CLEATED PRINT SURFACE FOR FUSED DEPOSITION MODELING

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Abstract

Fused Deposition Modeling (FDM) has become popular among Additive Manufacturing technologies due to its low cost, speed, and geometric scalability; however, the primitive nature of the FDM build surface fundamentally limits the utility of FDM in terms of reliability, autonomy, and material selection. Currently, FDM relies on adhesive forces between the first layer of a print and the build surface; depending on the materials involved, this adhesive bond may or may not be reliable. Thermal contraction between the build plate and build materials can break that bond, which causes warpage and delamination of the part from the build surface and subsequent failure of the part. Furthermore, with each print, the user must use tools or special maneuvering to separate the printed part from the build surface as well as retexture or replace the used build surface. In this paper we present a novel build platform that allows for a mechanical bond between the print and build surface by using dovetail-shaped features. The first layer of the print flows into the features and becomes mechanically captivated by the build platform. Once the print is completed, the platform is rolled or flexed open to release the part from the mechanical bond. This design not only lowers the risk of delamination during printing but also eliminates the need for a user to reset or replace the build surface between print jobs. The effectiveness of each geometry was determined by measuring the distance at the pinch point compared to the distance that the extrusion filled below the pinch point. The Captivation Ratio was measured to compare the different geometries tested and determine which direction of extrusion creates a better ratio.

Introduction

Over the course of development of Fused Deposition Modelling (FDM) Additive Manufacturing (AM), many improvements have been made to allow for a wide range of materials to be printed. The advancements that have been made to print surfaces, however, are each geared toward specific materials. Considering the narrow range of print surfaces currently developed, it is unknown whether or not other materials may be compatible with the particular surface. This leads to one major limitation all FDM printers have, which is that materials can only be successfully printed if they are compatible with the build surface. Furthermore, build surfaces must be carefully monitored and maintained to ensure sufficient sticking during printing, which constitutes a significant operator burden. In order to adhere prints to the print bed, many of the build surfaces that are commercially available involve tapes, such as BuildTak™, Kapton® tape, and blue painter's tape. Others involve glues, such as CubeStick™, and WolfBite™. Unfortunately, large- and small-scale FDM printers still experience delamination issues due to thermal changes and raster orientation (1, 2). What is needed to solve this problem is a build platform that is compatible with all FDM materials, requires no replacing or resetting by the operator, and does not rely on adhesive bonding.

The initial bond of the first print layer of an FDM print to the build surface is critical in achieving a successful print. In this work, we sought to design a build platform that is indefinitely reusable and will work with virtually any material by creating a mechanical bond between the print and a dovetail-shaped, cleated build surface. With this design the extrusion of the first printed layer flows into the grooves, mechanically bonding itself to the platform. There are currently no other systems on the market for this type of application; the majority instead rely on adhesive bonding. The United States Patent pending 14/548,701 includes this and any other technology that utilizes "recessive and protrusive" areas in order to captivate the printed parts (3). The designs were created in order to create recessive areas that the extrusion would flow into and be captivated. The bond can only be released by bending the platform away from the part to open the grooves as shown in Figure 1.
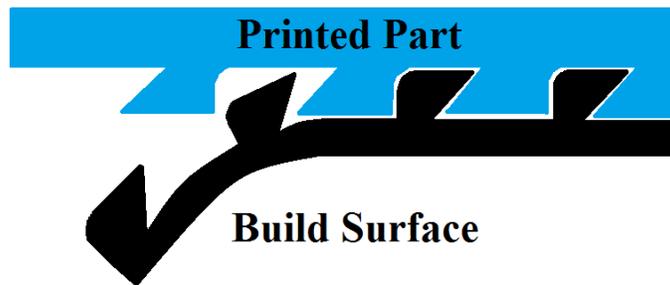
Figure 1: Removal of Captivated Polymer from Cleated Platform. This figure demonstrates how the build surface can be flexed to release from the printed part. Another design could be that each row is similar to links in a chain that can be rotated to release the printed part.

