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WEIBULL ANALYSIS OF THE EFFECT OF DEPOSITION TEMPERATURE AND NUMBER OF LAYERS ON STRENGTH OF FUSED DEPOSITION MODELING PLASTICS

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Abstract**—**Fused deposition modeling is an additive manufacturing process of building up a part layer by layer, with the strength of that part reliant on the bond strength between the fused layers. It is important to select printing parameters that result in a high inter-layer bond to maximize the overall structural integrity of the part. This research aims to explore the variation in the strength in addition to the mean strength in between the layers, which is critical to ensuring a more structurally sound part and should be kept in mind while choosing the printing parameters. This challenges the notion that the printing parameter that would yield the most structurally sound part would be the part with the highest mean bond strength. This research used special test samples to isolate the interlayer bonds for tensile strength testing. The tests were performed on samples with three interlayer bonds and the data was analyzed using Weibull statistics to determine the predicted tensile strength for up to 500 active layers. The tested parameter was nozzle extrusion temperature with a range of +/- 10 ºC from the manufacturer's recommended temperature. The printed polylactic acid (PLA) material had a higher average tensile strength at 205 ºC than at 215 ºC. However, the samples printed at 215 ºC had less variation in bond strength (lower Weibull modulus) and once the number of interlayer bonds in the parts surpassed 106 layers, the samples can be expected to have higher overall tensile strength.

Keywords-3D print, average tensile strength, tensile strength varibility, interlayer bonding, weibull statistics

I. INTRODUCTION

Fused Deposition Modelling (FDM) has become a common method of producing nonstructural parts with complex geometry. Its use has recently been expanded to structural parts such as hydraulic pumps [1], gears [2,3], small pressure vessels [4] and other structural parts [5].

While conventional materials such as structural steel are typically assumed to be continuous and isotropic, with the same mechanical properties throughout and in all directions, these assumptions are not the case of FDM parts. FDM parts are manufactured layer-by-layer. Typically, within a layer the material is deposited next to recently deposited material that is still warm but on top of a previous layer that has cooled. This leads to strong bonds within the layer, but the interlayer adhesion is usually weaker [6]. This suggests that the strength of the sample in the direction perpendicular to the deposited layers is typically less than in the other two directions. For example, an early datasheet from Prusa polyethylene terephthalate glycol (PETG) listed the tensile strengths in the x-, y-, and z- directions as 47+/2 MPa, 50+/-1 MPa, and 30+/-5 MPa, respectively where a reduction of 40% was reported in the z-direction which is the direction related to the interlayer bonds [7]. Interestingly, the current datasheet no longer lists the strength in the z-direction [8] .

Various research studies have been conducted on optimizing the printing parameters using theoretical models and simulation. For example, Tünçay et al. [9] used a model based on experimental data to find the optimal print angle, infill density and required number of walls. However, their test specimens were not loaded in the direction that stresses the interlayer bonds. Similarly, Wang et al. [10] showed the effect of the print angle on tensile strength (showing the weakening effect as the interlayer bonds are loaded) and considered the influence of printing temperature, but only investigated temperature in the directions that left the interlayer bonds unstressed. These and other papers [11–13] typically studied the effect of a large but unknown effective number of loaded interlayer bonds and typically reported their results as the mean of a relatively small number of tests. It is important to know the average strength of the bonds between the layers, but it is equally important to understand how consistent the bond strength is. While a certain printing condition would be able to make layers with higher strength, it is important that all layers are uniform at that strength because the weakest layer bond will be the one to fail first. This work will study the variability of the layer strength to determine the condition where the layer bonding strength is most consistent, resulting in the strongest overall part.

In addition to variation of strength from test sample to test sample, there is considerable variation in the strength from layer-to-layer. This effect can be compounded by part geometries such that the weakest layers will fails first. This means that "order statistics" must be applied. Given a distribution of values such as the distribution of the bond strength of a single interlayer, first order statistics can tell us what the expected strength will be of the weakest of a number of layers. If we know $\Phi(x)$, the Cumulative Distribution Function (CDF) and the integral of the Probability Density Function (PDF) of the underlying data (e.g. if we measured the bond strength of every layer in a number of specimens and fit it to a distribution), then the CDF of the weakest layer, Φ_1 in a number of specimens would follow

$$\Phi(x) = 1 - \left(1 - \Phi_1(x)\right)^{\frac{1}{n}} \tag{1}$$

where n is the sample size (e.g. the number of parallel layers in a single specimen). Rather than assuming that the distribution of the data follows the typical Gaussian distribution, it is more convenient to use a Weibull distribution [14], whose probability distribution function is given by

