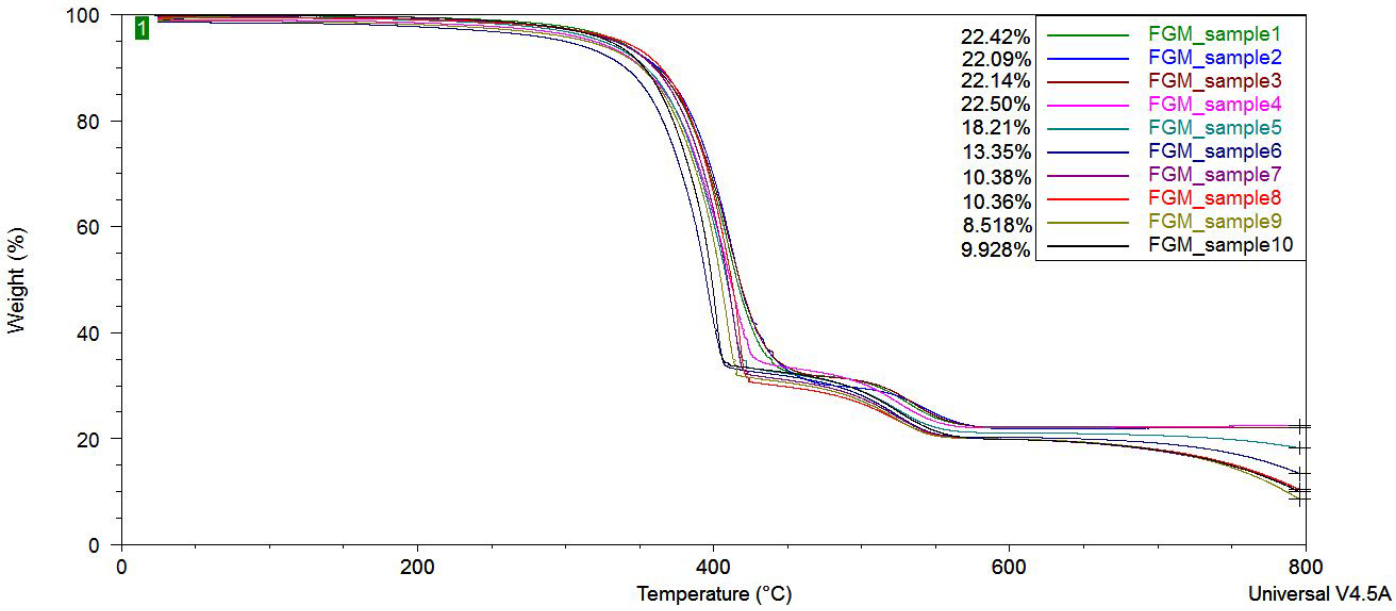

Figure 9a. TGA plots of sample 1-10 with values for residual fiber shown in the upper left hand

