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INCREASING INTERLAMINAR STRENGTH IN LARGE SCALE ADDITIVE MANUFACTURING

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Abstract

Interlaminar strength of extrusion-based additively manufactured parts is known to be weaker than the strength seen in the printed directions (X and Y). With Big Area Additive Manufacturing (BAAM), large parts lead to long layer times that are prone to splitting, sometimes referred to as delamination, between the layers. Fiber filled materials, such as carbon fiber reinforced ABS, are used to counteract the effects of thermal expansion by increasing the strength in the X and Y directions. These fibers stay in-plane meaning that no fibers span from layer to layer, which would help counteract the weak interlaminar strength that causes splitting. A solution to this is a patent pending approach called Z-Pinning. The process involves strategically positioning voids across multiple layers that are backfilled with hot extrudate. This paper will explore the benefits and results of using Z-Pinning in large scale additive manufacturing.

Introduction

3D printing with the fused deposition modeling (FDM) process, works by adding material layer by layer to build a part. When FDM is done with thermoplastics, hot material is added, or extruded, on top of a previous printed layer that has had time to cool. This difference in temperatures between layers causes a weakness in the bond between these layers. As layers grow larger, layer times also grow longer. This increase in layer time means that layers have more time to cool before the next layer is extruded on top. This results in an increased temperature gradient across the part. As thermoplastics cool, they contract. This cooling and contracting creates residual stresses throughout the printed part. If the stresses become too much, delamination, or splitting of the layers, occurs. The world’s first 3D printed car, Strati, had this issue as seen in Figure 1. Strati had layer times exceeding an hour which allowed the previous layer to cool to near room temperature before being extruded over.

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Figure 1: An early test print of the Strati that resulted in numerous delaminations that had to be glued together

To attempt to fix the problem of the delamination for large prints, Oak Ridge National Laboratory (ORNL) started looking for methods of increasing the strength in the Z-direction and improving the bond layer to layer. A process called Z-Pinning was developed that works by leaving a hole, or holes, in each layer and then coming back along and extruding material into the hole to fill it [1]. This allows hot material to span several layers at one time thus allowing the polymer chains to go between layers and not just stay within the layer plane (Figure 2). When using fiber reinforced materials, the fibers now span the layers which gives added strength in the Z-direction. This paper will explore the preliminary testing of Z-Pinning with BAAM.

