ISSN: 2640-5571

Research Article

Advances in Nanoscience and Nanotechnology

Increasing the Tensile Strength of 3d printed Poly lactic Acid (PLA) Using Design of Experiments (DOE)

A Cheng, C Burke and Rafiqul Noorani*

Loyola Marymount University, US

*Corresponding author
Rafiqul Noorani, Department of Mechanical Engineering Loyola Marymount University Los Angeles, CA 90045, US, E-mail: rnoorani@lmu.edu

Submitted: 03 May 2019; **Accepted**: 07 May 2019; **Published**: 29 May 2019

Abstract

Experimental design has been used to determine outlying factors that affect tensile strength of fused deposition modelling 3D printed PLA parts. A two level, three factor full factorial experiments were utilized to determine the best combination of factors that yielded the highest tensile strength of PLA tensile dog bones manufactured in accordance with ASTM D638-14. PLA is particularly desirable due to its environmental friendliness, biodegradability, low cost, and low melting point, allowing it to be built on a non-heated platform without risk of toxic fumes. Increasing the tensile strength of PLA will allow PLA to be used in a wider range of applications that demand stronger plastic parts. The chosen factors were infill percentage, nozzle temperature, and printing speed. The tensile strength was affected by all factors and combinations except for high levels of infill percentage, nozzle temperature, and printing speed combined.

Introduction

Fused deposition modelling (FDM) is an additive manufacturing technology that works by extruding material through a heated nozzle onto a build area layer by layer until the product is constructed [1]. This technology is desirable due to its ability to quickly produce prototype parts, reducing time and cost in the manufacturing process [2]. The material that was tested and analyzed was PLA, or Polylactic Acid. PLA is desirable due to it being a high strength, high modulus polymer that can be made from renewable resources [3]. Additionally, PLA is relatively low in cost and can be built on a non-heated platform [4]. In this study, a Maker Bot Replicator 3D printer was used to manufacture PLA tensile coupons in accordance with ASTM D638-14. The Maker Bot Replicator uses FDM to produce parts. The tensile data produced from testing the tensile coupons was then statistically analyzed using DOE to find the optimal combination that yielded the highest tensile strength. DOE, or Design of Experiment, is a methodology of testing and analyzing data that varies all factor combinations to see what factor combinations yield the best desired result [5]. The aim of this paper is to study the effects of nozzle temperature, infill percentage, and print speed on the tensile strength of PLA using DOE.

Theory

A two level, three factor (23) full factorial design was utilized in this experiment. The variables used in this study are (A) nozzle temperature, (B) infill percentage, and (C) nozzle temperature with high (+1) and low (-1) levels shown in Table 1, with the specimen factors and combinations shown in Table 2.

Table 1: Factors and levels

Factors	Description	Low Level (-1)	High Level (+1)
A	Nozzle Temperature	190 °C	210 °C
B	Infill Percentage	20%	40%
C	Printing Speed	40 mm/s	100 mm/s

Table 2: Specimen factors and combinations

Specimen	Factors			Combinations			
	A	B	C	AB	AC	BC	ABC
1	-1	-1	-1	1	1	1	-1
2	-1	-1	1	1	-1	-1	1
3	-1	1	-1	-1	1	-1	1
4	-1	1	1	-1	-1	1	-1
5	1	-1	-1	-1	-1	1	1
6	1	-1	1	-1	1	-1	-1
7	1	1	-1	1	-1	-1	-1
8	1	1	1	1	1	1	1

After results for eight experiments were gathered, a linear regression model was used to determine the maximum tensile strength response, Y_{max}. The notation for a linear regression model having three predicator variables with interactions is:

$$Y_{max}=\beta_0+\beta_1x_1+\beta_2x_2+\beta_{12}x_1x_2+\beta_3x_3+\beta_{13}x_1x_3+\beta_{23}x_2x_3+\beta_{123}xx_2x_3 \quad (1)$$

In Eq. 1, β_0 represents the response when both main effects are (-1), $\beta_1 x_1$ represents factor 1 at response (1), $\beta_2 x_1$ represents factor 2 at response (1), and so forth until $\beta_{123} x_1 x_2 x_3$ represents the interactions of factors 1,2, and 3 at responses of (1).

Only factors outside of 95% confidence interval are used. With the current data, only data set ABC is within the 95% confidence interval, so all data sets except ABC will be used in the calculation of Y_{max}. The beta values used in the Y_{max} calculation are listed below in Table 3.

