GEOMETRIC PARAMETER ANALYSIS OF VERTICALLY EXTRUDED PINS FOR STRENGTH IMPROVEMENT IN ADDITIVE MANUFACTURING WITH FIBER-REINFORCED THERMOPLASTIC

Seokpum Kim[1], Tyler Smith[2,3], Justin Condon[2,4], Alexander Lambert[1],
Vlastimil Kunc[1,3], Chad Duty[2,3,*]

[1] Energy and Transportation Science Division, Oak Ridge National Laboratory, Oak Ridge, TN 37831

[2] Materials Science and Technology Division, Oak Ridge National Laboratory, Oak Ridge, TN 37831

[3] Mechanical, Aerospace and Biomedical Engineering, University of Tennessee at Knoxville, Knoxville, TN 37996

[4] Civil and Environmental Engineering, University of Tennessee at Knoxville, Knoxville, TN 37996

*Corresponding author: cduty@utk.edu

ABSTRACT

Vertical directional strength is significantly weaker than planar directional strength in polymer extrusion additive manufacturing due to its layer-wise deposition method. The disparity between the planar strength and vertical strength is even larger for a printed part with a fiber-reinforced thermoplastic. A printing technique has been proposed in which continuous material is extruded across layers throughout the body of the part in order to improve the strength in the vertical direction. The mechanical engagement between the material extruded in vertically aligned holes (called "z-pins") and the surrounding layers is primarily influenced by the geometry of the hole and the extrusion volume of the z-pin. Previously, the z-pinning parameters that provide good penetration in the hole has been evaluated for neat polylactic acid (PLA). The current study investigates z-pinning parameters for carbon fiber-reinforced PLA as a function of the quality of mechanical engagement of the pins with the surrounding structure. The results of this parametric

study will provide guidance for general printing applications across multiple platforms with various materials.

1. INTRODUCTION

Additive manufacturing (AM) is “the process of joining materials to make objects from three-dimensional model data, usually layer upon layer, as opposed to subtractive manufacturing methodologies” as in Wohlers report [1]. Extrusion-based polymer AM is one of the common AM technologies which involves a viscous polymer extruded from a nozzle and deposited layer by layer. There are mainly three types of material systems used in extrusion-based polymer AM: thermoplastic, thermoset, and metals or ceramics with a polymer as a binding material. For metals or ceramics with a polymer as a binding material, polymer is removed in the printed part via a debinding process, and the part undergoes a sintering process, which increases the layer-wise bonding strength. For thermoset system, the layer-wise bonding strength increases during the curing process. For a thermoplastic system (thermoplastic with or without fillers), a molten plastic is extruded through a heated nozzle and deposited on a previously-deposited layer. The extruded material starts to cool after the exit of the nozzle. If the layer is cooled too much before the next layer is deposited, then due to not enough cross-linking of polymer chains between the two layers, the printed part often suffers from a weak bonding strength between layers.

To increase the bonding strength between the layers, we have introduced the z-pinning approach [2-5] which is currently patent pending [6]. In Ref. [2], z-pinning was used for neat polylactic acid (PLA) and showed 20% higher strength and 100% higher toughness as compared to a non-pinned sample. In Ref. [4], three parameters were varied, including hole depth, hole width, and the amount of pin extrusion (= pin volume) for neat PLA to determine the optimal parameters for z-pins. In Ref. [5], a z-pinned sample of carbon fiber reinforced PLA demonstrated 3 times higher strength and 8 times higher toughness as compared to a non-pinned sample. These studies show that the increase in mechanical performance by z-pinning can be more significant with carbon-fiber reinforced polymer than that with neat polymer. The mechanical interlocking between the z-pins and the surrounding base structure determines the effectiveness of the z-pin approach in terms of vertical strength. The mechanical interlocking is influenced by geometric z-pin parameters and the material. In Ref. [5], it was evident that a further study was needed to optimize the geometry of pin and hole pairs and their relative spacing using carbon fiber-reinforced PLA. In the current study, the z-pin parameters are varied to investigate the z-pin engagement with the surrounding structure using carbon fiber-reinforced PLA.