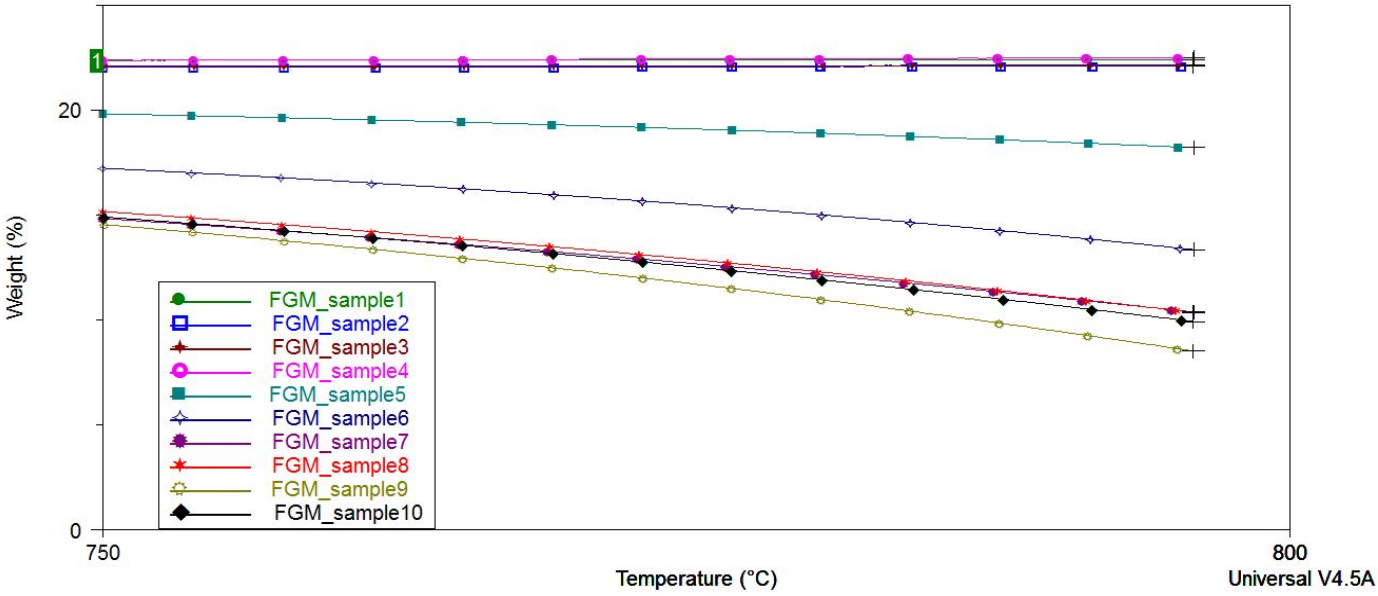

Figure 9b. Section view of plots showing the difference in weight loss percent for each sample.

Table 1. Weight percent values at 800C for each sample

Sample	Time (s)	Weight %
GF pellet	N/A	22.5
1	8	22.42
2	16	22.09
3	24	22.14
4	32	22.5
5	40	18.21
6	48	13.35
7	56	10.38
8	64	10.36
9	72	8.518
10	80	9.928
CF pellet	N/A	4.73

Since the remaining weight percent value at 800ºC (Table 1) correlates to the amount of glass fiber and residual ash for a particular point in sampling time, a system of equations was developed to relate the weight loss percent in Table 1 to fiber concentration.

$$X + \frac{4.73}{22.50}\, Y = W$$
$$X + Y = 22.50$$

X = % GF Y = % CF W = weight percent

Equation 1. System of equations to correlate weight percent values in Table 1 to glass and carbon fiber distributions in a sample. In the equation, X and Y are the unknown values of glass and carbon fiber percent, respectively; W is the value obtained from TGA.

The difference between the GF-ABS baseline and weight percent value of a sample correlates to the amount of glass fiber remaining after the carbon fibers have burned off. However, because carbon fibers leave residual ash while burning off, the difference is corrected by a linear factor of the carbon fiber pellet baseline of 4.73. Table 2 lists the glass and carbon fiber concentrations in each of the samples as well as the initial feedstock materials. The glass fiber concentration was plotted in Figure 10 against time to observe time dependency of fiber concentration (i.e. the shape function illustrated in Figure 3). Note that as the percentage of glass fiber content drops, the percentage of carbon fiber content increases accordingly.

Table 2. Weight percent values at 800C for each sample and associated fiber concentrations

Sample	Time (s)	Weight %	X (GF)	Y (CF)
GF pellet	N/A	22.5	22.50	0.00
1	8	22.42	22.40	0.10
2	16	22.09	21.98	0.52
3	24	22.14	22.04	0.46
4	32	22.5	22.50	0.00
5	40	18.21	17.07	5.43
6	48	13.35	10.92	11.58
7	56	10.38	7.16	15.34
8	64	10.36	7.13	15.37
9	72	8.518	4.80	17.70
10	80	9.928	6.59	15.91
CF pellet	N/A	4.73	0.01	22.49

