Z-PINNING APPROACH FOR REDUCING MECHANICAL ANISOTROPY OF 3D PRINTED PARTS

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Abstract

The mechanical strength of extrusion-based printed parts is often greatly reduced (25-50%) in the build direction (z-direction) compared to the in-plane strength due to poor bonding between successively deposited layers. This effect can be magnified (75-90% difference) when depositing fiber-reinforced materials or larger print areas with long layer times. Therefore, a patent-pending approach has been developed that deposits material into intentionally aligned voids in the z-direction, allowing continuous material to span multiple layers. The "z-pinning" approach can be applied to several concepts for improving the interlaminar strength of extrusion-based 3D printed parts as well as techniques for applying the technology across a broad spectrum of deposition platforms and material systems. Initial experimental results demonstrate a significant improvement (>3x) in mechanical strength and (>8x) toughness for fiber reinforced components.

Background

Extrusion-based printing technologies have dominated the 3D printing market over the last several years (with over half a million systems sold worldwide) [1], as the low cost of desktop fused filament fabrication (FFF) systems has greatly expanded the accessibility of personal 3D printing. Although FFF systems offer geometric flexibility, ease of use, and increasingly more diverse feedstock materials, their use in engineering applications is typically limited due to poor mechanical properties. The strength of FFF components is generally much less (25-50%) than the cited injection molded reference for a given material, and the properties of a printed part can vary considerably based on the print orientation. These reductions are largely due to the meso-structure created by the FFF process, which deposits aligned beads (or roads) in the x- and y-directions (i.e. the build plane) and stacks layers in the z-direction (i.e. the build direction). This process typically results in strands of continuous material extending throughout a given layer in the build plane, but only has discontinuous points of contact between successive layers in the build direction.

Such a directionally-biased structure gives rise to significant mechanical anisotropy in 3D printed parts. Shaffer et al [2] tested the effect of build orientation on the tensile strength for 3D printed parts made from unreinforced polylactic acid (PLA) and acrylonitrile butadiene styrene (ABS). For each material, the tensile load was applied either parallel to the continuously deposited material in a given layer (x-direction) or perpendicular to the successive build layers (z-direction). It was found that the z-direction strength was 45% lower than the x-direction strength for PLA, and over 85% lower for ABS. Torrado-Perez et al [3] found that ABS samples printed on a

MakerBot demonstrated a 50% reduction in strength in the z-direction compared to the x-y plane. A reduction in z-strength is also apparent as scale increases, as evident in a study by Duty et al [4] where Big Area Additive Manufacturing (BAAM) samples demonstrated an 80-90% reduction in mechanical strength in the z-direction compared to the x-direction. The BAAM samples compared in that study were fiber reinforced ABS with either glass or carbon fibers. Fiber reinforced materials are likely to have an increased degree of anisotropy when 3D printed using an extrusion-based technique due to shear-alignment of the discontinuous fibers in the flow direction. Tekinalp et al reported fiber alignment measurements for 3D printed carbon fiber reinforced ABS, showing that the fibers nearly perfectly align in the direction of deposition (the x-direction). Therefore, in order to achieve 3D printed components using fiber reinforced materials with reduced anisotropy, a new approach is needed.