2. Z-PINNING

The z-pinning approach involves vertical direction extrusion (pinning) into aligned holes across multiple layers of a pre-deposited structure. Specifically, in the z-pinning approach, the material from the nozzle is deposited to create a three-dimensional structure with pre-determined holes in a layer-by-layer fashion. The holes are not made by machining or drilling after the deposition. The holes are vertically aligned locations where materials are not deposited. After a given number of layers are deposited, the nozzle visits the holes and extrudes a material to fill the holes. The term "z-pin" is used to indicate the direction of the vertical fill. The material for the z-pins can be, but may not have to be, the same material as the base structure. In Ref. [2], the term "void" is used to indicate the hole intentionally designed in the structure. In this paper, we used "hole" instead of "void" to indicate a vertically aligned, intentionally non-deposited location. The term "void" will be used to indicate a sub-millimeter scale (or millimeter scale) gap between a z-pin and the surrounding base structure. The z-pinning process is illustrated in Figure 1. The details of the z-pinning process are provided in Ref. [3].

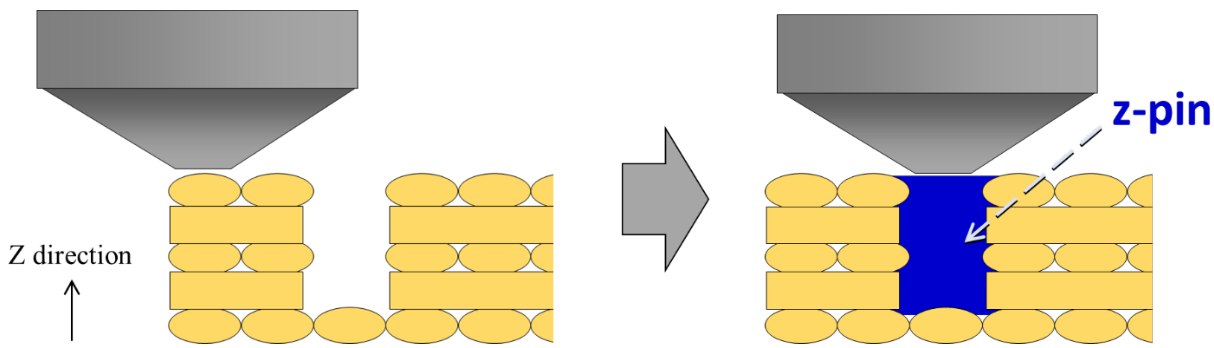


Figure 1: Illustration of z-pin approach

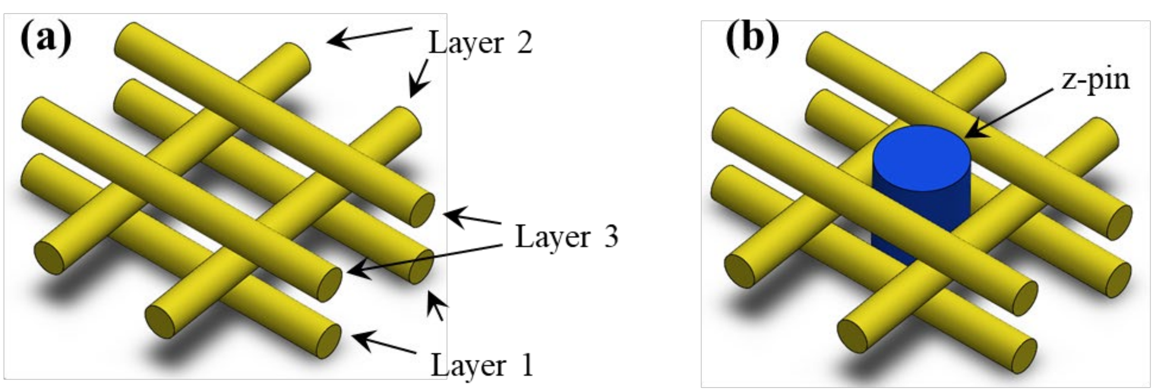


Figure 2: (a) Base structure layup configuration used in this study and (b) z-pin extruded in the hole of the base structure.

