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EVALUATION OF DISSOLVABLE ADDITIVELY MANUFACTURED MOLDS AND SUPPORTS FOR ELECTROIMPACTS INNOVATIVE ADDITIVE MANUFACTURING PROCESS

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ABSTRACT

Electroimpact inc. has developed a new additive manufacturing process involving continuous fiber reinforcement along with high-strength thermoplastics. A unique part of this process includes using additive manufacturing to print a base geometry that is then used as a tool for continuous fiber placement. Ideally the tool should be disposable and cost effective. After printing the base tool, continuous fiber is printed on top of the tool using a secondary additive head on the same system to create the final printed part. After continuous fiber printing is completed, the tool is removed and disposed of to leave only the final desired structure. Materials used for the base tool have several requirements that must be met in order to complete this process. First, the material must be rigid and strong enough to support the loads from the secondary printing operation (continuous fiber printing). In addition, the material must be able to adhere to the secondary process material as well be capable of being removed such that the only remaining structure is continuous fiber composite. Using innovative soluble materials allows for parts to be produced through additive with molds that are produced as non-reusable one-off shapes and sizes.

1. OBJECTIVES

- Develop a methodology for producing dissolvable molds/mandrel via large scale additive manufacturing process to aid Electroimpact's tape layup process.
- Process parameters development, including tuning of extrusion temperatures, printing speeds, motor torque management and managing the thermal history.
- Evaluating the molds/mandrel dissolvability and establishing dissolvability process parameters (i.e., temperatures, water pumping digitation, etc.).

2. TECHNOLOGY DESCRIPTION

Additive Manufacturing (AM) enables unique capabilities that standard production methods are unable to compete with, particularly cost, lead time, complexity, and mechanical property tailoring. Many common structures, molds, and tests are one-off components and can be made in a fast low-cost method by utilizing an AM process. While most AM systems on the market specialize in printing objects layer by layer using a standard plastic, metal, or ceramic, other AM systems such as automated tape placement (ATP) processes exist as well. ATP is commonly used to build continuous fiber reinforced composites with varying ply directions on top of a mandrel or substrate. Metal based substrates can be used in the ATP process to wrap a continuous fiber part, followed by the removal of the continuous fiber structure from the metal substrate. The removal process can only occur if the geometry of the substrate allows for the continuous fiber wrap to slide off the metal without collision, thus limiting possible geometries. In addition, metal substrates are required to be machined from billets to create the desired substrate geometry adding cost and lead time to the fabrication process. AM can be utilized to create base print structures in a time efficient and relatively with low cost.

Standard materials such as Carbon Fiber (CF) reinforced Acrylonitrile butadiene styrene (ABS) can be used to create rigid base structures that can be machined and support the loads during the ATP process as well as provide the necessary adhesive properties for the continuous fiber composite to adhere to the substrate during the wrap print. Geometry limitations for part removal; however, are not able to be overcome unless the base substrate can be broken down, melted, or dissolved. CF/ABS can be broken down by acetone simply by sonicating the liquid encasing the substrate print. Acetone digestion of the polymer; however, can be expensive, time consuming, and hazardous when conducted at larger quantities. Ideally, polymers that can be dissolved using water as the solvent are ideal for removing the substrate print. New material developments have led to the capability to manufacturing parts that can be dissolved with water using a pellet fed extrusion system. Electroimpact Inc. and Oak Ridge National Laboratory (ORNL) are currently investigating the use of AM as well as ATP to produce large scale components at scale by utilizing dissolvable mandrels and Polyether ether ketone (PEEK) continuous fiber on a robotic platform.

3. MATERIAL TESTING

Materials processed using extrusion-based AM systems are optimized in extrusion/bed temperatures, thermal history, and tuned for each individual extruder model. While the baseline parameters can be used as a starting point, due to differences in the shear, barrel length, maximum motor torque, etc. each extruder design will have different limitations on what can be processed and how fast materials can be pumped through the system. For instance, a system with a 1ft extruder length and only two heat zones and a small extruder motor may not be able to extrude a material due to torque limitations while a larger more powerful extruder may be able to process the material without issue. Simultaneously, in some cases, by altering some the extrusion rates and temperature profiles, both systems may be able to run the material but at different throughput proportionally. Initial print trials were conducted using the Big Area Additive Manufacturing (BAAM) technology at ORNL to create baseline extrusion profiles, gain an understanding of material behavior, and produce testing coupons for machining/adhesion tests for the ATP process. BAAM print tests were conducted using three different water dissolvable polymer formulations. Base prints were created though manufacturing of single wall hexagons. These walls where manufactured such that a cut off wall would exceed 14x14 inches for a suitable machining and ATP adhesion testing area [Figure 1].