Z-Pinning Approach

The authors of this paper introduced a patent-pending [5] 3D printing approach for extrusion-based systems at the 2017 Solid Freeform Fabrication Symposium called "z-pinning" [6]. The z-pinning approach allows for semi-continuous deposition of material along the z-direction (i.e. across layers) by holding the extrusion nozzle stationary over intentional voids in the x-y plane that are aligned to span multiple layers. As material exits the extrusion nozzle, it fills the void that extends a given number of layers into the part (see Figure 1). A pattern of voids extends across the part which are filled in a staggered pattern in order to offset the interface between neighboring pins. In Figure 1, the separate pins are represented by different colors to emphasize that each of the pins is deposited in separate operations after a given number of conventional layers are deposited. The classification convention for describing pins extending "P" layers deep that are deposited every "R" layers is "P-R" pins. For instance, since the pins in Figure 1 extend 4 layers deep and alternating sets of pins are deposited every 2 layers, the pins in Figure 1 would be described as "4-2 pins".
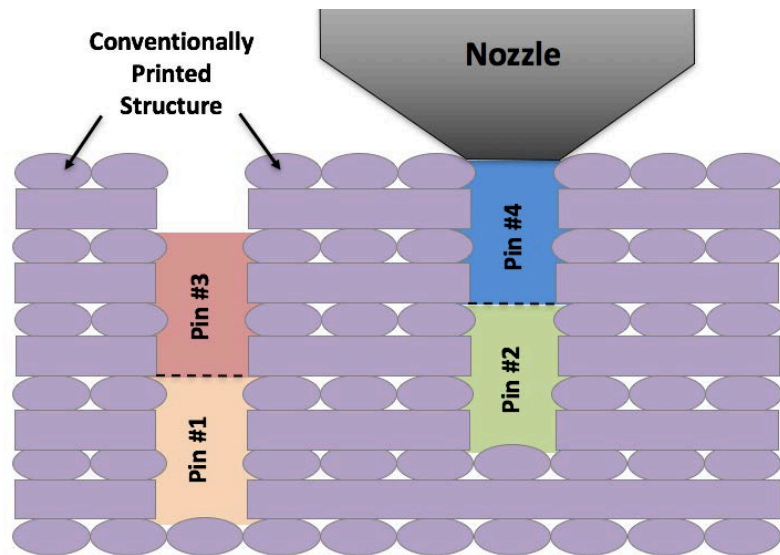

Figure 1. Z-Pinning approach for depositing continuous material across successive layers.

The pins are typically deposited into a rectilinear grid on the x-y plane, where continuous beads within a given layer alternate between the x- and y-directions, leaving gaps between neighboring beads to result in a relatively low volumetric infill (30-55%). The extruded volume of the individual pins is considered to be a percentage of the theoretically prismatic void space. In the case where the extruded volume exceeds 100% of the theoretical volume, the "overfill" material of the pin typically extends into the space between successive layers which results in a fair degree of mechanical interlocking between the pin and surrounding structure. In order to avoid interference with overfilled material from neighboring pins, the pins are typically arranged in an "A-B" configuration as shown in Figure 2.
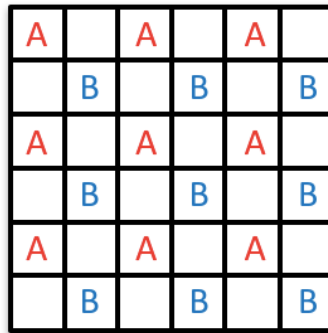

Figure 2. Pin spacing configuration for filling rectilinear grid (top view, x-y plane).

The dimensions of the pin, hole, and relative pin volume can have a significant impact on the overall mechanical properties of the printed part. An initial parametric study of printing parameters shows that an 80% pin volume is the practical maximum to avoid overflow and printing problems [7], but it was anticipated that additional overflow would aide with mechanical interlocking of the pin with the surrounding structure. The initial experiments that applied z-pins to printed PLA samples [6] used an 80% pin volume on a 35% rectilinear grid pattern and showed a 20% increase in strength and a 100% increase in toughness compared to a sample without pins. The current study extends that concept to carbon fiber reinforced PLA and varies the pin volume amount.

Experimental Procedure

In order to evaluate the z-strength of x-pinned components, tensile specimens were printed on a MakerGear M2 using carbon fiber reinforced PLA (CF-PLA) from 3DXTech (CarbonX CFR HT-PLA). The material was deposited at 240°C using customized g-code to generate the rectilinear infill grid pattern described above. A volumetric infill of 35% was used for all of the pinned samples. Pins were designed to penetrate 8 layers deep and alternating pins were deposited every 4 layers (8-4 pins) using the A-B configuration shown in Figure 2. The pin volume extruded was 80%, 120%, and 160% of the theoretical prismatic void. Control samples without z-pins were also printed with volumetric infills of 35% and 55%. The 55% control sample was intended to be an "equivalent weight" sample, representing the same amount of material as the 35% infill sample with 80% volume z-pins. Four replicate samples were printed using each of the parameters listed above.