In this study, the base structure consists of multiple layers of [0/90/0/90] cross-ply stacking, each of which consists of unidirectionally printed lines in parallel from one line to another within the layer but perpendicular to the printed lines in the previous layer, which is similar to a log cabin layup as shown in Figure 2(a). This structure is the same as an infill structure generated by Slic3r [7] with a rectilinear pattern. The infill lines have a regular spacing between them, and therefore, the base structure has periodic holes in the x- and y-directions from the top view. The z-pins are extruded into the holes as shown in Figure 2(b).

3. EXPERIMENTS

A standard MakerGear M3 printer was used for printing. The filament was carbon fiber-reinforced PLA (model name: CarbonX™ PLA+CF) with the diameter of 1.75 mm purchased from 3DXTech. The bed temperature was 65°C and the extruder temperature was 220°C. The nozzle diameter was 0.5 mm, the layer height was 0.25 mm, and the bead width was 0.55 mm.

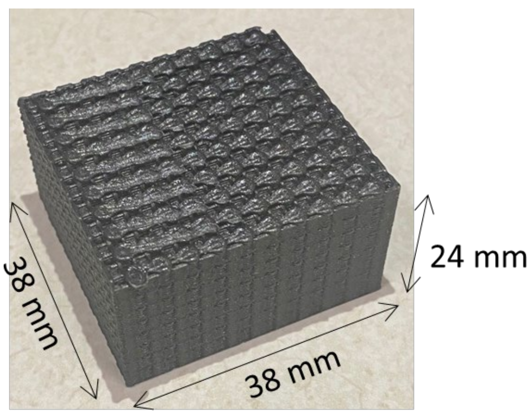


Figure 3: A sample with z-pins. The dimensions vary depending on the spacing of the infill lines.

The sample geometry was a box shape as shown in Figure 3. The length in x- and y-directions of the sample varied from 25 mm to 38 mm, and the height of the sample varied from 16 mm to 38 mm depending on the spacing of the infill lines. As the spacing between the infill lines was increased, the sample dimensions became longer and higher to maintain a consistent geometric ratio. The spacing between the infill lines determined the hole width.

The effect of three z-pin parameters were investigated in this study: hole width, hole depth, and the amount of pin extrusion (= pin volume). The hole width varied from 1.5 mm to 3 mm, the hole depth varied from 8 layers to 20 layers (= 2 mm – 5 mm), and the pin volume varied from 80% to 120% of the hole volume. The hole width was the same as the spacing between the infill lines subtracted by the bead width (0.55 mm). In Ref. [4], the hole volume was calculated by a square of the line spacing multiplied by the hole depth subtracted by the infill line volume as illustrated in Figure 4(a). Therefore, although practically not possible, if every hole was filled with a z-pin with 100% of the hole volume, the sample would have 100% solid block of material. In this study, the method of calculating the hole volume was changed to equal the square of the hole width multiplied by the hole depth as illustrated in Figure 4(b). Therefore, if every hole in the sample were filled with a z-pin with 100% of the hole volume, the sample would still have empty spaces between the infill lines as marked by a red circle in Figure 4(b). This modified method of calculating the hole volume provides a more intuitive relation between the z-pin volume ratio to the visually observable hole volume from the top view. The hole width and depth have been normalized by the nozzle diameter (0.5 mm). Therefore, a hole with of 1.5 mm – 3 mm corresponds to a normalized hole width (W_h) of 3 – 6 and a hole depth of 8 – 20 layers corresponds to a normalized depth (D_h) of 4 – 10. The z-pin volume was also normalized by the hole volume, and was varied from 80% to 120%.