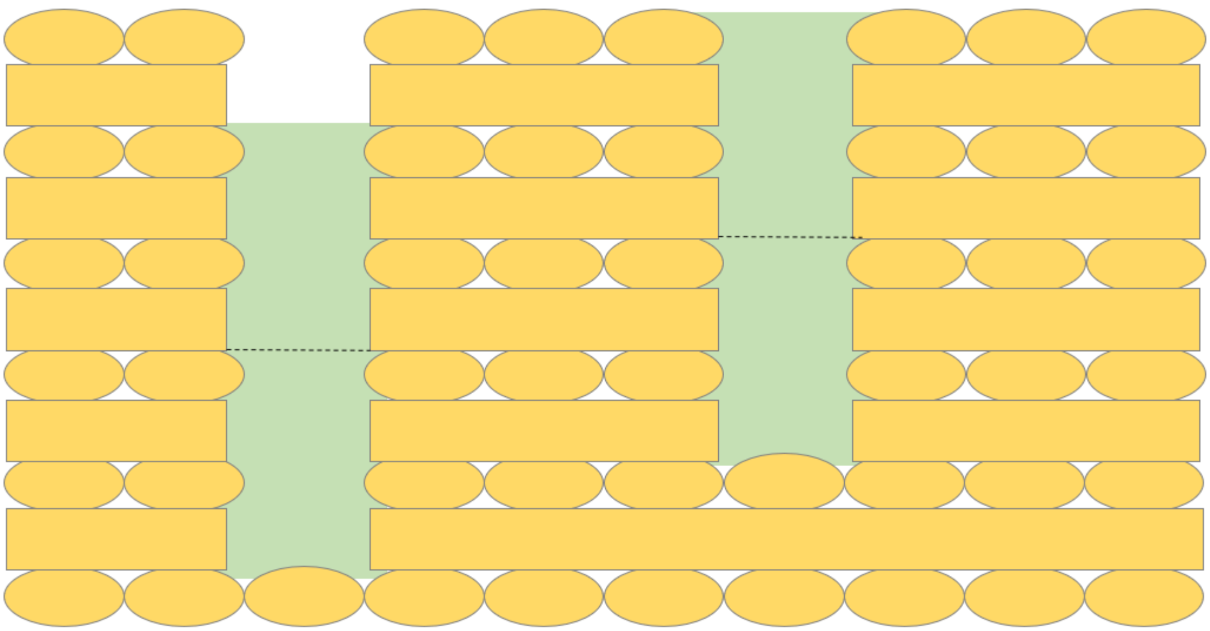

Figure 2: Cross-section showing pins in green

Z-Pinning Tests on BAAM

Testing on BAAM started with simple, single pin prints. This was done to determine the best pin size. A pin that is too small won't properly fill the void, whereas a pin that is too large will take too long to fill. Another issue is a pin that is too tall; a pin that is too tall won't fill to the bottom. To test these variables, holes of various sizes were printed and tested at one time. The holes were cut in half so that a piece of clear polycarbonate could be placed in front and video could be captured. The testing showed that a hole of diameter four times that of the nozzle diameter filled best and that eight layers was the best height.

Figure 3: A print done to find the optimal hole size. Outer holes show the polymer didn't reach the base of the hole.

After the appropriate hole size was found, full pieces were made with one single central pin. This was done to ensure that the pin filled appropriately and didn't have negative effects, like overfilling or swelling, on the surrounding area. These parts were then cross-sectioned to ensure a fully dense pin was created (Figure 4).

Figure 4: Two cross-sectioned parts with one central pin. The pin is not distinguishable because it is fully dense.

Multi-pin test pieces were printed after the single pin pieces. These were done using an "8-4" pinning scheme. This means eight-layer tall pins that start every four layers, which is also known as an A-B approach (Figure 5). These parts were five inches by five inches and thirty inches long. Five sets of four test pieces were made with each of the sets representing a different fill pattern. To test the sets against each other, they were loaded in a three-point bending machine, which will be discussed in the next section.

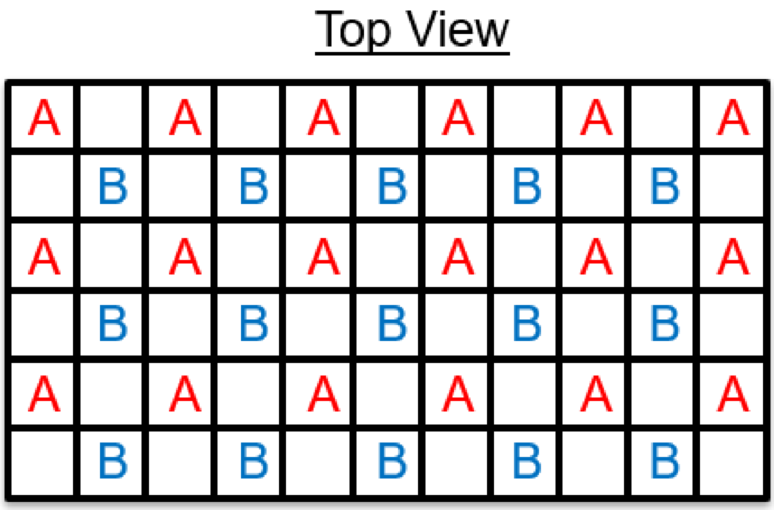

Figure 5: Overhead view of the AB Pinning approach

The first set was a control set where the infill pattern was fully dense (Figure 6). The parts were printed with one outer contour and a horizontal raster infill that rotated by 90 degrees each layer. The second set was made in a similar fashion but with a sparse infill pattern (Figure 7). The infill spacing for this was set at 0.45in, which results in a density of 75%. The resulting part would have a similar weight to the third set, which had five pins. Having a similar weight would allow for a direct comparison of strength to weight.