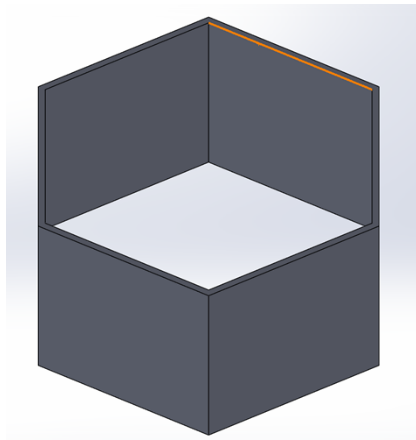


Figure 1: CAD model of BAAM print test hexagon for ATP samples.

Different dissolvable materials grades were used in this work. The temperature profile for the different grades varied due to the different melt temperatures and flash points of the various formulations [Table 1]. During the initial printing process, the first formulation was observed to have large amounts of warping and distortion as well as very brittle response both of which are not ideal for mandrel manufacturing. This material was excluded from the machining and ATP adhesion tests. Both the second and third material showed less warping and were machined flat by Electroimpact. Material formulation two showed smooth machining with no signs of cracking or breakage during the machining process. However, the third formulation while machinable tends to crack or break during machining making the material more difficult for end use. ATP adhesion tests were conducted on both surfaces and was proven to work using both material formulation [Figure 2]. Based on the testing results, the second material formulation was determined as the ideal candidate for production.

Table 1: Extruder temperature settings on the BAAM for printing the three developmental polymers.

	Extruder Temperature Settings on BAAM (°C)		
	Material 1	**Material 2**	**Material 3**
Barrel Zone 1	182	210	210
Barrel Zone 2	188	210	215
Barrel Zone 3	196	215	220
Barrel Zone 4	204	220	225
Nozzle Tip	210	225	230

