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Reviewed Paper

A COMPARISON OF LAYER DEPOSITION AND OPEN MOLDING OF PETG BY FUSED PELLET FABRICATION IN AN ADDITIVE MANUFACTURING SYSTEM

A. Gibson*, J. M. Weaver*
*Department of Manufacturing Engineering, Brigham Young University, Provo, UT 84602

Abstract

Additive manufacturing continues to offer new possibilities in both production and economics. The industry has quickly adopted it to rapidly produce parts that would be difficult or cost preventative otherwise. Recent innovation has expanded its capabilities, however there are still significant limitations. Most AM processes are restricted by materials available, in producing large parts, or by not achieving material deposition speeds to make certain products feasible. In addition, tight tolerances for features and surfaces cannot be produced without substantial post processing. High-speed Fused Pellet Fabrication (FPF) in combination with Hybrid Manufacturing (HM) offers expanded capabilities as additive and subtractive process are used within the same space. It also allows for a different kind of additive process where an open mold can be cut from a substrate and then filled using the FPF process to fabricate parts without layers. This, in combination with Large Area Additive Manufacturing (LAAM), enables parts that leverage the strengths of new and traditional methods at scales and speeds previously unavailable.

Introduction

Additive Manufacturing (AM), often referred to as 3D printing, is a process that creates a three-dimensional part by building it up layer by layer. There are a variety of polymer materials that an AM system can utilize through deposition or curing to create each layer. These materials are usually in the form of a filament, wire, powder, or resin. Each have their advantages and drawbacks, but they all allow for parts that would be difficult, time consuming, or impossible to create through machining or other traditional subtractive methods. Even still, there are limitations on the speed and scale that these processes can produce at. For decades AM has been relegated to prototyping, this however is changing because of advances in hardware and software. The flexibility and increasing speed allow for smaller runs or one-offs to be produced with lead times and costs that make it feasible and profitable. Multi-material parts are also becoming more common as they offer improved properties and functionality [1]. More and more goods are being produced directly by AM processes and there is increased effort to expand the capabilities of AM technology.

High-speed Fused Pellet Fabrication (FPF) systems are a recent innovation in additive manufacturing. This system is a pellet fed which allows for more material to be rapidly extruded than in a filament or powder-based machine. A specially designed extrusion screw retrofitted on to existing spindle-based platforms (such as a CNC mill) heats, stirs, and pressurizes the material and extrudes it as fully melted plastic. Being spindle driven allows for the production of parts in which the size is only limited to by the size of the machine it is attached to. This is one example of what is referred to as Large Area Additive Manufacturing (LAAM) [2,3,4]. In addition, a CNC mill brings with it the ability to utilize traditional machine tools in-line with the LAAM process.

This combination of additive and subtractive capabilities is called hybrid manufacturing and presents great potential for allowing new methods and strategies to rapidly create parts and tooling that would have been more difficult, expensive, or time intensive to produce through traditional methods.

Hybrid systems will be able to leverage this in switching between the additive extrusion head and subtractive tools. This would open doors to increased production of multi-material parts and provides more options in design [1]. There is also growing interest in printing parts made from low friction polymers for moving parts, mechanical systems and joints. There has been much research done for traditional methods, but only on limited materials in additive and not on a hybrid system [5,6]. It is well suited for the hybrid process as friction interactions between bearing surfaces require tighter tolerances then any additive process can deliver alone.

Methodology

The devices used in the project include a HAAS Mill and a Hybrid Manufacturing Technology XTRUDE (FPF additive process) There is a hopper that dries and feeds the pellets into the print head where the mill spindle drives a heated screw which melts, compresses, and extrudes plastic into a continuous 6mm bead. The coolant lines were modified to blow compressed air in order to regulate the temperature of the material as each layer was printed in order to keep the part wall as uniform as possible and reduce warpage from the heat that would accumulate as the part was built up. In order to produce the most consistent flow of material for testing samples, a simple pattern was selected so that parts would be as consistent as possible in process as well as dimensions. The design was then processed by a developmental beta slicer created by Oak Ridge National Labs [13]. This produced G code that was run on the mill where the feed rate and spindle speed were tuned over a number of experimental runs to get the best results for the individual plastic. In this paper the results from the PETG samples produced will be discussed.