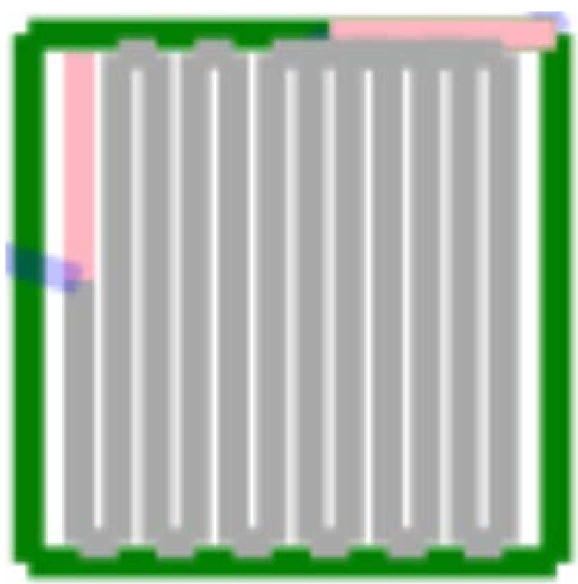

Figure 6: Three-Point Bend set 1, fully dense infill.

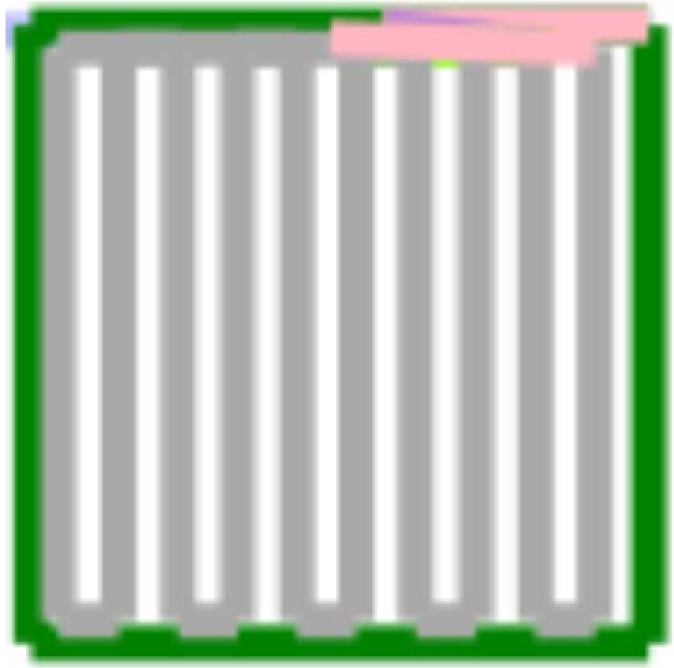

Figure 7: Three-Point Bend set 2, sparse infill with 75% density.

As previously mentioned, set three had five pins in an 8-4, AB, pinning style. The pins along one diagonal were the A pins and the remaining two pins, which were on opposite corners, were the B pins. A G-Code rendering of a single layer where three pins are filled is shown in Figure 8.

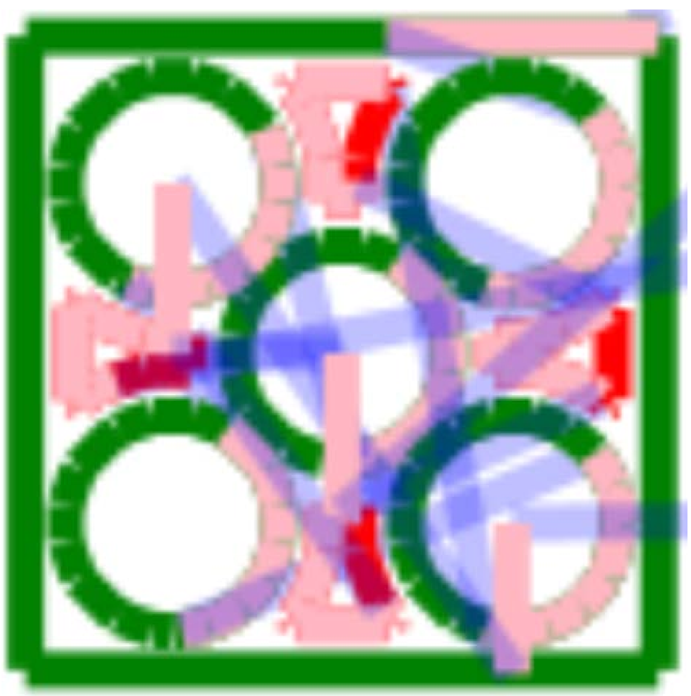

Figure 8: Three-Point Bend set 3, five pins in a 4-8 style.