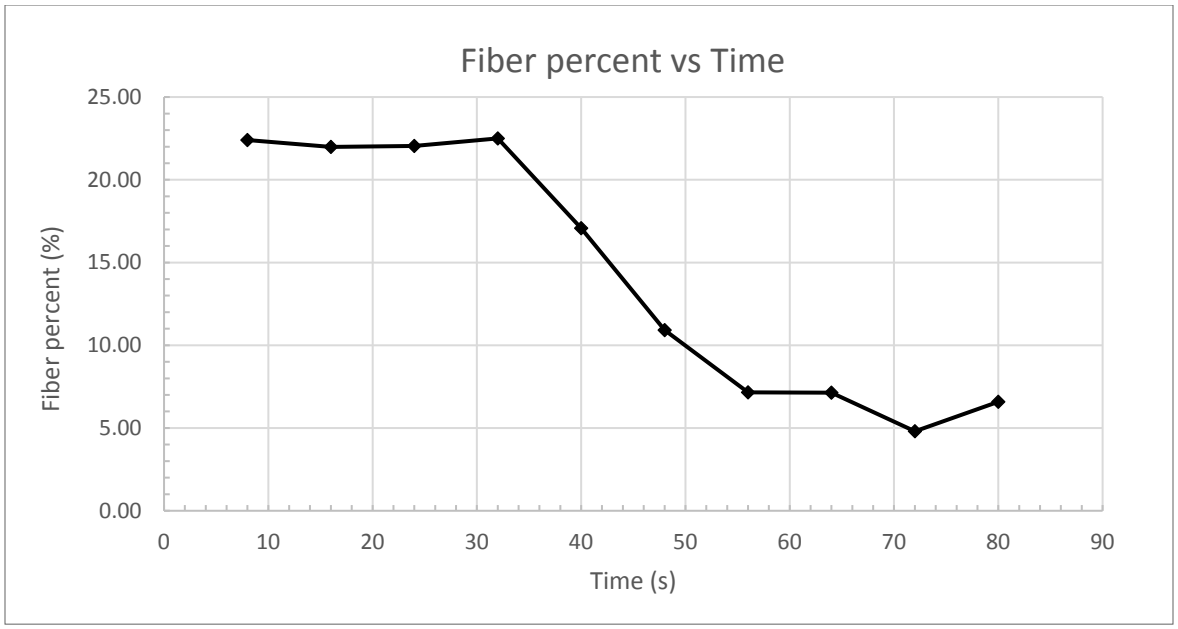

Figure 10. Fiber content vs Time plot using values from Table 2

The shape function in Figure 10 indicates that the transition from glass fiber to carbon fiber reinforcement occurs roughly 32 seconds after the CF-ABS was introduced into the extruder. Also, the time required to reach a steady state of carbon fiber content is approximately 53 seconds. At a spindle speed of 100 RPM, the BAAM extruder travels at ~3 inches per second. Under these conditions, the BAAM system would deposit up to 8 feet of material during the time required to initiate a material transition (32 s). Once the material transition is initiated, an additional 5 feet of deposited material would be required to achieve a steady state condition for the second material.

IV. Conclusions

The unique pelletized feedstock of BAAM allows materials to be mixed during the printing process, which can be used to create functionally graded materials. The study was an initial assessment on transitioning from glass fiber filled ABS to carbon fiber filled ABS. Glass Fiber-ABS was extruded, and then 500 mL of Carbon Fiber-ABS was introduced into the extruder. Samples were taken every 8 seconds after the introduction of carbon filled material. Thermogravimetric analysis was performed on the samples, and the weight loss at 800ºC was correlated to the glass/carbon fiber content of that sample. The glass fiber content was plotted against time to observe the characteristic shape function for the transition and to quantify the lag time before the transition was initiated (32 s) and the saturation time required to complete the transition (53 s). Under the deposition conditions of BAAM, these times correspond to deposited lengths of 8 feet and 13 feet, respectively, to initiate and complete a material transition. These initial results have not been statistically verified, and could vary as tests are repeated. Future studies will focus on reducing both time constants by testing at higher RPMS, different input functions that pre-blend pellets, and multiple transitions .

V. Acknowledgements
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