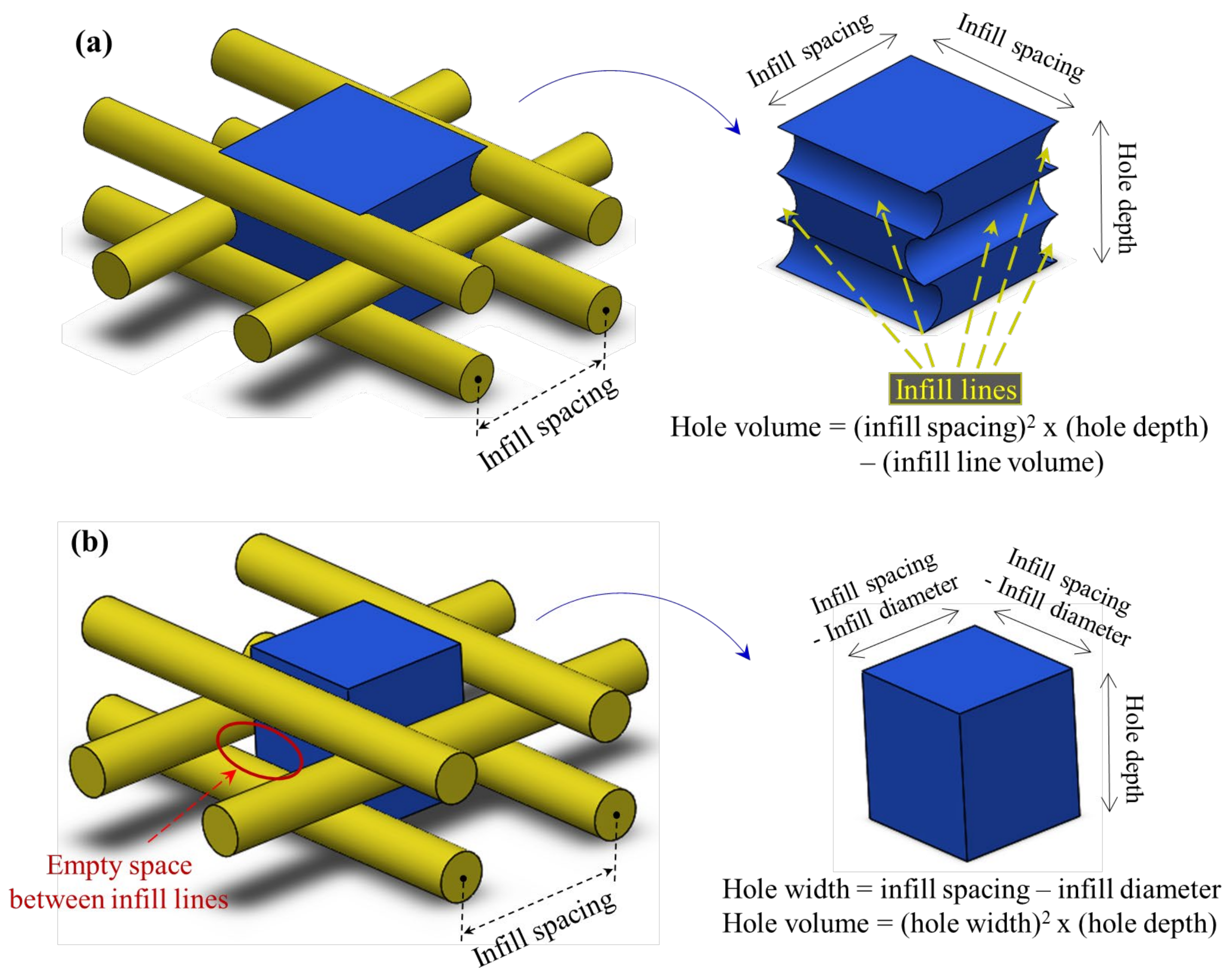
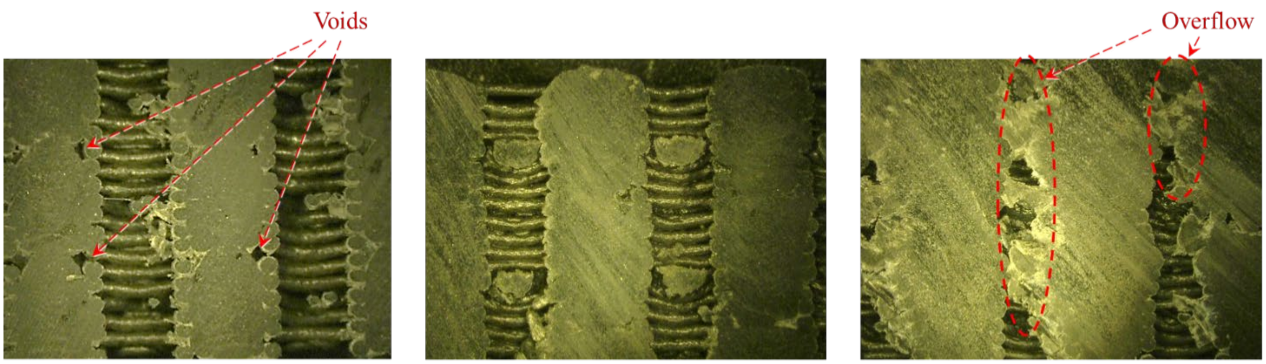