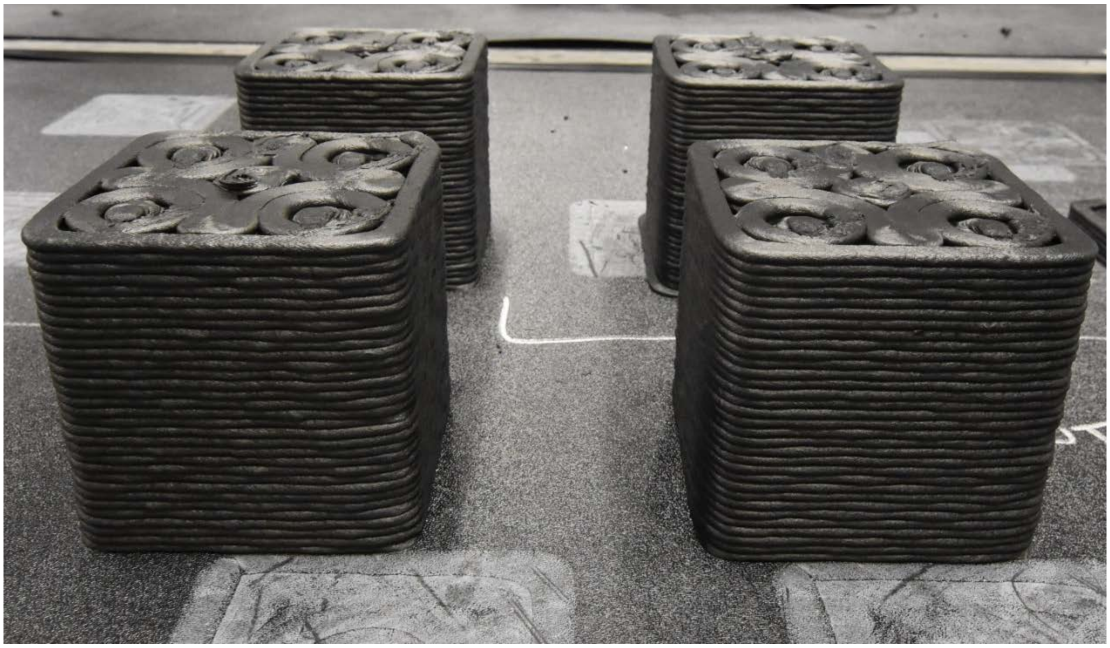

Figure 9: Short test version of set 3

The fourth set was made without pins. It was made using a special infill pattern designed to mimic the geometry of set three. This was done by creating tiny holes at the centers of the pin locations and forcing the slicer to print around the holes, Figure 10.

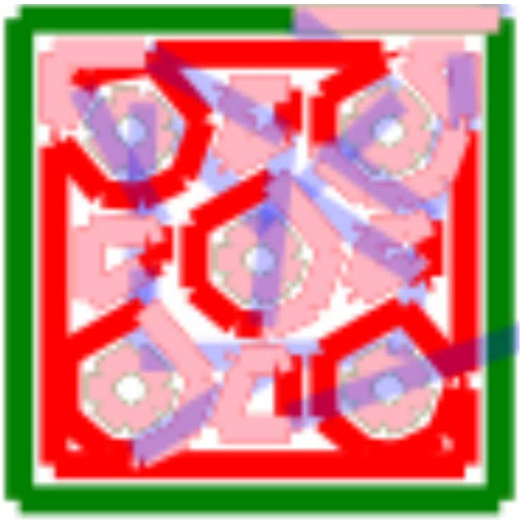

Figure 10: Three-Point Bed set 4, infill that mimics the geometry of set 3

The remaining set of test beams were created using a custom infill pattern with four pins. The pins in set 3 were circular with a perimeter bead surrounding them (Figure 8). This caused a non-uniform infill pattern surrounding the pins that ultimately made the layer take more time and caused a lot of voids. The combination of these two factors made the layer to layer bond very weak. A suitable solution was found that four pins could be placed at the corners in square holes with the remainder of the volume being filled with a raster infill pattern (Figure 11). This meant a better layer to layer bond and less starts and stops causing a shorter layer time.

