OPTIMIZING THE TENSILE STRENGTH FOR 3D PRINTED PLA PARTS

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Abstract

This research investigates on how extruder nozzle temperature, model infill rate (i.e. density) and number of shells affect the tensile strength of three-dimensional polylactic acid (PLA) products manufactured with the fused deposition model technology. Our goal is to enhance the quality of 3D printed products using the Makerbot Replicator. In the last thirty years, additive manufacturing has been increasingly commercialized, therefore, it is critical to understand properties of PLA products to broaden the use of 3D printing. We utilize a Universal Tensile Machine and Quality Engineering to comprehend tensile strength characteristics of PLA. Tensile strength tests are performed on PLA specimens to analyze their resistance to breakage. Statistical analysis of the experimental data collected shows that extruder temperature and model infill rate (i.e. density) affect tensile strength.

Keywords: Additive Manufacturing (AM), Fused Deposition Modeling (FDM), Polylactic Acid (PLA), Design of Experiments (DOE)

Introduction

Over the past few years, the increase on the use of additive manufacturing (AM) products has resulted in higher demands from the manufacturing industry (Kim *et al.*, 2017). Nowadays, AM influences a variety of fields such as medical (Liu *et al.*, 2016), metal casting and automotive. Some of the AM applications are in high-risk industries such as defense and aerospace (Roach *et al.*, 2018). In Harbaugh (2014), a Computer-Aided Design (CAD) of a ratchet wrench was transmitted from the ground to space. In previous years, printing the object in space would not have been possible, but due to technological innovations AM has surpassed such limitation. The wrench was printed in space to test the feasibility of producing objects difficult to manufacture on earth because of the gravity effect and to simulate if in practice the crew could produce new tools in the space stations. NASA's greatest challenge in this mission was to contrast the quality of the wrench and other objects printed with the same printer before and after it was launched to space.

Fused Deposition Modeling (FDM) also known as Fused Filament Fabrication (FFF) is an AM process pioneered by Scott Crump, founder of Stratasys Inc, about two decades ago (Stratasys, 2019). FDM is a demanded technology by industry, academia and consumers because it is affordable, simple to use and reliable (Masood, 2014). FDM can produce prototype products and functional parts of complex geometries. The FDM fabrication process is used to rapid prototype plastic objects with specialized 3D printers like the Makerbot Replicator Desktop 3D printer (Makerbot, 2009a). At the instant the printer nozzle reaches its desired temperature, it starts extruding melted thermoplastic material (i.e. filament). A tool path pattern moves in the XY plane helping to construct every layer. One of the most common filament materials used in FDM is the polylactic acid (PLA) due to its low cost, feasibility and high quality. Even if the behavior of the thermoplastic PLA has been defined previously in the literature, the performance of a printed PLA prototype depends on the layer structure created on the actual printing process (Torres *et al.*, 2015).

The main purposes of this research are: (1) to statistically analyze the resulting tensile strength of parts manufactured with the FDM technology and the PLA material in the Replicator Desktop 3D printer and (2) to determine the best 3D printer settings to manufacture products where tensile strength is a relevant mechanical property. To achieve these objectives, we construct a 3D CAD of the specimen to be manufactured by following the American Society for Testing and Materials (ASTM) specifications (ASTM, 2014) and run a full factorial design of experiment (DOE) to validate the hypothesis regarding to the significant effect that any of three pre-selected 3D printing factors (i.e. independent variables) may have over the tensile strength (i.e. response or dependent variable).

The contributions of this paper are: (1) to establish the dependence of tensile properties on three selected printing factors or parameters (extruder nozzle temperature, model infill rate and number of shells) through the use of a DOE and (2) to provide a validated mathematical model to accurately represent such dependence. The rest of the paper is organized as follows. First, we present the fundamental steps to produce additive manufactured products with the Makerbot Replicator 3D printer. Then we describe the DOE performed, the custom settings that can be manipulated in the Makerbot Replicator and the method used to obtain the tensile strength data. Next, the results of the DOE are analyzed. The last section of the paper presents the conclusions and future research.

Additive Manufacturing Process in the Makerbot Replicator 3D Printer

The Makerbot Replicator 3D printer uses the FDM methodology to print plastic objects. The FDM technique starts with a 3D object designed by the user using a CAD software. The Makerbot Desktop software accepts the CAD input file exported to a stereo lithography (STL) format. STL files follow a tessellation process to generate a sliced version from the original solid model by constructing triangular surfaces (facets) that specify binary representations in the sliced object (Pandey *et al.*, 2003).

Printing parameters such as the layer height, infill, number of shells, and a variety of other options can be set by the user on the Makerbot Desktop software. The .STL file is used by the MakerBot Desktop software to create the G-code language that will instruct the printer with specific actions to perform to print the 3D object. The Makerbot Replicator 3D printer receives as input the G-code directly from the software or by plugging a universal serial bus (USB) flash drive directly into the machine. The Makerbot Replicator 3D printer lays down successive layers of melted PLA filament on a build platform until the three dimensional solid is created.

In this research, the 3D printing material used is PLA plastic. The reason for deciding to experiment with this material is because the finish quality of the products produced with PLA is very good and one of the authors of this paper is interested in the long-term on producing parts that are not only functional but also highly aesthetic for potential commercialization. The PLA produces final parts that are glossy, strong, and durable. PLA has higher compressive strength, tensile strength and flexural strength than Acrylonitrile Butadiene Styrene (ABS), another thermoplastic material commonly used for AM, but PLA is more brittle. The PLA thermoplastic material has also low cost and the fumes emitted are considered safe.