Experimental

To test the effectiveness in captivating the first layer of an FDM print, cleated build surfaces of varying geometries were printed on a Fortus 900mc FDM printer out of ULTEM 9085; this material was chosen for its toughness and resistance to heat. The cleated platform geometry is comprised of linear rows of "cleats" which are raised features that produce an overhang to capture the extruded plastic from the first layer of the FDM print. The cleat geometries tested were similar to a dove-tail groove geometry; however, one of the cleat edges is rounded. The rounded back of each cleat is representative of a future design where the cleats can rotate and release the printed part. The depth of the cavity between rows was approximately 0.5" deep, into which the extrusion would flow. These shapes were arranged in repeating rows in which all of the rounded edges were facing the same direction. Figure 2 shows a side view of two cleat profiles chosen for this study. One cleat profile is a simple, one-sided dovetail groove with a varying angle (Figure 2a), and the other is a "wave" profile (Figure 2b).
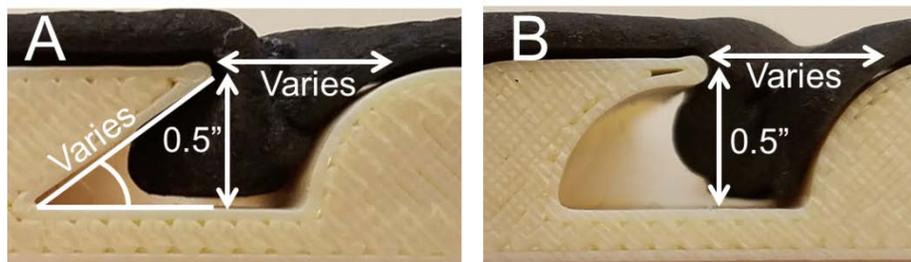
Figure 2: Cleat Surfaces printed via FDM (tan) in A) angled and B) wave profiles.

The overall dimensions of the cleated surfaces were roughly 3" wide and 8" long, depending on the spacing between rows of cleats. Each printed cleat surface was affixed to the build plate of the Big Area Additive Manufacturing (BAAM) FDM printer, and Carbon Fiber-doped Acrylonitrile Butadiene Styrene (ABS) plastic was extruded over each surface. The molten ABS was printed in both directions on the build surface in a "U" shape and flowed into the grooves in two different directions, as shown in Figure 3.
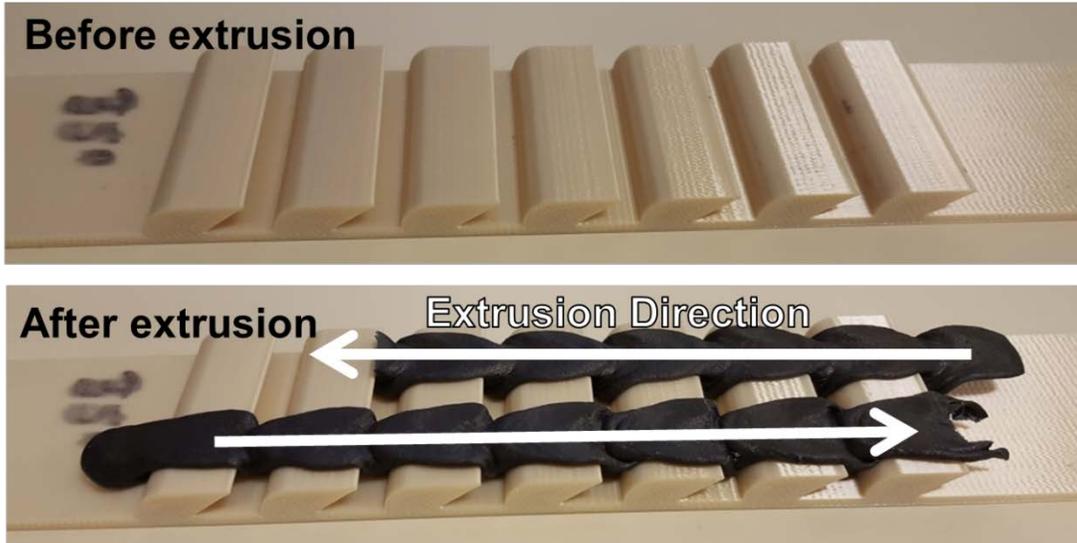
Figure 3: Cleat geometries (tan) A) before and B) after polymer extrusion (black) with the BAAM system. The arrows indicate the direction of extrusion on the cleat surfaces.