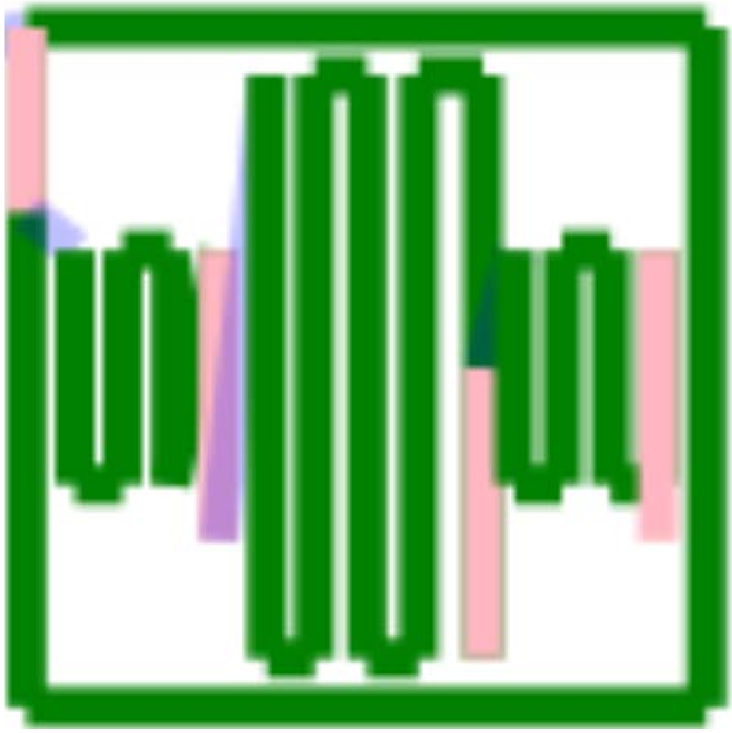

Figure 11: Custom infill pattern with four pin locations in the corners

Three-Point Bend Testing

The initial small-scale research for Z-Pinning involved material strength testing using tensile bars and a pulling machine [2]. For large-scale, it was challenging to determine a print that could be properly used to measure tensile strength. Tensile bars need to be cut in a way that pins are fully included without being cut with the tensile bar spanning across all layers. This would have made for very large samples to pull. An alternate solution to tensile samples was a three-point bend test. A three-point bend test involves placing a beam that is supported on the ends and loaded in the middle [3]. Large beams could be printed with many pins inside, then broken on a large bending machine to measure the load.

The printed beams were 5in x 5in x 30in each. The printed height was 30in so that pins would be stacked on top of each other. This also allowed the samples to be laid flat in the testing rig so that the load would be applied between the layers and force the pins to break. Figure 12 shows an example of the testing setup with one beam loaded in the bending machine.

Figure 12: Three-point bending machine setup

Results

For each sample set, four bars were broken on the three-point bending machine. From that data, the average was taken for each set and can be seen in table 1. The highest bending load was seen in set 4. This is because the infill pattern created an increased layer to layer bond strength by maximizing the contact area from layer to layer (Figure 13), even in comparison to solid infill (Figure 14). This was also the result of the part being overfilled causing more material to be packed into each layer.

	Load (lbs)
Set 1	5089
Set 2	3698
Set 3	4252
Set 4	8984
Set 5	5585

Table 1: Max loading weight for each beam sample set

Figure 13: Set 4 showing the increased contact area between layers.

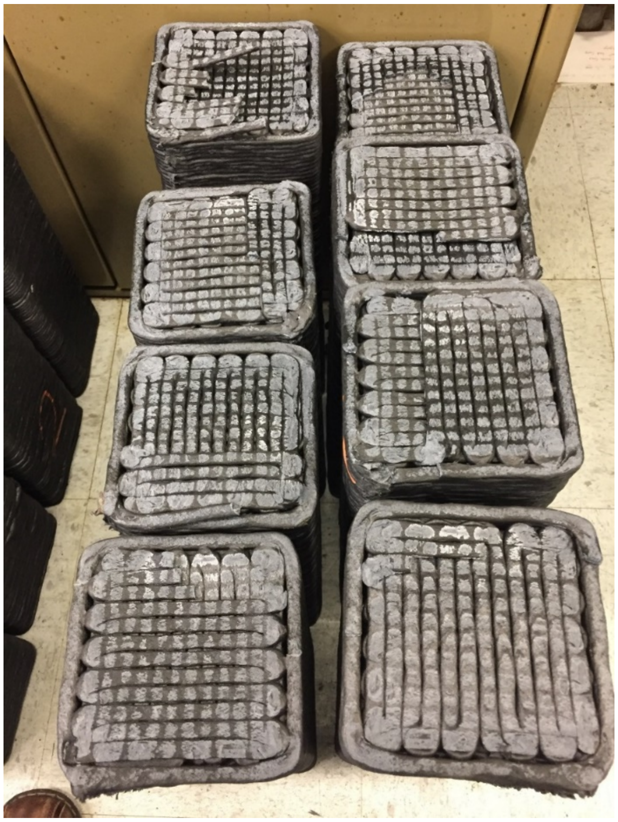

Figure 14: Set 1 with less contact area than set 4.