To characterize the material properties of the prints, Type 1 samples (165mm overall length) according to the ASTM D638 standard were to be tested for tensile strength. Because of the nature of layer deposition, and the weakness associated with interlayer bonds, samples were produced in both the in line with direction of deposition (x direction) and perpendicular to the direction of deposition (z direction). The x direction samples were run with the screw temperature of 265 degrees Celsius, spindle speed of 90 rot/min, a feed rate of 0.029 m/s, depositing 196 cubic mm of material per second, and the compressed air blowing at 15 psi. The Z direction prints were run at the same speed and feed, but with 30 psi as the smaller footprint and taller part would accumulate more heat during printing.

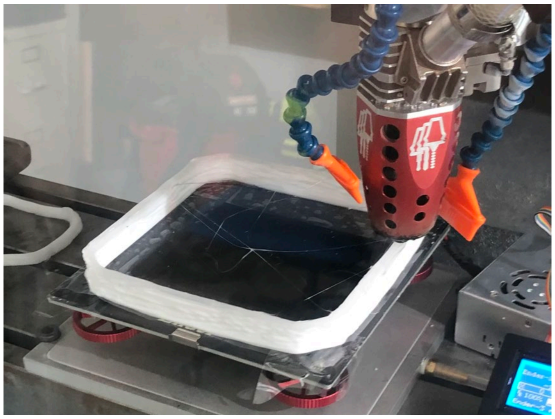

Figure 1: FPF Layer Deposition Printing (X Direction Part)

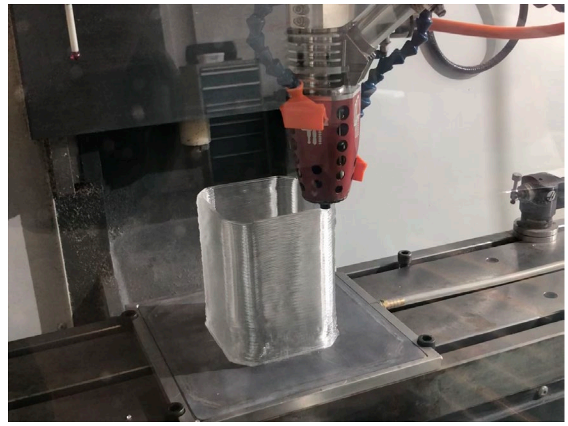

Figure 2: FPF Layer Deposition Printing (Z direction part)