During extrusion with the BAAM, the molten plastic flows between the cleats, creates a foot-like profile, and solidifies upon cooling. These feet are what provide the mechanical bond to the print surface (See Figure 4). The critical features of the captivation are the width of the foot and the pinch point provided by the cleat profile. As the foot width exceeds the cleat pinch point, the extrusion becomes captivated.
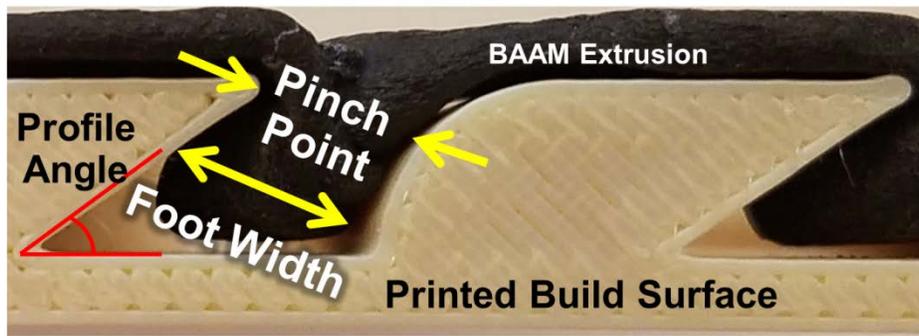
Figure 4: Side view of cleat profile with captivated polymer extrusion. Above is a side view of the build surface; the lightly colored section of the image is the cleated build surface and the dark section is the extrusion. The pinch point can be seen between the rounded back of one row and the knife-edge of the adjacent cleat. The area below the pinch point is where the mechanical bond is formed. The "Foot Width" distance was used for ratio measurements.

Multiple angles of the dovetail profile were tested for BAAM extrusion captivation, including 35°, 45°, and 55°. Two wave shapes were also tested with different spacings between rows. The cleat profiles, their dimensions, and the results of extrusion with the BAAM are given in Table 1.

Table 1: Cleat geometries (tan) with polymer extruded (black) within vs. extrusion direction. This figure shows all of the geometries as printed on with the extrusion direction indicated. In most cases, it is easily seen that there is a larger foot in the with direction than the against direction.

Geometry	Extrusion Direction: ← With Cleats	Extrusion Direction: ←Against Cleats
35° Angle, 0.225" Pinch Point		
45° Angle, 0.30" Pinch		
55° Angle, 0.14" Pinch		
55° Angle, 0.38" Pinch		
Wave Geometry, **0.28" Pinch**		
Wave Geometry, **0.50" Pinch**		

After extruding over each cleated build surface with the BAAM system, the solidified extrusion (as shown in black in Figure 3 and Table 1) was removed by flexing the cleated substrate, and it was then measured with calipers. The size of the cleats and BAAM extrusion made measurement trouble-free. After measuring the "pinch-point" length of the cleated profile and the "foot widths" of each extrusion from each extrusion direction, the measurements were compiled. The "captivation ratio" was calculated for each cleat and extrusion direction by dividing the foot width by the pinch point in each cleat. An example calculation would be as follows: If the pinch point at the top of the trough was measured to be 0.5 inches and the extrusion was measured to be 1.0 inches, then using an extrusion to pinch point ratio would result in 1.0"/0.5" which equals 2.0. An average of three feet of the extrusion was used in the ratio calculation for both directions of extrusion. The ratio data was compiled and displayed in a graph depicting the ratios of with and against the direction of the build surface for all of the variations, as shown in Figure 4.