Figure 4: Method of calculating hole volume (a) in Ref. [4] and (b) in this study

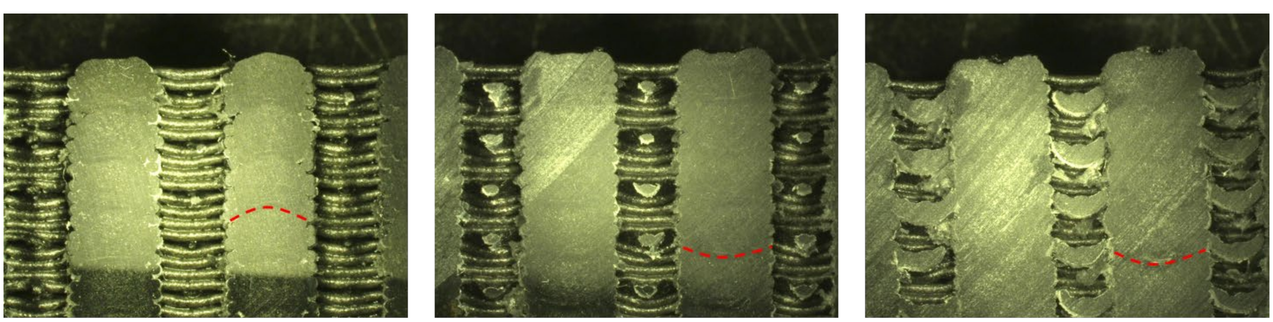
3.1 Effect of pin volume

The pin volume was varied from 80% to 120% of the hole volume. Figure 5 shows the cross-section view of z-pins with a hole depth of $D_h = 8$, a width of $W_h = 4$, and a varying pin volume of 80%, 100%, and 120%. The sample with 80% pin volume shows voids between the pins and the base grid structure, especially near the interfaces between upper pins and lower pins. It is presumably because the amount of material extruded as z-pins was insufficient to fill the holes. On the other hand, the sample with 120% pin volume showed distorted boundaries adjacent to the z-pins. This was presumably because the amount of material extruded as z-pins was too much for the hole, and the excessive material flowed into the adjacent holes.



(a) Vol **80%**, $D_h = 8$, $W_h = 4$ (b) Vol **100%**, $D_h = 8$, $W_h = 4$ (c) Vol **120%**, $D_h = 8$, $W_h = 4$

Figure 5: Cross-section views of z-pins with consistent hole depth ($D_h = 8$) and width ($W_h = 4$), and varying pin volume (80% - 120%). Voids were seen for small pin volume (80%), and overflow materials were seen for large pin volume (120%).



(a) Vol **80%**, $D_h = 4$, $W_h = 5$ (b) Vol **100%**, $D_h = 4$, $W_h = 5$ (c) Vol **120%**, $D_h = 4$, $W_h = 5$

Figure 6: Cross-section views of z-pins with varying z-pin volume. The quality of z-pins was good for all volume cases (80%, 100%, and 120%). The red dotted lines show that the shape of the interface between stacked z-pins (= upper pin and lower pin) changed from upward convex to downward convex as the pin volume increased from 80% to 120%.

It was, however, interesting to see that some samples with different hole dimensions (depth and width) showed a good quality of z-pins even for small pin volume (80%) and large pin volume (120%). Figure 6 shows the cross-sections of z-pins with a hole depth of $D_h = 4$, a width of $W_h = 5$, and a varying pin volume of 80%, 100%, and 120%. All three figures (Figure 6 (a),(b), and (c)) with the pin volume of 80%, 100%, 120% showed a good quality of z-pins. The disparity of z-pin quality between Figure 5 and Figure 6 indicates that it is not sufficient to study a single volume fraction (e.g., 100% volume fraction) to determine the z-pin quality for different hole dimensions. A quality analysis required samples with 80%, 100%, and 120% pin volume to be made with all combinations of hole widths and depths.