Table 3. Beta values

Coefficients						
β_0	β_1	β_2	β_3	β_{12}	β_{13}	β_{23}
3.1796	-0.0125	0.0450	0.0125	-0.0487	0.1813	0.0862

The 95% confidence interval was calculated by first finding the standard error and pooled variance. The pooled variance estimate, $\overline{\sigma^2}$, was calculated with the following equation:

$$\overline{\sigma^2} = \frac{\Sigma(\sigma_i^2)}{2^k} \tag{2}$$

In Eq. (2), $\overline{\sigma^2}$ is the pooled variance estimate, σ_i is the individual standard deviation for the factor, and k is the number of factors, 3. This equation is needed to find the standard error, se, which is then used to formulate the 95% confidence interval in the DOE plot. The equation for standard error is shown as:

$$se = \sqrt{\frac{\overline{\sigma^2}}{n \cdot 2^{k-2}}} \tag{3}$$

In Eq. (3), $\overline{\sigma^2}$ is the pooled variance estimate, the denominator denoted by $n \cdot 2^{k-2}$ is the number of measurements, and k is the number of factors. The standard errors are then used to calculate the 95% confidence interval for the DOE plot, seen by taking CI = $\pm 2 \cdot se$.

Procedure

Tensile coupons were modelled in Solid Works in accordance with ASTM D638-14 and converted to a machine readable STL file. The STL file was then imported to the Maker Bot Print slicer software to be read by the Maker Bot Replicator machine. The parameter settings on the Maker Bot Print software were then adjusted accordingly to the high and low levels shown in Table 1, while keeping all other parameters and settings as the default (i.e. the tensile specimens were printed parallel to the bottom of the build area). The material used was a large spool of "True Green" PLA material bought from the Maker Bot website. Figure 1 shows a set of finished specimens. A total of 32 samples were printed on the Maker Bot Replicator, yielding four samples for each of the eight trials. The samples were then tested in an Instron 5900 R 4505 tensile testing machine, and the data was gathered using the Instron Blue hill LE software. Once the data was extracted from the broken specimens, DOE was used to statistically analyze which factors had the biggest influence on tensile strength.

Figure 1: A set of finished specimens

Results

The measured tensile strength for each specimen is recorded below in Table 4. Some specimens did not print properly and are denoted with a * next to the specimen. These specimens and their impact are discussed further in the discussion section. Broken samples from set 1 can be seen below in Figure 2.

Figure 2: Samples from set 1

Table 4: Specimen tensile values

Specimen	Measurement (ksi)				
	Sample 1	Sample 2	Sample 3	Sample 4	Mean
1	3.32	3.19	3.23*	3.28	3.26
2	3.09*	3.1	3.46	3.22	3.22
3	3.31	3.22	3.31	3.24	3.27
4	3.32*	3.3	3.27	3.34	3.31
5	3.09	3.27	3.17	3.19	3.18
6	3.09	2.95	3.01	2.98	3.01
7	3.1	3.04	2.92	3.02	3.02
8	3.07	3.11	3.17	3.12	3.12

The average tensile strength of all samples was calculated to be 3.17 ksi, and the maximum tensile strength response, Y_{max}, was calculated to be 3.99 ksi. Y_{max} was calculated as shown:

$$Y_{max}=\beta_0+\beta_1x_1+\beta_2x_2+\beta_{12}x_1x_2+\beta_3x_3+\beta_{13}x_1x_3+\beta_{23}x_2x_3+\beta_{123}x_1x_2x_3$$

$$Y_{max}=3.18+(-.01)(3.18)+(.04)(3.15)+(.01)(3.17)+(-.05)(3.20)+(.18)(3.08)+(.09)(3.13)$$
$$=3.99\ ksi$$

The maximum tested tensile strength was measured to be 3.46 ksi in run 2, with low (-1) values of A (190°F) and low (-1) values of B (20%), and high (+1) values of C (100 mm/s). The lowest tested tensile strength was measured to be 2.92 ksi in run 7, with high (+1) levels of A (210°F) and high (+1) values of B (40%), and low (-1) levels of C (40 mm/s). The full response table can be seen below in Table 5 which shows the average and influence of each factor and factor combination.