Results and Discussion

The calculated captivation ratios were plotted against the pinch point widths as shown in Figure 5. A trend can be seen in the plot between suggests that the captivation ratio decreases with an increase in pinch point width. Although the groove angle also decrease for two of these data

points, comparing the two data points for the 55 degree groove angle at low and high values for pinch point further supports this trend. Further work is needed to isolate groove angle as a variable to discover its effect on captivation. Also an investigation into the relationship between the nozzle size and/or extrusion rate with the pinch point width is needed.
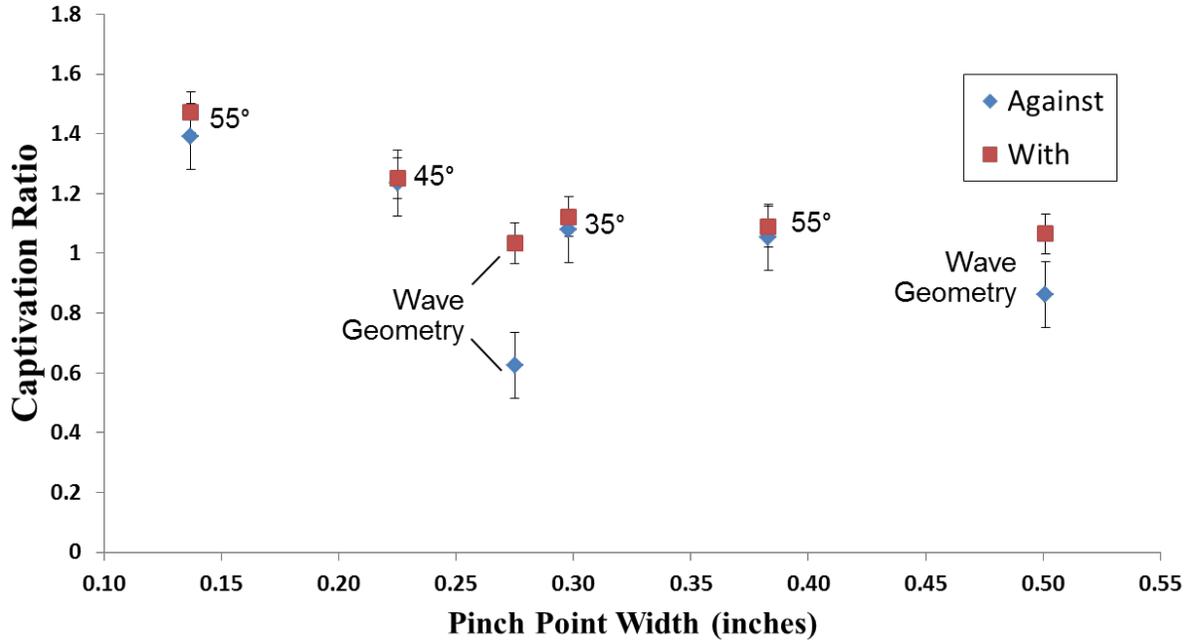
Figure 5: Captivation Ratio vs. Extrusion Profiles Plot. This graph shows that there was a greater extrusion width in all of the build surfaces when extruded in the with direction, toward the rounded back first. The straight angled designs all fared better than the wave-shaped designs. The wave shape has a greater directional dependence than the straight angle designs.