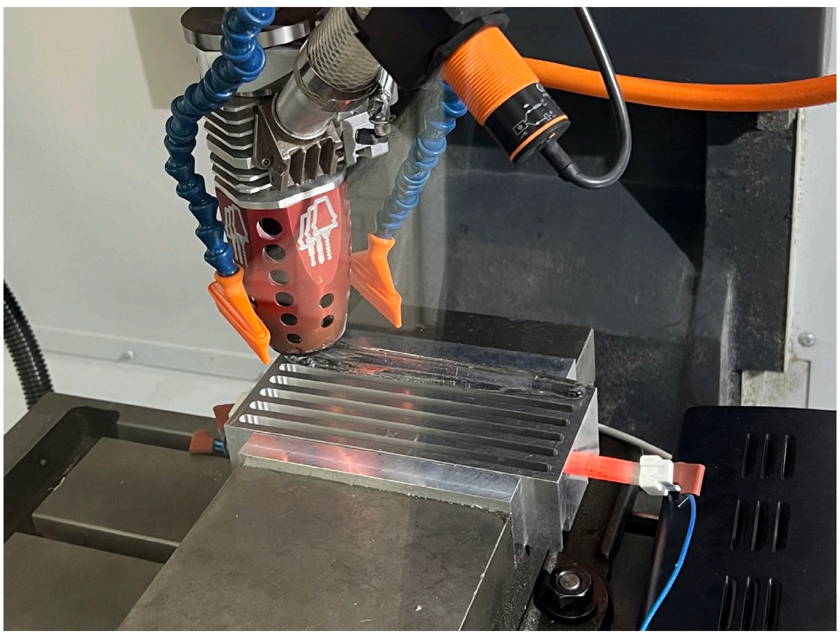

Figure 3: FPF Open Molding

In addition to this, this system can extrude much larger amounts of molten plastic than other forms of additive manufacturing. This allows for a different approach to depositing material to form a part. In this study it took the form of an open mold. An aluminum mold was created with a slot 32mm in depth, 6mm wide and 178mm long with a 1-degree taper from the base to the opening to allow clearance for the part to be removed after cooling. The print head would then hold 3mm from the opening and extrude into the mold with a spindle rate of 30 rot/min and move across the opening with a feed rate of 0.021 m/s until the cavity was filled. This produced a continuous part that was free of layers.

After all parts were produced in each orientation, 5 standard size samples of each were machined where material was removed from all 6 sides using a 12.7 mm 2 flute end mill at a spindle speed of 1500 rot/min and a feed rate of 0.016 m/s. They were then cleaned and deburred in preparation of the testing (See Figure 4). The samples were kept in a dehumidifying cabinet after machining to maintain the integrity of the material. These samples were then prepared and tested on a Mini Instron device with an Epsilon laser extensometer, pulled at a rate of 46 mm per minute (See Figure 5).

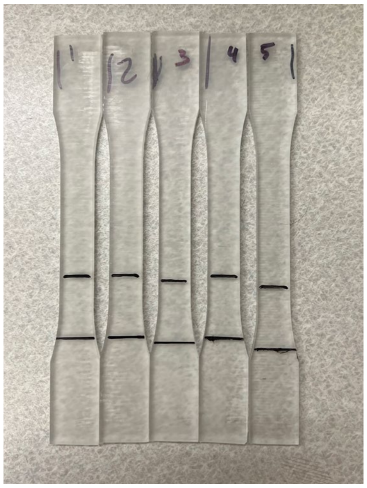

Figure 4: Machined and Prepared Samples

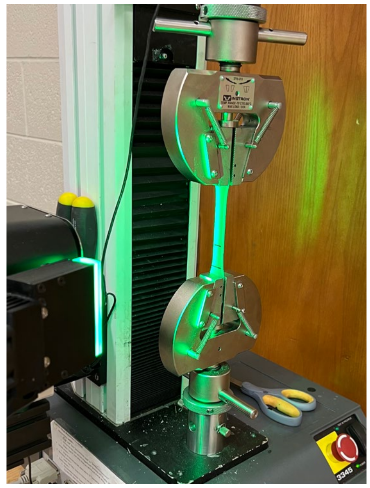

Figure 5: Tensile Testing

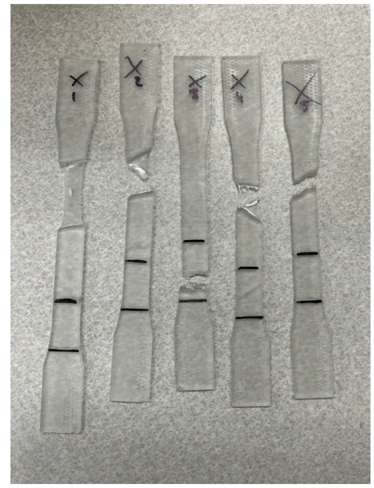

Figure 6: Tested Samples

Results

Table 1 shows the results for the test samples with the layers in the x direction or direction of deposition (layer direction), and samples of the z direction or perpendicular to the direction of deposition (against layer direction), and the samples that were open molded (no layers). Yield strength was determined by the 0.2% offset method.

Table 1: Tensile Test Results

	Average Tensile Yield Strength	**Standard Deviation**
Layer direction	51.17 MPa	0.67133
Against Layer Direction	47.82 MPa	1.13075
Open Molded	49.41 MPa	1.34927
Manufacturer Injection Mold Data [11]	50 MPa	n/a

Some notable characteristics of each set of samples is that both the open molded and layer direction samples experienced significant elongation, ranging from 6mm to 18mm. There were a few samples the broke after the maximum tensile strength both sets, but the majority had visible plastic deformation between the maximum tensile point and break points. The reverse was true for the samples with layers against layer direction. There was one sample that had this significant plastic deformation, the rest however broke cleanly soon after the maximum tensile point.