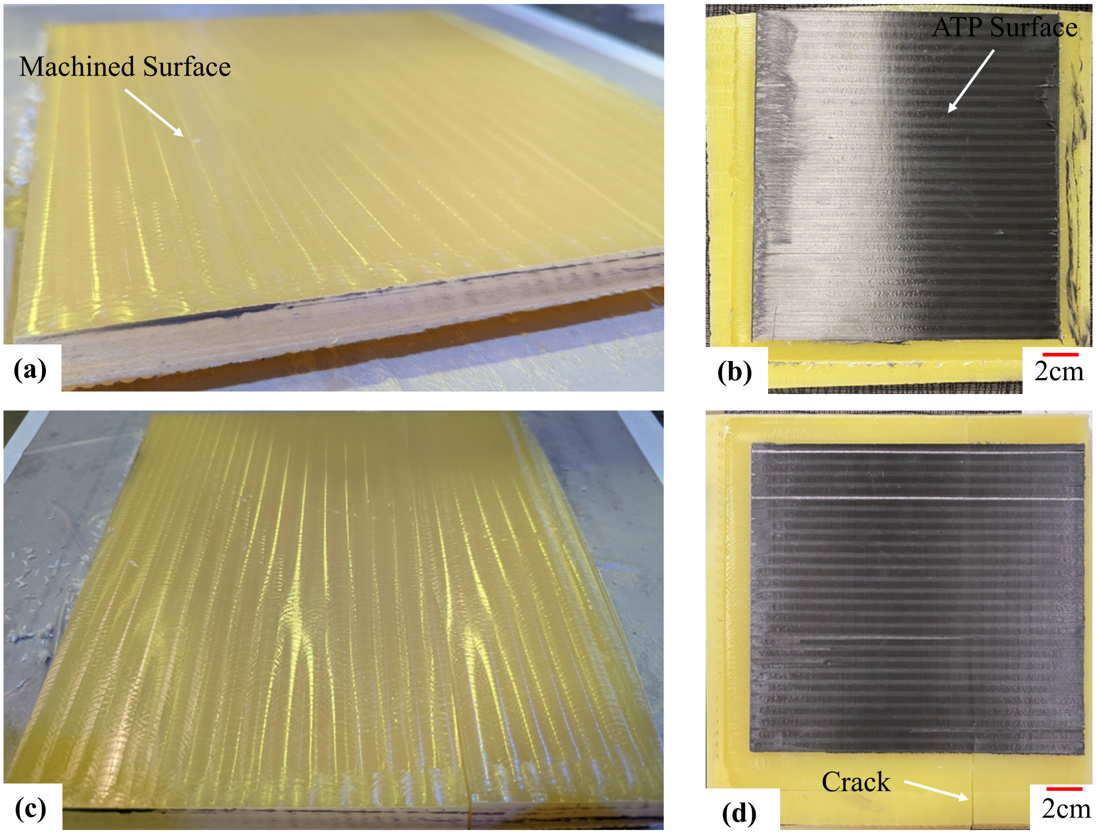


Figure 2:Machined large scale AM samples and ATP Trials for varying material formulations; a)Machined surface of second material formulation, b)ATP on top of second material formulation,c)Machined surface with crack during machining of third material formulation.

Secondary print trials conducted at the Electroimpact facility, Washington utilize the extruder used for their robotic arm AM and ATP hybrid process. As different extruder designs have different limitations, heating zones, barrel lengths, etc. processing conditions for the materials are required to be tuned for each individual system. The second formulation was the primary focus of testing as the best machining and ATP results came from this exact material mixture. Printing structures with various temperatures as well as overhang angles coupled with torque observations on the motor, print defects, and warping/cracking allow for optimization of the process.

Initially, hexagon prints are created to optimize extrusion temperature and layer time without concern of wall collapse from overheating. During the print trials, several samples created failed due to over-torque motor faults. These over-torque events occurred due to the high viscosity of the polymer and can be lowered by increasing the processing temperature. Later trials where over-torque was removed; however, showed signs of internal bubbling and air pockets formed by the polymer overheating [Figure 3]. Overheated samples have a chance of being polymerized which causes the polymer to lose its dissolvability which is a critical feature for the desired results.

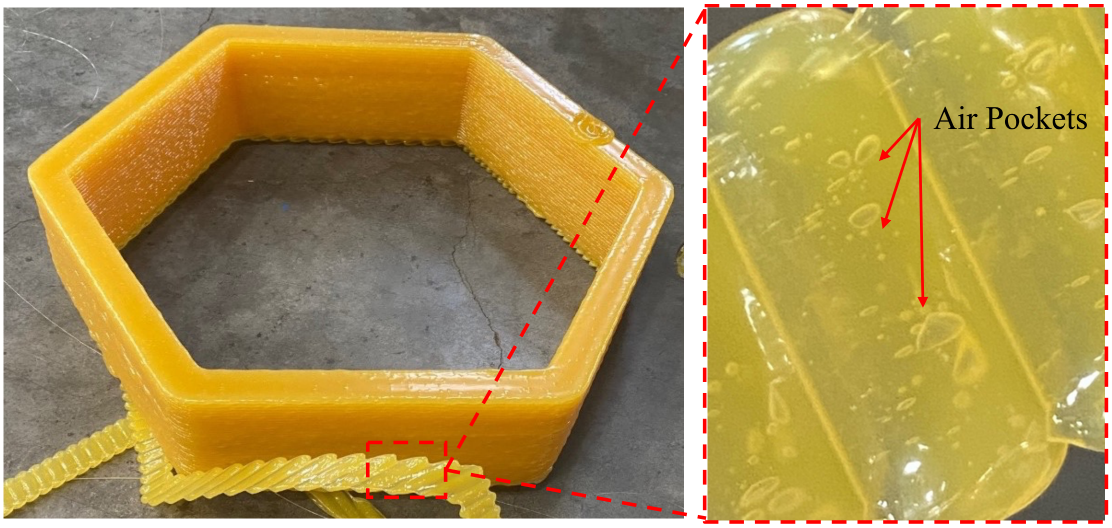


Figure 3: Large scale AM hexagon samples test print with signs of overheating.

Despite the overheating observed, a secondary geometry test was conducted without addressing the overheating as the material was able to flow from the extruder well without motor faulting out. The secondary geometry consisted of a cone design with a 45º overhang to investigate for wall collapse. Overheating signs were observed in the overhang test as well as some non-uniform bead thickness leading to a wavy appearance on the outer wall [Figure 4].