The tensile samples were directly printed to the dimensions shown in Figure 3. The tensile samples were tested using a MTS Series 40 Electromechanical Universal Test System with a 100 kN load cell at a strain rate of 5 mm/min. Engineering stress was calculated based on the nominal apparent cross section of 25 mm x 9 mm and strain measurements were taken from the machine crosshead displacement. A discontinuity in the print code was observed in the transition sections between the gauge length and the grip sections (Figure 4), likely causing several of the samples to break in this region. Future studies will address this issue by printing prismatic rectangular blocks from which the tensile specimens will be machined.
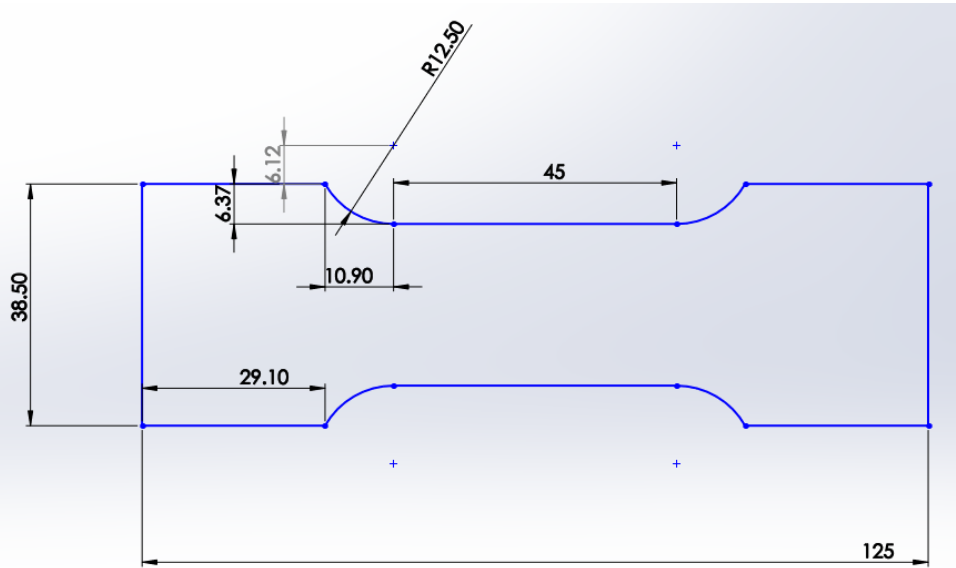

Figure 3. Tensile sample dimensions (mm). Samples were 9 mm thick.
Note: z-direction is horizontal as shown here.

Figure 4. Printed sample showing discontinuities in the print pattern near the transition region.