Another interesting feature shown in Figure 6 is the interface shape (= top surface shape of z-pin) between two vertically stacked pins (lower pin and upper pin) as indicated by the red dotted lines. For a low pin volume (80%), the material bulged upward in the z-pin which created an upward convex shape at the interface between two stacked pins. This shape was consistantly seen at all interfaces and the top surface of the top pins in Figure 6(a). As the pin volume increased from 80% to 100% and to 120%, the interface shape changed to a downward convex shape as shown in Figure 6 (b-c). The difference of the shape was presumably because of the material flow near the nozzle tip. It was assumed that the pressure from the material at the nozzle tip pushed the existing material as illustrated in Figure 7(a). If the volume was too much for given hole dimensions, the extra material flows upward as illustrated in Figure 7(b). The top surface shape of z-pin was also influenced by the aspect ratio of the z-pin, which is presented in the next two sections.

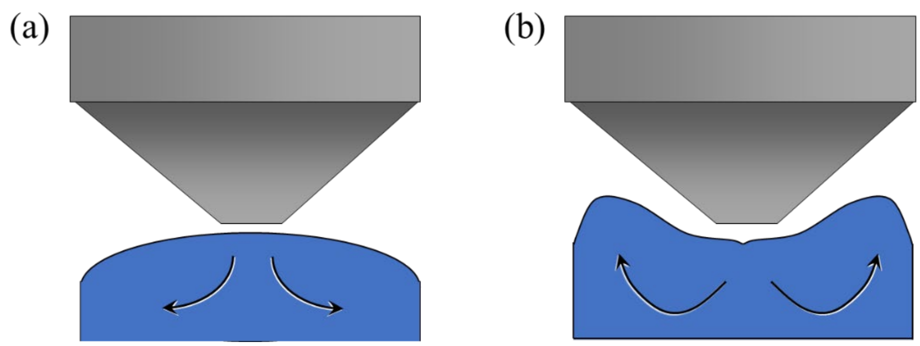
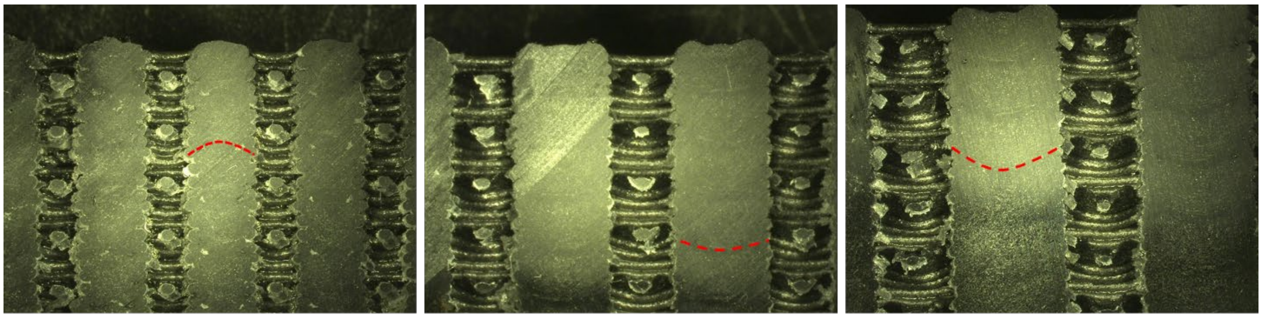


Figure 7: Estimated flow mechanisms of the two shapes of top surface of z-pin (a) Upward convex: material flows down and toward sides (b) Downward convex: material flows down and sides and pushes the existing material to the upward direction.

3.2 Effect of hole width

The hole width was varied from $W_h = 3$ to $W_h = 6$. Figure 8 shows the cross-sections of z-pins with the pin volume 100% (= same as the hole volume) and the hole depth of $D_h = 4$. As the hole width became larger, the aspect ratio reduced, and the top surface of z-pin changed from an upward convex shape to a downward convex shape.