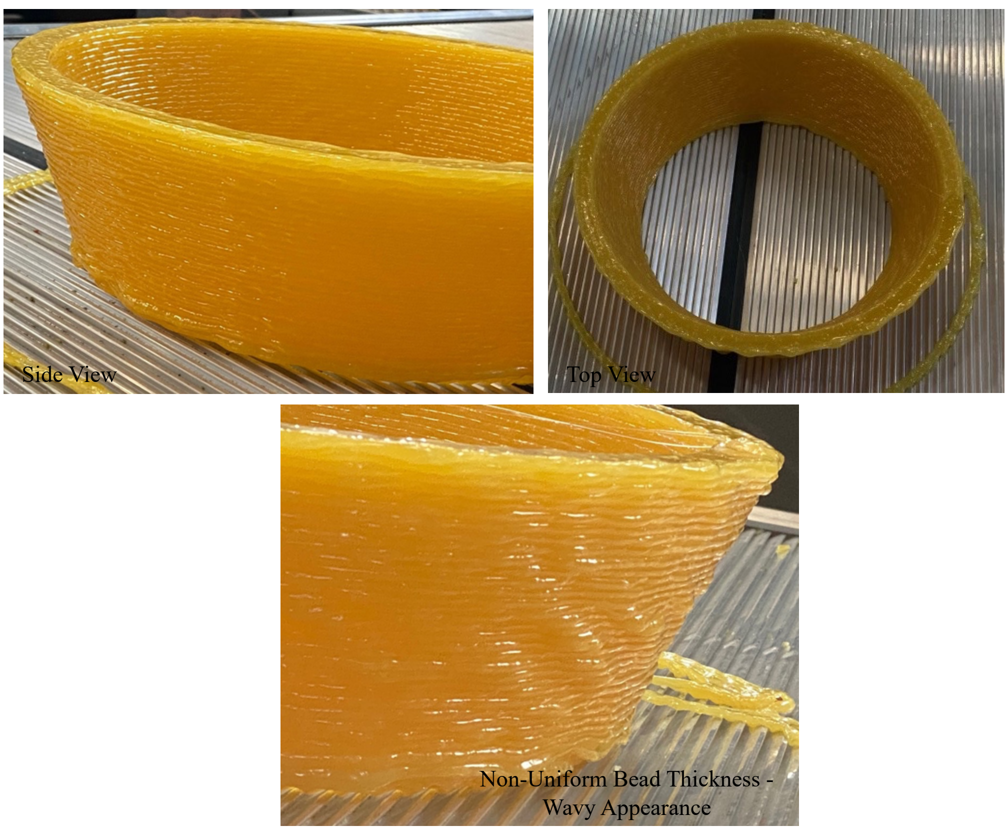
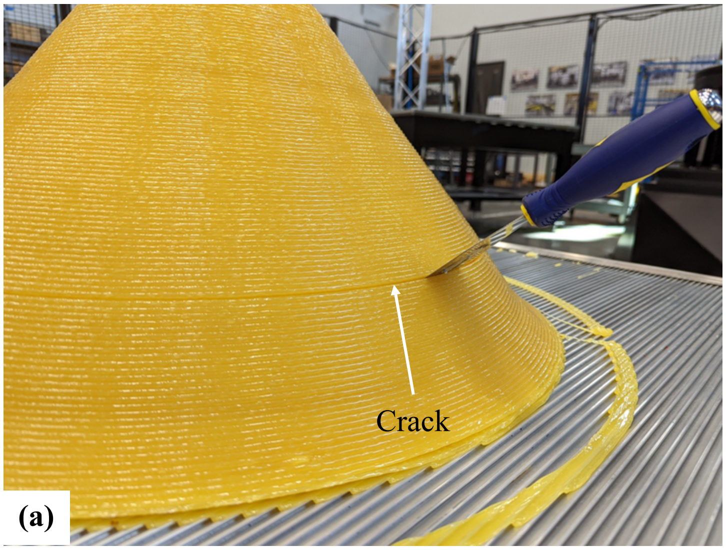


Figure 4: Overhang print test (45º) with overheating showing signs of non-consistent bead width and wavy appearance.