Solid and sparse line infill patterns, like sets 1 and 2, are most commonly printed on large scale machines. When comparing the two sets to the improved pin set, set 5, a strength increase is seen for the pinned set. The pinned set increases the strength by 9.75% over the solid infill and 51.03% over the sparse infill (Table 2).

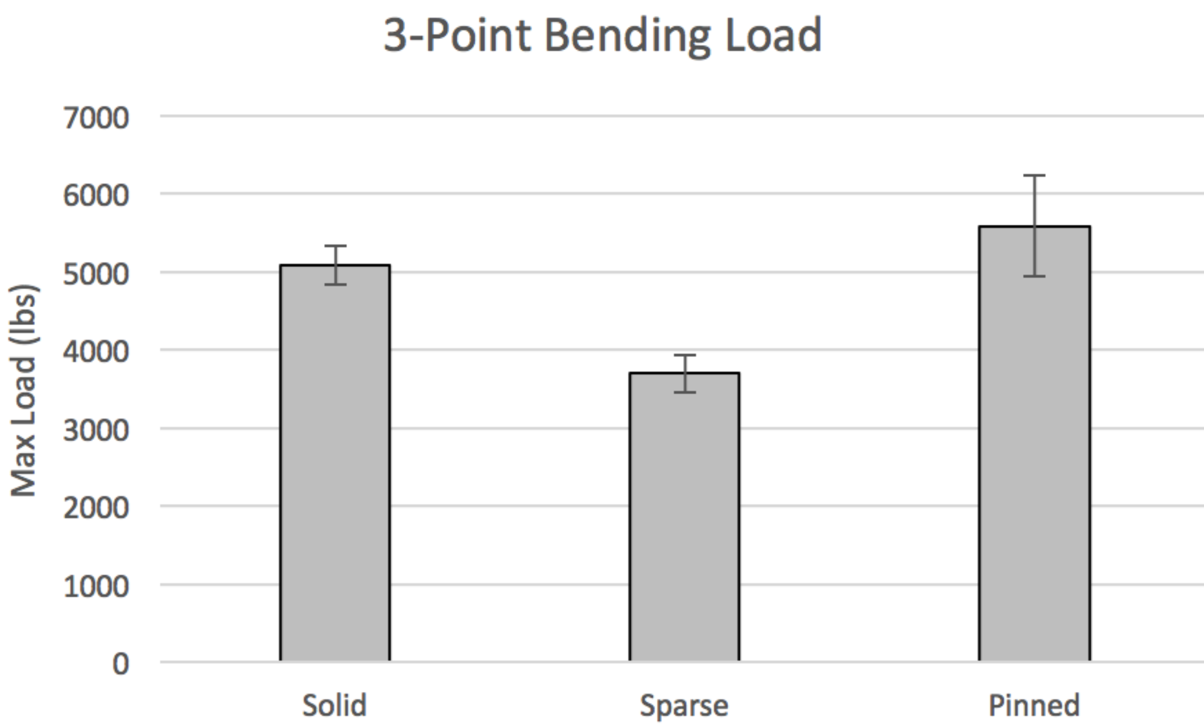

Table 2: Comparison of solid (set 1), sparse (set 2), and pinned (set 5) maximum bending loads.

Non-Cylindrical Pins

As seen in the results of the three-point bend testing, pins don't always shear during testing and sometimes break off at the boundary between pins (Figure 15). This causes the pin to be pulled out of the part and remain intact. The force to break a pin at the layer boundary is less than the force required to shear the pin in half causing a lower load strength for the beam.

Figure 15: Fracture of a three-point bend sample. The bottom right pin illustrates a pull-out.