$$\phi(x) = \begin{cases} \frac{k}{\lambda}\left(\frac{x}{\lambda}\right)^{k-1} e^{-\left(\frac{x}{\lambda}\right)^{k}}, & x \geq 0 \\ 0, & x < 0 \end{cases} \tag{2}$$

where λ is the scale parameter and k is the shape parameter (also known as the Weibull Modulus). In this case, the probability goes to zero at x = 0 and is equal to zero for all x < 0 (avoiding probability of any non-physical negative values which would not be the case of a Gaussian distribution). Unlike the Guassian distribution, which requires a transcendental function to write the Cumulative Density Function, the Weibull CDF is given by:

$$\Phi(x) = \begin{cases} 1 - e^{-\left(\frac{x}{\lambda}\right)^{k}}, & x \geq 0 \\ 0, & x < 0 \end{cases} \tag{3}$$

Assume that $\Phi_1(x)$ also follows a Weibull distribution with parameters λ_1 and k_1:

$$\Phi_1(x) = 1 - e^{-\left(\frac{x}{\lambda_1}\right)^{k_1}} \tag{4}$$

If we substitute Equation 3 (for x > 0) into Equation 1, we obtain:

$$\Phi(x) = 1 - \left(1 - \left(1 - e^{-\left(\frac{x}{\lambda_1}\right)^{k_1}}\right)\right)^{\frac{1}{n}} \tag{5}$$

which can be simplified to

$$\Phi(x) = 1 - \left(e^{-\left(\frac{x}{\lambda_1}\right)^{k_1}}\right)^{\frac{1}{n}} \tag{6}$$

$$\Phi(x) = 1 - e^{-\left(\frac{x}{\lambda_1 n^{\frac{1}{k_1}}}\right)^{k_1}} \tag{7}$$

We can then compare the forms of Equation 7 and 3 to obtain

$$k = k_1 \tag{8}$$

$$\lambda = \lambda_1 n^{\left(\frac{1}{k_1}\right)} \tag{9}$$

Therefore, if the strength of the weakest of n layers is measured for a number of specimens and from the data fit k_1 and λ_1, then we can use Equations 8 and 9 to calculate Weibull parameters of all layer bonds (k and λ). In order to obtain the scale parameter λ we need to know the number of effective layers (which may be difficult due to stress concentrations biasing failure in a smaller number of layers than are physically present), but the shape parameter *does not require n* and is the same for both the first order distribution and the underlying one. Therefore, a good estimate of k can be obtained from a dataset without needing to know the number of effective layers, n.

Also note that once the Weibull parameters are evaluated, Equations 8 and 9 can be used to estimate the effect of the number of layers. E.g. how much is the strength of an object reduced by having a large number of layers in it?

Table I gives some typical values of the Weibull modulus for some engineering materials, ranging from chalk with very low modulus (highly variable strength) to high values for steel (very reliable). Keles et al. [15] measured the Weibull modulus of FDM printed acrylonitrile butadiene styrene (ABS), but only in the stronger flat orientation which did not load the weaker inter-layer bonds. In this paper, we intend to measure the Weibull modulus for the inter-layer bonds of FDM polymer materials and the effect of printing parameters, particularly extruder temperature. The hypothesis is that there are examples of particular situations where the mean strength of a single bond may be high, but the Weibull modulus is low, resulting in a weaker multi-layer part.

TABLE I. WEIBULL MODULUS OF SOME TYPICAL MATERIALS (FROM [16])

Material	k	Source
Traditional Ceramics: Brick, Pottery, Chalk	<3	[17]
Engineered Ceramics: SiC, Al2O3, Si3N4	5-10	[17]
Metals: Aluminum, Steel, Magnesium	90-100	[16,17]
FDM ABS (no interlayer-bonds)	26-41	[15]

II. METHODOLOGY

There are many parameters for 3D printing that will affect tensile strength such as printing speed, cooling rate, material extrusion rate, bed temperature, and printing temperature. This work will focus on printing temperature, the internal temperature of the extruder that melts the material. This study will answer the question: how will different temperatures affect the variability of tensile strength of the bonding layers in a 3D printed sample?