After successful overhang prints were achieved, further tuning was conducted on the temperature profile for the extruder to prevent extruder faults and overheating from occurring. Adjusting the temperature profile created a part that showed no signs of overheating as well as no apparent bubbles along with no motor faults triggered (over torque) during the printing process. During printing parts with long layer times/larger part diameters, the material high Coefficient of Thermal Expansion (CTE) and building residual stresses led to crack propagation [Figure 5a]. It was observed that when the diameters begin to get smaller, the parts begin to overheat and part walls start to collapse [Figure 5b]. Currently the material is being modified to lower the CTE and prevent future failures from occurring. Cooling methods during printing could be added in future runs to aid the cooling of the material to allow printing short layer times without resulting in part wall collapse.



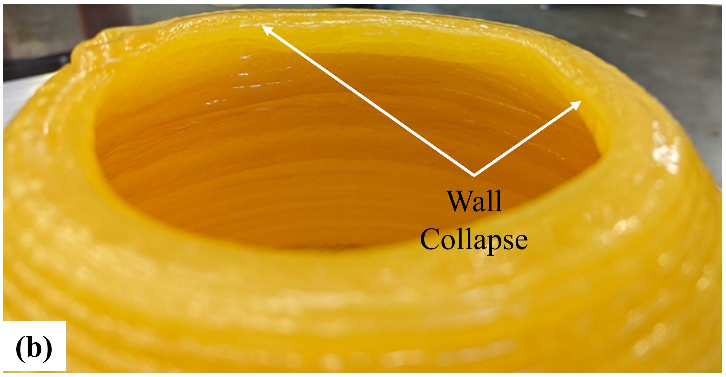


Figure 5: Optimized extrusion temperature print for a conical shape; a) Crack due to long layer time and high material CTE, and b) Wall collapse due short layer time and temperature build up.

After the printing, machining, and ATP processes are completed, the base printed structure must be dissolved from the continuous fiber structure. Variables such as water agitation and temperature will alter the time required to fully dissolve the printed structure. Room temperature water with and without agitations showed very slow and prolonged dissolvability and was observed to be non-desirable. With a pump added to the water tank to create water flow and with the water heated to 180F, structures with approximately 0.3-0.5in thickness are dissolved in approximately 48hr. Water temperatures below 160F appeared to dissolve little to no material.

4. Impacts

Incorporating dissolvable polymers in the AM process enables several key advantages. Multi-material printing allows for dissolvable supports, as well as allowing for the creation of dissolvable mandrel printing. These mandrels can be utilized for filament winding as well as for ATP processes. While conventional metal mandrels are used for many shapes, geometry and cost restraints can limit the use of the ATP technology. Incorporating the dissolvable material printing with the pellet fed system creates a base structure for a mandrel support. After printing, the polymer is machined and then wrapped with a continuous fiber composite followed by a dissolving process. Utilizing a water based dissolving polymer is a cost effective, less hazardous, and cleaner option than other alternatives such as breaking down ABS in acetone. Optimizing the water flow within the dissolving chamber as well as temperature can aid in speeding up the process of breaking down the support mandrel to further decrease the overall lead time and cost for the part as well as ensure that all the support material is broken down and removed from the continuous fiber wrap. While the process may need to be tuned for the different systems (primarily on the mandrel printing side), the general processing conditions and limitations shown can be used as a baseline for industries looking to utilize this technology.

5. CONCLUSIONS

Additive manufacturing can be used to create end use products, design tests, and mandrels in a fast low-cost method. Utilizing dissolvable materials enables the practice of creating mandrels used for filament winding or ATP processes. Electroimpact has created a machine capable of printing base mandrel structures using a pellet feed extruder as well as machining and ATP. Water soluble structures can be critical for creating removable mandrels for this process without introducing hazardous, costly, or environmentally unfriendly methods. Processing these materials requires a large amount of extrusion profile optimization to prevent machine over-torque issues as well as material overheating, cracking, and wall collapse from occurring. The materials used must also be able to be machined without getting damaged and handle the loads from the ATP process. The ATP materials must also be able to adhere to the printed structure. For the base structure to dissolve away, the water tank must have the water agitated as well as heated above 160F. Future work will need to be conducted to further optimize the material formulation to help prevent cracking, wall collapse during low layer times, and reduce the torque on the printer to prevent machine faults from occurring.