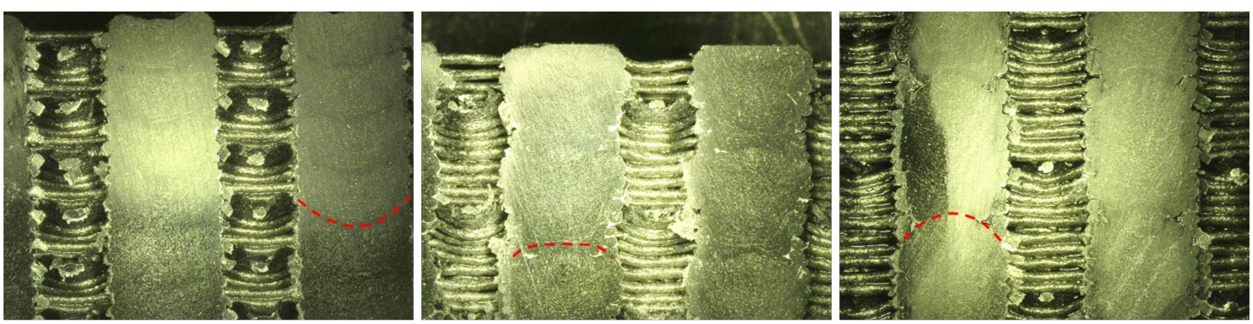


(a) Vol 100%, $D_h = 4, \boldsymbol{W_h} = \mathbf{3}$ (b) Vol 100%, $D_h = 4, \boldsymbol{W_h} = \mathbf{5}$ (c) Vol 100%, $D_h = 4, \boldsymbol{W_h} = \mathbf{6}$

Figure 8: Cross-section views of z-pins with varying hole width

3.3 Effect of hole depth

The hole depth was varied from $D_h = 4$ to $D_h = 10$. Figure 9 shows the cross-sections of z-pins with a pin volume 100% (= same as the hole volume) and a hole width of $W_h = 6$. As the hole depth became deeper, the aspect ratio increased, and the top surface of z-pin changed from a downward convex shape to an upward convex shape.



(a) Vol 100%, $\boldsymbol{D_h} = \mathbf{4}, W_h = 6$ (b) Vol 100%, $\boldsymbol{D_h} = \mathbf{8}, W_h = 6$ (c) Vol 100%, $\boldsymbol{D_h} = \mathbf{10}, W_h = 6$

Figure 9: Cross-section views of z-pins with varying hole depth

3.4 Z-pin quality with various hole widths, hole depths, and pin volumes

In the previous sections (Sec. 3.1 – 3.3), the effects of individual z-pin parameters (pin volume, hole width, and hole depth) were shown while the other two parameters were fixed. However, all three parameters can have a combined influence the z-pin quality. Therefore, the z-pin quality was investigated across a variety of combinations of the three z-pin parameters. Multiple samples (> 60 samples) were prepared, each having different combination of pin volume, hole width and hole depth. Table 1-3 summarizes the z-pin quality for various hole widths, hole depths and pin volumes. "G" indicates good quality of z-pins with the upward convex shape or flat shape of z-pin top surface. Examples of good quality z-pins include Figure 5(b), Figure 6(a), Figure 8(a), and Figure 9(b, c). "G_{ov}" indicates good quality of z-pins with the downward convex shape of z-pin top surface. Examples of good quality z-pins include Figure 6(b,c), Figure 8(b,c), and Figure 9(a). "OK" indicates somewhat good quality of z-pins with some defects. An example of "OK" quality z-pins was shown in Figure 5(a).

Table 1: Z-pin quality for the pin volume of 80%

80% Vol		Hole width ratio, W_h			
		3	4	5	6
Hole depth ratio, D_h	4	OK	G	G	G
	6	OK	G	G	G
	8	B	OK	G	G
	10		B	B	G

G = good quality, B = bad quality, OK = quality between B and G

Table 2: Z-pin quality for the pin volume of 100%

100% Vol		Hole width ratio, W_h			
		3	4	5	6
Hole depth ratio, D_h	4	G	G	G_{ov}	G_{ov}
	6	OK	G	G	G
	8	B	G	G	G
	10		B	B	G

G = good quality, B = bad quality, OK = quality between B and G,
G_{ov} = good but over the nozzle tip level