Experimental Results & Discussion

Figure 5 shows representative tensile test results for a z-pinned sample compared to a non-pinned sample with a higher infill percentage. The z-pinned sample shows a significant increase in strength in the z-direction and almost an order of magnitude increase in toughness. The z-pinned sample used a standard 35% infill and a relatively high pin volume (160% of theoretical). This result illustrates the potential of the z-pinning approach to dramatically improve the z-strength of 3D printed parts, especially when using fiber reinforced materials. A more detailed understanding of the impact of pin volume and relative material usage follows from analysis of the remaining data.
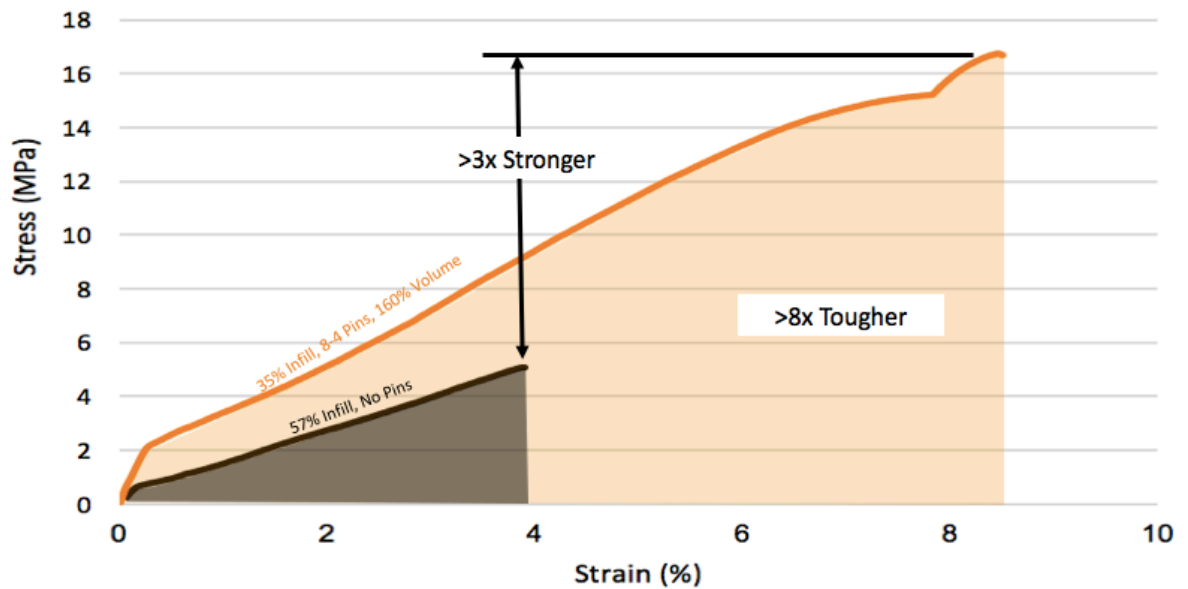

Figure 5. Representative tensile test result comparing strength and toughness of pinned vs non-pinned samples.

The ultimate tensile strength for all of the samples investigated is shown in Figure 6. The error bars represent one standard deviation for a sample set of four (n=4) for each condition. A statistically significant increase in z-strength can be observed between each of the print conditions evaluated. An ~80% increase in strength is achieved simply by increasing the infill percentage from 35% (2.8 MPa) to 55% (5.1 MPa) for the two control samples without z-pins. This increase in strength can be attributed to the increased contact area between successive layers due to the reduced void size.
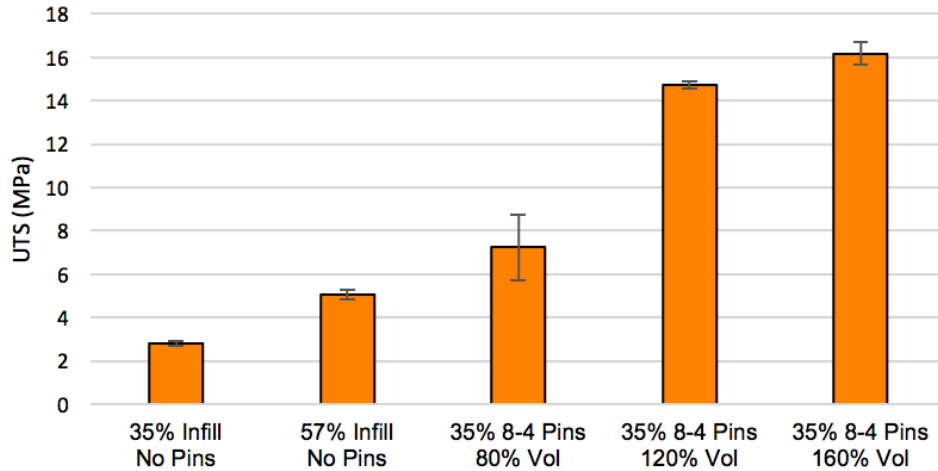
Figure 6. Ultimate tensile strength of pinned CF-PLA samples using various fill volumes.