Table 5: Response Table (units in ksi)

Rand. Order	Std. Order	Response	A		B		C		AB		AC		BC		ABC	
			-1	1	-1	1	-1	1	-1	1	-1	1	-1	1	-1	1
			1	2	1	2	1	2	1	2	1	2	1	2	1	2
1	1	3.255	3.255		3.255		3.255			3.255		3.255		3.255	3.255	
3	2	3.27	3.27			3.27	3.27		3.27			3.27	3.27			3.27
2	3	3.0075	3.0075		3.0075			3.0075		3.0075	3.0075		3.0075			3.0075
4	4	3.18	3.18			3.18		3.18	3.18		3.18			3.18	3.18	
6	5	3.2175		3.2175	3.2175			3.2175	3.2175			3.2175	3.2175		3.2175	
5	6	3.1175		3.1175	3.1175		3.1175		3.1175		3.1175			3.1175		3.1175
8	7	3.3075		3.3075		3.3075		3.3075		3.3075		3.3075		3.3075		3.3075
7	8	3.02		3.02		3.02	3.02			3.02	3.02		3.02		3.02	
Total		25.38	12.71	12.66	12.60	12.78	12.66	12.71	12.79	12.59	12.33	13.05	12.52	12.86	12.67	12.70
# of Values		8.00	4	4	4	4	4	4	4	4	4	4	4	4	4	4
Average		3.17	3.18	3.17	3.15	3.19	3.17	3.18	3.20	3.15	3.08	3.26	3.13	3.22	3.17	3.18
Effect			-0.01		0.04		0.01		-0.05		0.18		0.09		0.01	

The tensile strength response of all samples and interaction diagrams for the three factors is shown below in Figure 3. All factors and combinations lie outside the 95% confidence interval, denoted by the red dotted line, except the combination of factors ABC. The mean is denoted by the solid red line in between the confidence interval lines. The 95% confidence interval was calculated to be between 3.166 and 3.177 ksi.

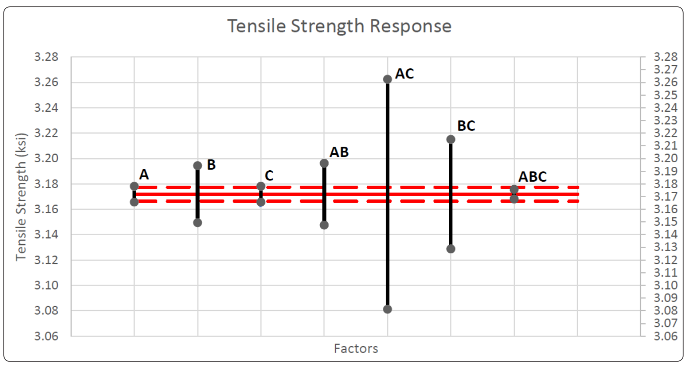

Figure 3: Tensile strength responses of samples

The interaction diagrams for the three factors are shown below in Figures 4,5,6. Figure 3 shows the interactions between (A) nozzle temperature and (B) infill percentage. Figure 4 shows the interactions between (A) nozzle temperature and (C) printing speed. Figure 5 shows the interactions between (B) infill percentage and (C) printing speed. The factors interact with each other due to all two factor combinations intersecting each other.