To determine the bonding strength between two layers, first there is a need to isolate and identify the layers. The bonding layers that are actively holding the samples together are perpendicular to the tensile force being applied; these will be referred to as active layers. There are no current standards for tensile testing of FDM printed material, but a common standard used for conventional plastics is the ASTM D638-22 tensile test. While this standard is appropriate for certain tests, the number of equally loaded active layers that are likely to fail need to be identified. A test sample was made for this purpose by using the nature of 3D printing to isolate the sample to a small number of active layers. As shown in Figure 1, the sample grip area was sliced in parallel to the pulling force for maximum strength and the active layers were sliced perpendicular to the tensile force to load the interlayer bonds. The parallel layers are stronger, and the sample will always break at the bonding layers that are perpendicular to the tensile force. The sample dimensions are 83 mm x 19 mm x 3.2 mm, including 1 mm x 19 mm x 3.2 mm in the middle being the active layers as shown in Figure 1. A value of n=3 was selected for the active layers in order to keep the number of layers small.

Preliminary statistical power analysis predicted that 854 samples would be required to achieve a 5% uncertainty in the Weibull modulus, 231 for 10% and 63 samples for 20% uncertainty. Due to time constraints, 63 samples were targeted at each temperature condition. The selected testing materials were Prusament PLA in lipstick red color and Prusament PETG clear with a filament diameter of 1.75 mm. The sample was

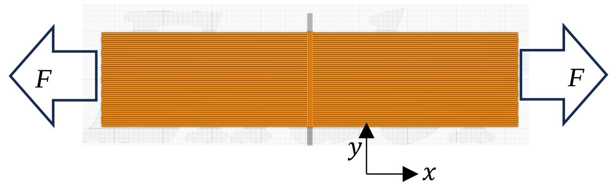

Figure 1. 3D printed sample, as sliced by the Cura slicing software, showing the direction of the tensile force, F.

printed using an Ender 3v2 printer, a popular commercial 3D printer. The tensile test was performed on an ESM 1500LC Mark-10 force test stand using a 3.5 kN load cell and a retraction speed of 5 mm/min. The printing parameters can be found in Table II. The PLA samples were printed at extruder temperatures of 205 ºC, 215 ºC, and 225 ºC, while the PETG samples were printed at 240 ºC, 250 ºC, and 260 ºC. The temperatures were chosen based on recommendations from the manufacturer data sheet ± 10 ºC.

TABLE II. PRINTING PARAMEETERS FOR TEST SAMPLES

Parameter	Value
Layer Height	0.2 mm
Wall thickness	0
Top bottom thickness	0
Infill density	100%(PLA) 90%(PETG)
Infill pattern	lines
Speed	50 mm/s

Each test sample was tensile tested to failure and the ultimate loading force, F, was recorded. The tensile strength was calculated using:

$$\sigma_3 = \frac{F}{A} \quad (10)$$

where A is the cross-sectional area of the undeformed sample. Note that the subscript indicates that this is the strength of a test sample with 3 active layers.

For each material and temperature, the Weibull coefficients k and λ_3 were fit using the Matlab function wblfit, which is numerical solution for a system of implicit equations. Equation 9 was then used to calculate the scale coefficient for a single active layer, λ_1. Note that the shape coefficient, k, is the same for any number of active layers.

III. RESULTS AND DISCUSSION

Table III shows the mean tensile strength, $\overline{\sigma_3}$ for the 3-layer test samples. This table also shows the calculated shape parameter, k, and the scale parameters for 3 and 1 layer. As the shape parameter values increase, the reliability of the strength improves and the width of the probability distribution narrows, as shown in Figure 4.

TABLE III: TENSILE TEST RESULTS: MEAN TENSILE STRENGTH FOR THE 3-LAYER TEST, WEIBULL COEFFICIENTS FOR THE 3-LAYER TEST AND CALCULATED WEIBULL SCALE PARAMETER FOR A 1-LAYER TEST.

Material	T (°C)	$\bar{\sigma}_3$ (MPa)	k	λ_3 (MPa)	λ_1 (MPa)
PLA	205	41.3+/-1.1	10.8+/-2.1	43.2+/-1.3	47.9+/-1.4
PLA	215	53.1+/-0.4	29.8+/-5.4	54.0+/-0.5	56.0+/-0.5
PLA	225	57.3+/-0.8	17.9+/-3.3	58.9+/-1.0	62.6+/-1.0
PETG	240	33.7+/-1.4	8.6+/-2.0	35.6+/-1.8	40.5+/-2.0
PETG	250	42.0+/-1.0	14.1+/-3.3	43.6+/-1.1	47.1+/-1.2
PETG	260	47.2+/-0.7	24.4+/-5.4	48.4+/-0.6	50.6+/-0.6