The strength of all of the z-pinned samples were signifcantly higher than the control samples without pins, with a noticeable increase in strength observed each time the pin volume increased. Specifically, the 80% volume pinned sample showed twice the increase in strength (7.2 MPa) from the 35% infill control compared to the 55% infill. The average weight for the printed samples are shown in Table 1. Although the 55% infill was intended to be an "equivalent weight" comparison to the 35% infill with 80% volume pins, Table 1 indicates that the pinned sample was slightly heavier (~7%). However, given that the strength of the 80% pinned sample was ~50% higher than the "equivalent weight" control, this indicates that the use of z-pins has more of an impact on the z-strength of the part than the overall increased contact area achieved by additional rectilinear infill.

Table 1. Average weight and UTS for each condition.

Sample	UTS (MPa)	Mass (g)	Specific UTS (kPa/g)
35% Infill - No Pins	2.8	12.5	22.5
55% Infill - No Pins	5.1	17.7	28.6
35% Infill - 80% Pins	7.2	19.0	38.1
35% Infill - 120% Pins	14.7	21.8	67.7
35% Infill - 160% Pins	16.2	25.1	64.3

It can also be noted that the strength of the part increases considerably as the volume of the pin increases. This behavior is to be expected since the overfill expands into the surrounding structure and increases mechanical interlocking, making the z-pins more effective. However, the data in Table 1 indicates that on a per-mass basis, the 120% volume pins provided more strength than the additional volume of the 160% pins.

The area under the stress-strain curve was calculated for each condition to obtain the material's toughness. Figure 7 shows that the use of z-pins to span layers significantly increases

the material toughness, providing over an order of magnitude increase when comparing the 160% volume pins (806 kJ/m^3) to the 35% infill without pins (37 kJ/m^3). As seen in the previous study [6], the fracture surface of the pinned samples was much more tortuous than the relatively planar fracture surface of the non-pinned samples. The effect of the pins to deflect the crack pathway effectively consumes energy, increases the apparent ductility, and adds to the toughness of the material. As with the strength results, increasing the pin volume has a significant impact on toughness. However, comparing the 120% pin volume sample to the 160% pin volume sample shows that adding 15% more mass to the sample increases the toughness by 43%. This indicate that the optimal pin geometry, void geometry, and pin volume combination that maximizes toughness may not be the same as the combination for optimal strength.
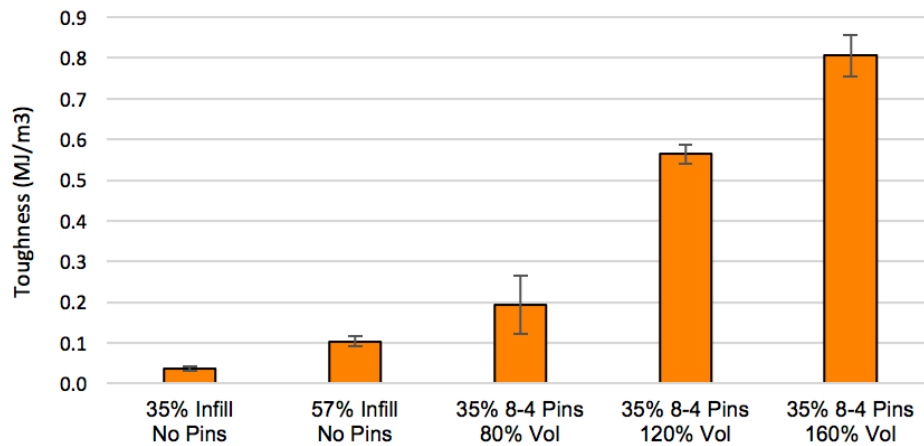

Figure 7. Toughness of pinned CF-PLA samples using various fill volumes.

Conclusions & Future Work

The z-pinning approach has been demonstrated for fiber reinforced materials. The initially modest improvements (~20%) in ultimate tensile strength realized a year ago with unreinforced PLA have shown dramatic improvements (>300%) when a similar approach was applied to fiber reinforced materials. The amount of the pin material extruded into the void was found to be a critical factor affecting both strength and toughness. Additional studies are needed to optimize the geometry of the pin/void pairs as well as their relative spacing throughout the part to maximize material performance. In order to validate this approach for reducing anisotropy in a printed part, appropriate control samples in the print direction (x-direction) are also needed for comparison.

Acknowledgements

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