Other trends from the plot include better captivation in extrusions that were deposited "with" the cleat profiles rather than against. This trend is significantly more pronounced for the wave profiles. When extruding in the direction of the cleat profile, the bead curls under the edge and is pushed farther down as the nozzle passes over, as indicated in Figure 5 by the white arrow. Conversely, in extruding against the cleat profile, the extrusion starts from the bottom of the cavity and is cut off by the overhang feature before it can push the plastic underneath it. Figure 6 illustrates the difference in flow behavior of the extruded polymer when extruded with and against the cleat profile.
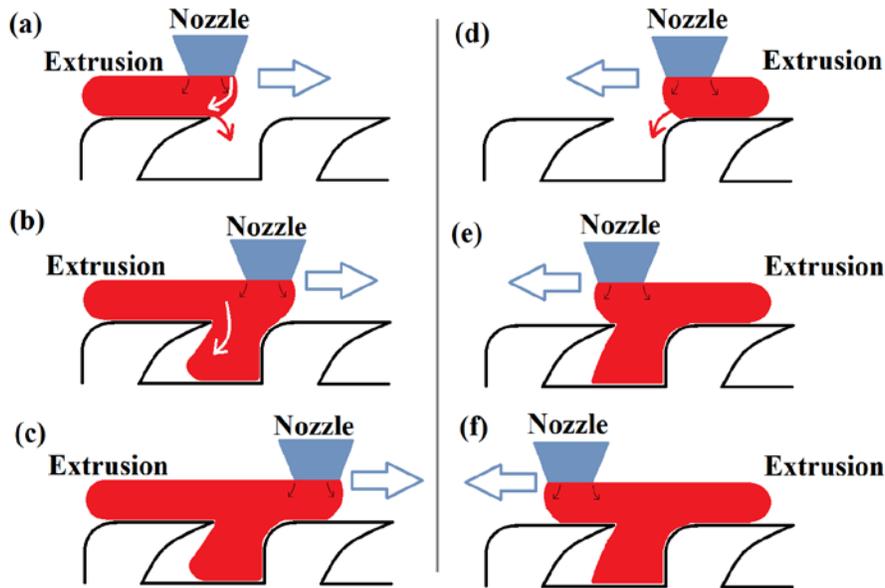
Figure 6: Flow of molten polymer between cleats during deposition. Section (a,b,c) demonstrates the flow of plastic exiting the nozzle in the with direction, and section (d,e,f) demonstrates the against direction. It was hypothesized that the with direction would roll more plastic underneath the pinch point than the against direction due to the currents exiting the nozzle.

Conclusion and Future Work

Cleated build surface geometries were fabricated and tested for their ability to captivate a molten extrusion of thermoplastic as produced in the first layer of an FDM print. The cleat profiles were printed via FDM on a large scale and tested for captivation by the BAAM polymer FDM system. A captivation ratio was calculated based on measurements of the cooled extrusion and the cleat dimensions. The captivation ratio was plotted verses the cleat dimensions, and a general trend was seen between the captivation of the extrusion and the pinch point width of the cleats. Further work is needed to explore the effect of cleat geometry (groove angle and wave or dovetail design) on the captivation of extruded polymer. Also, future work will consist of pull tests between printed parts and the build surface to more accurately characterize the captivation of extruded polymer in the cleats. Overall, a cleated build platform would provide a reusable and reliable build surface for FDM printers. This work is protected by United States Patent pending 14/548,701.

Acknowledgements

References

1. T. Letcher, B. Rankouhi and S. Javadpour, Experimental study of mechanical properties of additively manufactured ABS plastic as a function of layer parameters, ASME 2015 Int. Mech. Eng. Cong. and Exp., 2015, p. V02AT02A018-V02AT02A018.

2. MakerBot Replicator 2X Troubleshooting Maintenance. Brooklyn, NY: MakerBot (2013)

3. Elliott, Amelia M. Build Platform That Provides Mechanical Engagement with Additive Manufacturing Prints. UT-Battelle LLC, assignee. Patent US14548701. 20 Nov. 2014. Print.