The PLA and PETG results show that the mean value of the interlayer bonds increases with an increase in printing temperature. The highest mean tensile strength was PLA printed at 225 °C. However, looking at the Weibull coefficients, the PLA samples printed at 215 °C had the highest shape parameter which indicates the narrowest peak and the most consistent layer bond strengths. This has the greatest effect for a part with many parallel layers, which allows for a higher probability of a single weak layer. If we use Equation 9 to calculate the strength of the weakest of n layers, the results are shown in Figure 5. In this case, although for a single layer the average strength of PLA is highest at a temperature of 225 °C, the more consistent 215 °C material is stronger if the sample has more than 106 layers.

On the other hand, the PETG samples had an increase in shape parameter with an increase in printing temperature and interlayer bond strength. In this case, the samples printed at 260 °C had the highest average strength as well as the most consistent interlayer bond strength, making it the strongest sample. Future testing could be performed to explore whether the trend from the PLA material is found at higher temperatures.

During the testing, while most samples failed in the expected interlayer bond area (Fig. 2), it was observed that some samples failed outside of this area (Fig. 3). The data from these samples were discarded. This mainly occurred with the PETG samples where the infill was at 90% which could have caused some of the parallel layers to have voids or bonding issues which caused them to be weaker than the targeted active layers. Another possible contributor to the failure is excessive clamping force used to prevent the sample from slipping during the tensile test which added stress concentrations in the grip area.

One outstanding question is the validity of the assumption that the three active layers were equally loaded. It is recommened that a stress analysis be performed on the samples to determine the distance the active layers should be from the clamp to avoid any internal stress differences from the clamp holding the sample.

Figure 2. 3D printed PETG sample breaking at interlayer bonds, as expected.

Figure 3. 3D printed PETG sample not breaking at interlayer bonds.

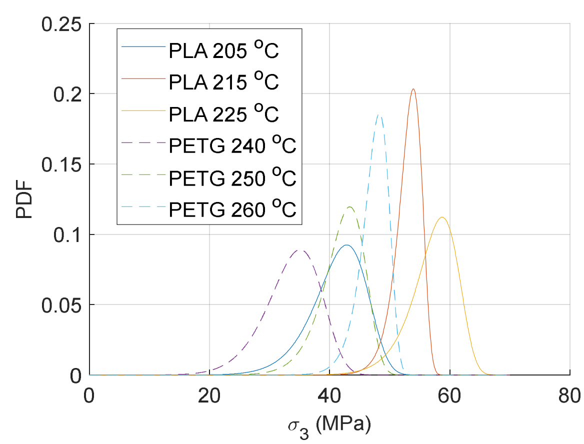

Figure 4. Weibull distribution of measured tensile strengths for samples with three active layers.

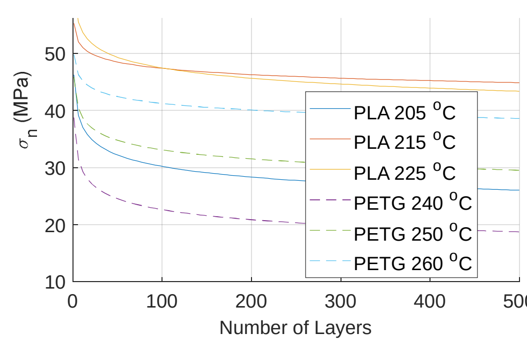

Figure 5. Expected tensile strength for a sample with n active layers.

IV. Conclusions

In conclusion, it was demonstrated that there are some situations where the mean strength of a single bond is high but has a low shape parameter resulting in an overall weaker part when considering multiple parallel layers. As most FDM 3D printed parts consist of dozens to hundreds of layers, it is important to consider not only the mean strength, but the variability of the bonding layer strength to result in an overall higher strength part.

It is very challenging and often not feasible to conduct this type of study on a wider scale due to the high volume of samples needed. To achieve a 5% uncertainty in the shape parameter for just 3 different temperatures, it was estimated that 2562 samples would be required. In addition, each different manufacturer of 3D printer filament comes with different printing temperature recommendations, so there are no ideal nozzle extrusion temperature recommendations that will apply to all FDM 3D printed parts to yield the highest strength. However, it is important to keep in mind that the average strength of the sample is not always indicative of the strength of a different sample geometry due to the variability of the interlayer bonding strength of multiple layers.

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