Discussion

Some interesting observations can be made from the data collected. The difference between the layer deposited samples is apparent, though there is only about 6.5% less strength in the samples against layer direction compared to those in layer direction. The standard deviation between them shows that there is more variance in the performance in the against grain samples, this is expected as the stress is applied in a direction that tests the strength of the interlayer bonds. It is much more likely to have defects and cavitations in the inter-layer bonds and region then within the layer itself. In comparison to a Fused Filament Fabrication (FFF) process, the yield strength is significantly higher. Data from manufactures indicate that the typical yield strength for PETG filament produced parts is about 50 MPa in layer direction and 30 MPa against layer direction [12]. The FPF process can produce much stronger parts. This is likely the case because the layers are much larger and so the number of layers in each sample is comparatively reduced and the pellets are fully melted in the process so the temperature between the layer deposited and the previous layer is higher, allowing for a stronger bond to form.

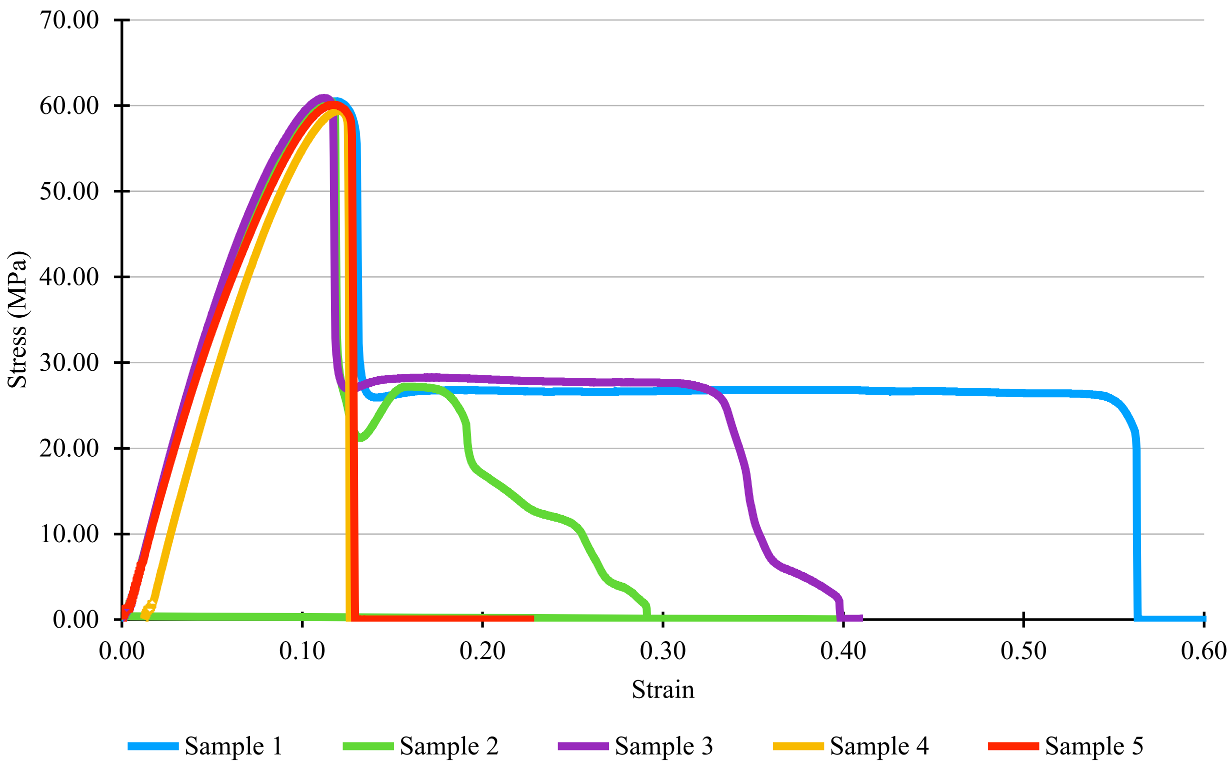

Figure 7: Layer Direction Stress-strain

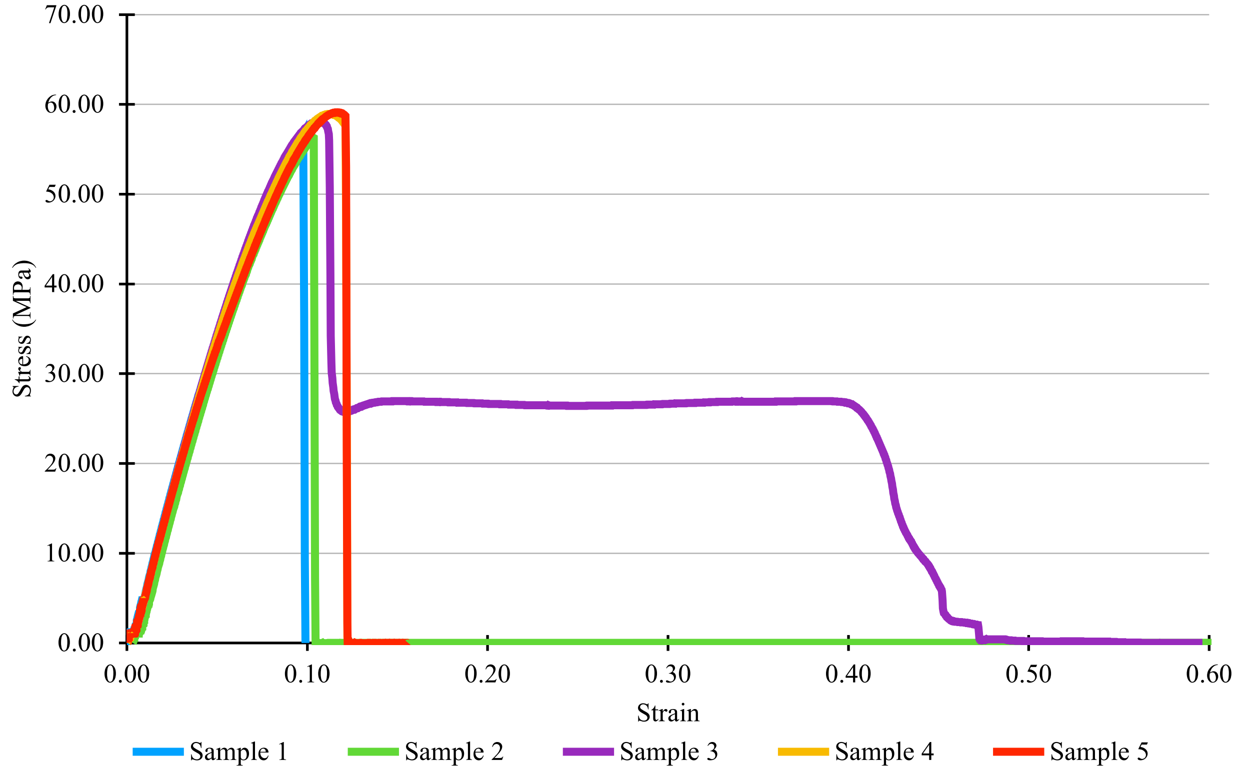

Figure 8: Against Layer Direction Stress-strain

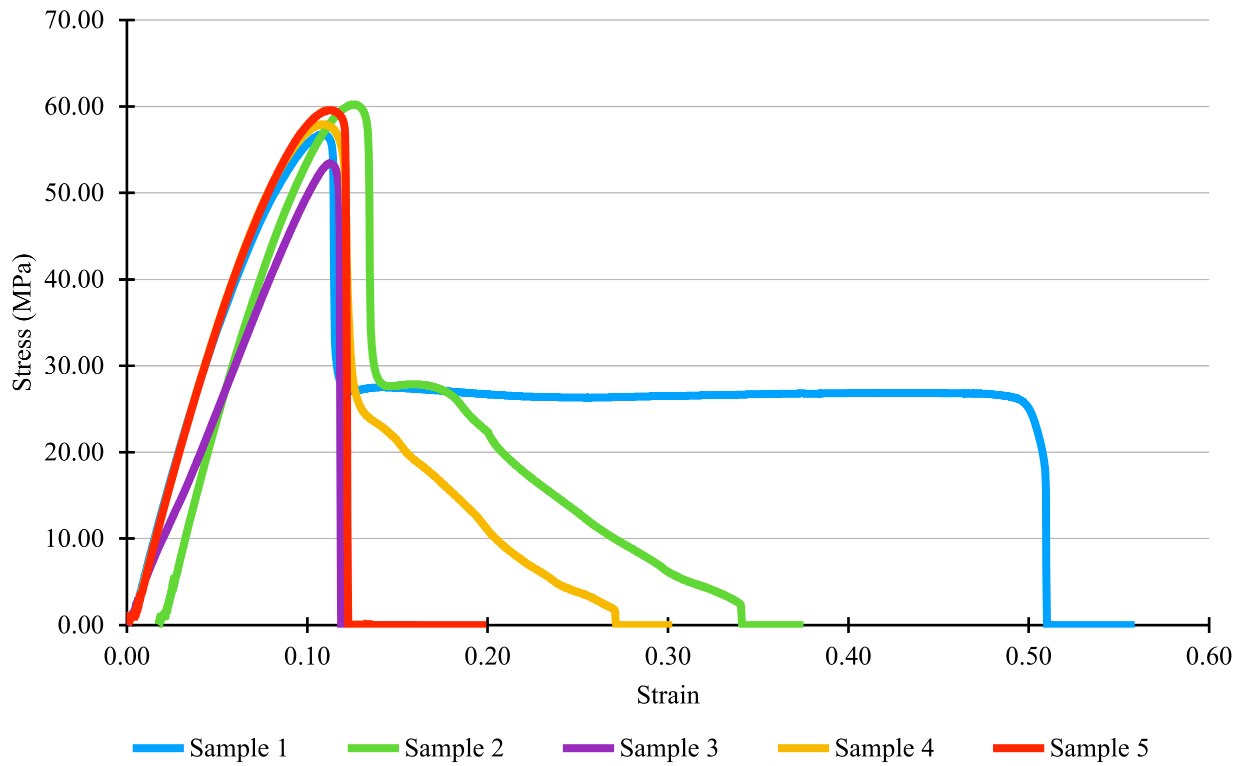

Figure 9: Open Molded Stress-Strain

The samples that were open molded show a mix of results from the other sample sets. They are very close only having about 3.5% less strength that the average of the layer direction samples. There is a higher standard deviation in the sample results than the layer deposited samples; this could be that because there are no layers and from the nature of how the plastic flow is more turbulent as it fills the mold, thus the defects and cavitations are more randomized throughout. This demonstrates that the open molding process can produce parts that are high performing, can be produced quickly, and are not as anisotropic in nature in com parison to the layer deposited parts. The machining of the additive parts to meet tolerance of the ASTM demonstrates that a Hybrid process can indeed produce parts of both high tolerance and of good mechanical properties.

Additionally, this study shows that FPF, in combination with hybrid manufacturing, can allow for parts to be produced quickly and cheaply that can perform very close to that of injection molded parts of the same material without the overhead costs of an injection machine and molds. This method spans the gap of purchasing extruded plastic and the time and wasted material of having to machine down from stock where lower part runs are required and the need to produce parts in numbers that justify the cost of injection molding equipment. Open molding would also allow for shapes and sizes off parts that would be difficult or expensive to produce in small numbers.

The next step in future research is to employ this method and process to create multi-material parts. This will be done by filling a cavity in a substrate with the FPF process and then machining the low friction plastic to a specified dimension and surface finish to compare the durability of this multi-material part with one that relies on mechanical fastenings.

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