To fix the issue of pins pulling out, testing was done with pins that are non-cylindrical, or have flanges (Figure 16). These non-cylindrical pins expand at the bottom such that they cannot be pulled up out of the part. If the cylindrical section has a diameter equal to that of the nozzle, fibers should be aligned in the Z-direction with the extrudate. Testing of samples with this pin geometry has not happened yet but is upcoming.

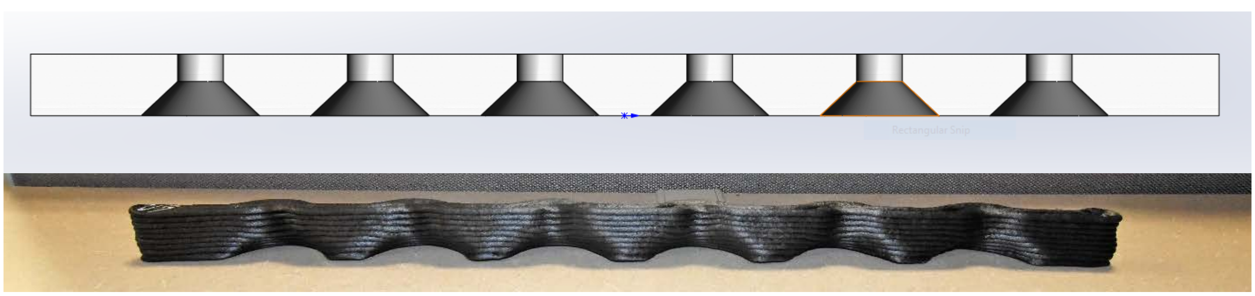

Figure 16: Top, CAD model of a test piece with non-cylindrical pins. Bottom, printed sample pieces without pins filled.

Future Work

This paper and the research it entailed is just the beginning of the testing and development of Z-Pinning for BAAM and other large scale additive manufacturing systems. Future work will include Z-Pinning during infill, automating the pinning process with slicing software, mixing of materials, and testing hot pins.

In this paper, all the pins were specifically designed into the CAD model. The slicer would leave the pin area as a void that could be later filled with a post-processing script. Future development will remove the need to design the pins in CAD. Instead the pins will be placed within the infill sections using a grid-based infill (Figure 17). The goal is to fully automate this within ORNL Slicer.

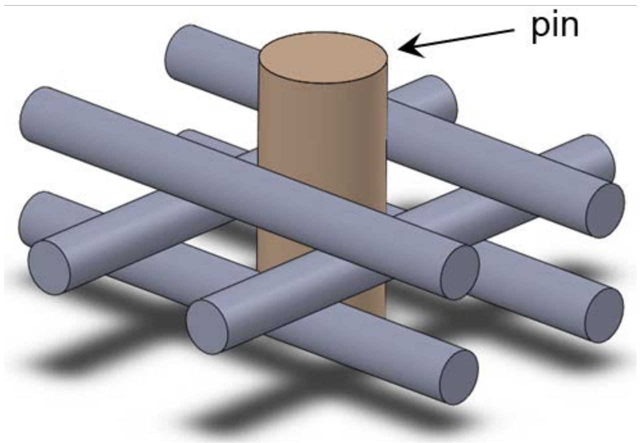

Figure 17: Example of a Z-Pin within a section of grid infill

Mixing materials will allow the main structure of the part to be made with one material, while the pin is made with a separate material. This will provide the opportunity to use a pin material that has a higher fiber loading, which would increase strength in the Z-direction. It will also allow for dissimilar materials to be used for the pins to help the layers bond together better. Low melt strength polymers, such as HDPE, can be used to help tightly fill the pin voids. Mixing materials leads to the idea of “hot pins,” which are pins extruded at a higher temperature to help better fill the void. Hot pins can be done using the same material or a dissimilar material.

Conclusion

Z-Pinning is a new approach to solving the issue of poor interlaminar strength with FDM parts. Small scale testing has proven that Z-Pinning is effective for increasing the bond between layers, and this paper documented very early research into its application with large scale 3D printing. With Carbon Fiber ABS, an increase in layer to layer strength was seen by applying the Z-Pinning technique. A 9.75% increase was achieved in comparison to a part with solid infill and a 51% increase was found in comparison to a part with 75% dense infill. This is just the beginning of testing and applying Z-Pinning to BAAM and other large scale processes, but the results show promise for printing parts with improved Z-strength.

Acknowledgements

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