Table 3: Z-pin quality for the pin volume of 120%

120% Vol		Hole width ratio, W_h			
		3	4	5	6
Hole depth ratio, D_h	4	B	G	G_{ov}	G_{ov}
	6	N/A	OK	G_{ov}	G_{ov}
	8	B	B	G	G_{ov}
	10		B	B	B

G = good quality, B = bad quality, OK = quality between B and G,
G_{ov} = good but over the nozzle tip level

As shown in Table 1-3, the z-pin quality tended to degrade when the hole depth was too deep for a given hole width. Likewise, the z-pin quality tended to degrade if the hole width was too narrow for a given hole depth. As the pin volume increased, some of the z-pin samples with marginally good quality degraded due to overflow of extra material from the z-pins.

4. SUMMARY

Z-pinning parameters (hole width, hole depth, and pin volume) have been investigated for carbon fiber-reinforced PLA. The base structure of the samples had a rectilinear pattern (0°/90° cross-ply) with the hole width varying from 1.5 mm to 3 mm (W_h = 3 – 6) and the hole depth varying from 8 layers to 20 layers (D_h = 4 – 10). The z-pin volume varied from 80% to 120% of the hole volume. The cross-section of all samples was analyzed and the quality of the z-pin structure was categorized as bad ("B"), good ("G"), good with the z-pin top surface higher than nozzle tip ("G_{ov}"), and moderate quality between good and bad ("OK"). Overall, the z-pin quality tended to degrade when the hole depth was too deep for a given hole width. Likewise, the z-pin quality tended to degrade when the hole width was too narrow for a given hole depth. As the pin volume increased, some of the z-pin samples with marginally good quality become bad. There is not yet sufficient evidence in this study to determine which category of z-pin shows the highest mechanical performance, so this remains an ongoing effort.

Acknowledgement

Research was sponsored by the U.S. Department of Energy, Office of Energy Efficiency and Renewable Energy, Advanced Manufacturing Office and used resources at the Manufacturing Demonstration Facility, a DOE-EERE User Facility at Oak Ridge National Laboratory, under contract DE-AC05-00OR22725 with UT-Battelle, LLC. Research was supported by an appointment to the Oak Ridge National Laboratory Advanced Short-Term Research Opportunity (ASTRO) Program and Higher Education Research Experiences (HERE) program, sponsored by the U.S. Department of Energy and administered by the Oak Ridge Institute for Science and Education. Research was also sponsored by the U.S. Army Combat Capabilities Development Command Aviation & Missile Center.

References

1. T.T. Wohlers, W. Associates, I. Campbell, T. Caffrey, O. Diegel, and J. Kowen, *Wohlers Report 2018: 3D Printing and Additive Manufacturing State of the Industry : Annual Worldwide Progress Report*. 2018: Wohlers Associates.
2. C. Duty, J. Failla, S. Kim, J. Lindahl, B. Post, L. Love, and V. Kunc. *Reducing Mechanical Anisotropy In Extrusion-Based Printed Parts*. in *Solid Freeform Fabrication Symposium*. 2017. Austin, TX.
3. C. Duty, J. Failla, S. Kim, T. Smith, J. Lindahl, and V. Kunc, *Z-Pinning approach for 3D printing mechanically isotropic materials.* Additive Manufacturing, 2019. **27**: p. 175-184.
4. S. Kim, T. Smith, J.A. Failla, J.M. Lindahl, V. Kunc, and C.E. Duty. *Parametric Analysis on Vertical Pins for Strengthening Extrusion-Based Printed Parts*. in *SAMPE 2018*. 2018. Long Beach, CA.

5. C. Duty, J. Failla, S. Kim, T. Smith, J. Lindahl, A. Roschli, . . . , and V. Kunc. *Z-Pinning Approach for Reducing Mechanical Anisotropy of 3D Printed Parts*. in *The 29th Annual International Solid Freeform Fabrication (SFF) Symposium*. 2018. Austin, TX.
6. C. Duty, S. Kim, V. Kunc, L. Love, B. Post, J. Failla, and J. Lindahl. *Z-axis improvement in additive manufacturing*. in *U.S. Patent Application 15/965,106*. Nov. 1, 2018.
7. *Slic3r Infill Patterns*. Available from:" https://manual.slic3r.org/expert-mode/print-settings", Cited.