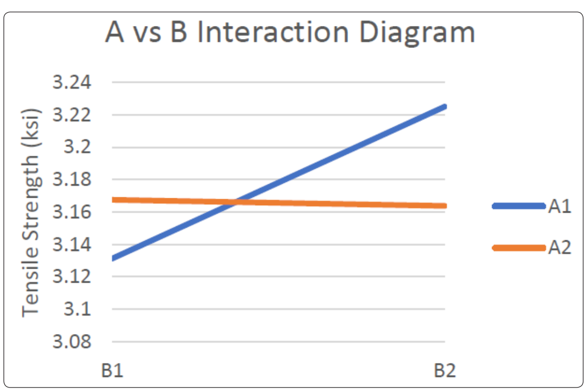

Figure 4: A vs B interaction diagram

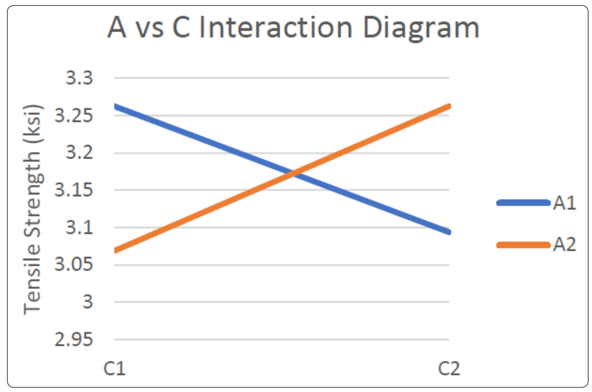

Figure 5: A vs C interaction diagram

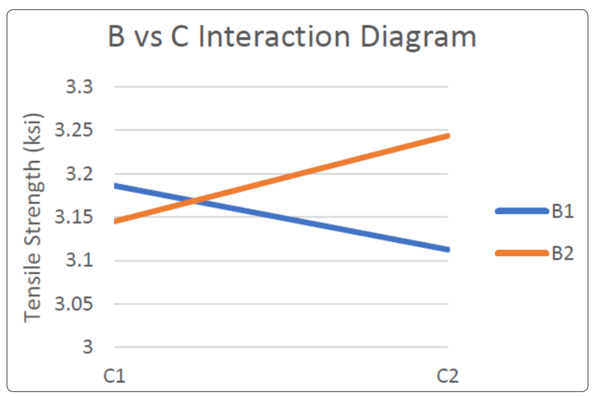

Figure 6: B vs C interaction diagram

Discussion

All factors except for combination ABC lie outside ±2se of the grand average, indicating that all the chosen factors except combination ABC do not have an impact on the tensile strength [6]. The chosen factors do not have a significant impact on the overall tensile strength, as seen from the values obtained in Table 4. The interaction graphs also show that all factors depend on each other. If the lines cross each other, the interaction is strong whereas if the lines do not cross, the interaction is weak and has little impact on the results [6]. In the future, another test to conduct may be three point bending tests to test the effect of the additional structural support within the sample.

There were also some tensile specimens that broke outside of the reduced area section, in the neck region, and as a result, may yield faulty results. These data values and calculations were still included in the calculations, indicating that the tensile strength may be higher than the recorded value. These values have been denoted with a star (*) next to the value. This consideration should be kept in mind when analyzing the tensile strength and factors. However, the affected samples did not yield tensile strengths much higher or lower than the rest of the samples with the same parameters. Sample 3 in set one produced a tensile strength of 3.23 ksi compared to the set mean of 3.26 ksi, sample 1 of set 2 produced a tensile strength of 3.09 ksi compared to sample 2 which produced a tensile strength of 3.10 ksi, and sample 1 of set 4 produced a tensile strength of 3.32 ksi compared to the set mean of 3.31 ksi. Lastly, though the samples were printed using different parameters, they all physically looked similar to each other.

Conclusion

Through DOE, it was shown that infill percentage, nozzle temperature, and print speed do not have significant impacts on the tensile strength of PLA material printed on a Maker Bot Replicator. The highest tensile strength value was recorded in run 2 at 3.46 ksi, with low (-1) values of A (190°F) and low (-1) values of B (20%), and high (+1) values of C (100 mm/s). All two factor combinations interact with each other due to all two factor combinations intersecting each other. Though all factors and combinations lie outside the 95% confidence interval except the ABC combination, the maximum deviation of the run averages from the mean is only .09 ksi, or 2.8%. In the future, a three-point bending test should be implemented to further test the impact of 20% vs 40% infill percentage. Additionally, other factors can be tested such as infill pattern and layer height.

References

1. https://www.3dhubs.com/knowledge-base/introduction-fdm-3d-printing
2. Noorani Rafiq (2006) Rapid Prototyping: Principles and Applications. Hoboken, N.J.: Wiley.
3. Farah Shady, Anderson DG, Langer R (2016) "Physical and Mechanical Properties of PLA, and Their Functions in Widespread Applications-A Comprehensive Review." Advanced Drug Delivery Reviews 107: 367-92.
4. Behzadnasab Morteza, Yousefi Ali (2016) Effects of 3D printer nozzle head temperature on the physical and mechanical properties of PLA based product.
5. https://www.isixsigma.com/tools-templates/design-of-experiments-doe/design-experiments-%E2%90%93-primer/
6. Daniel Horvath, Rafiq Noorani, Mel Mendelson (2007) "Improvement of Surface Roughness on ABS 400 Polymer Using Design of Experiments (DOE)", Materials Science Forum 561-565: 2389-2392.