The Makerbot Replicator has a compartment towards the back of it to position the filament spool. This thick filament is led by a motor to the extruder through plastic tubes. The extruder takes the filament and passes it to the heated nozzle where the filament is melted at a pre-determined temperature and extruded. The melted filament is used to construct layers of the solid object onto the replicator build platform (i.e. print platform) according to what it is specified in the G-code. The PLA material does not require a heated build plate. The melted filament rapidly cools and crystalizes. A road of is known as a single line of material deposited into the platform. When the extrusion head finishes depositing the roads required by the part side-by-side on the x-y plane, it is known as a single layer. Once the extrusion head prints a layer, the build platform moves in the *z*-axis according to the selected layer height. The process of depositing layers of filament repeats until the object (i.e. part or product) is completely printed. Figure 1(a) shows a picture of the Makerbot Replicator where the build platform can be seen inside the machine. Figure 1(b) shows a picture of the Makerbot Replicator smart extruder that magnetically attaches against the back of the 3D printer extruder carriage. It has a filament detection mechanism that stops printing and informs the user when the filament runs out and is specifically designed to work with the Makerbot PLA filament.

Figure 1: (a) The Makerbot Replicator 3D Printer (b) The Smart Extruder for the Makerbot Replicator.
Source: https://store.makerbot.com

The Experimental Design Performed

In Montgomery (2017), it is mentioned that to understand cause-and-effect relationships in a system or process it is needed to intentionally change the input variables to the process and observe the variations in the system output produced by those alterations on the input variables. A

DOE consist of (1) runs in which changes are deliberately made to the input variables to statistically identify the relevant variables causing the changes in the process output or response, (2) a mathematical model to relate the response to critical input variables and (3) an evidence of using the model for process improvement.

In the DOE terminology it is customary so refer to the input variables as controllable factors or simply factors and to the process output as the response. Montgomery (2017) also states about the existence of uncontrollable variables, such as environmental factors. Thus, a DOE practitioner needs to identify: (1) factors that will be intentionally varied, (2) factors that will be held constant, (3) factors that will be allowed to vary and (4) nuisance factors which can be sub-classified as controllable, uncontrollable but measurable and pure noise.

The correct DOE approach is to conduct an experiment in which the factors are varied together instead of one at a time. If the experimental runs set the factors in each of the possible combination of factor levels the design is named a full factorial design. The objective of a full k-factorial DOE is to measure how k factors influence a response. The statistical technique known as analysis of variance (ANOVA) is used to detect if there is a significant factor or a significant interaction of factors. Because of the time frame allowed to this project, the smallest full k-factorial DOE is selected. It is the 2^k design where each of $k=3$ selected factors is studied at two levels. A selection of levels for each factor is known as an experimental condition. Thus, the DOE has 8 (i.e. 2^3) experimental conditions. In addition, three replicates (i.e. independent repeated runs of each factor combination) of such design are performed for a total of 24 runs.

Characteristics of the Material Used in this DOE

The only material used in this DOE is the Makerbot PLA filament (Makerbot, 2009b). This is a material suitable for FDM. The Makerkot company states that their PLA filament is the most reliable to use with the Makerbot Replicator because (1) it is produced specifically to work with the Makerbot 3D printers, (2) has consistent diameter and (3) the Makerbot Replicator is also designed to work optimally with the Makerbot PLA filament.

The filament used in the DOE has a diameter of 1.75 mm (0.07") and it comes in spools of 1.36 kg (3 lb) with a net weight of 0.9 kg (2 lb). According to the filament specifications, it melts at 150-160°C (302-320° F). The Makerbot PLA filament is a non-toxic resin derived from corn and similar agricultural products that can be recycled and at some extend can be considered biodegradable. In the DOE, the filament wasn't pre-treated; it was taken directly from the storage cabinet located at the Ingram School of Engineering Additive Manufacturing (AMA) lab (Additive Manufacturing Lab, 2016), unpacked, threaded on the machine and used. The filament was purchased on August 2016 and the DOE was performed on Summer 2018. The lab temperature is set to 23° C and the relative humidity is 50%

The Model and Printing Settings Available on the Makerbot Replicator

There are several model and printing settings that a user can control or manipulate for the Makerbot Replicator though the Makerbot Desktop software. The default settings under the device settings category and the extrusion speeds (ES) category are shown in Tables 1 and 2, respectively.

Table 1. Makerbot replicator default settings under the device settings category

Setting	Default value
Extruder temperature	215°
Platform temperature (if connected to a heated build chamber)	112°
Travel speed (this is for parts of the toolpath where the extruder moves but doesn't extrude plastic)	150 mm/s
Z-axis travel speed (this is the build plate movement between layers)	23 mm/s
Use active cooling fan (it applies if printed is equipped with it)	On
Fan power	50% of max power
Fan Layer (i.e. layer number at which the cooling fan turns on)	1
Minimum layer duration (or minimum layer print time)	5 s

Table 2. Makerbot replicator default settings under the extrusion speeds (ES) category

Setting	Default value
ES on bridges	40 mm/s
ES on first layer (if not using raft)	30 mm/s
ES on first layer raft (if using raft)	30 mm/s
ES on infill and insets (all the fill areas and the shells except the outermost)	90 mm/s
ES on outlines (outermost shell in each layer)	20 mm/s
ES on raft (i.e. raft interface) and raft base	90 mm/s

The Makerbot Desktop software also provides options for selecting the infill density and pattern. The default option for infill density is 10%. The hexagonal infill pattern is strong and it is the default. Other pattern options are linear or parallel straight lines that are perpendicular to the lines on the previous layer, diamond shaped, morrocanstar and catfill. The last two options are more related to decorative purposes. Four of the infill pattern options are presented in Figure 2. The settings under the model properties category and their default values are given in Table 3. The roof and floor thickness set the height of the solid layers at the top and bottom of the print. Coarseness is used to include or exclude details in the model outline.

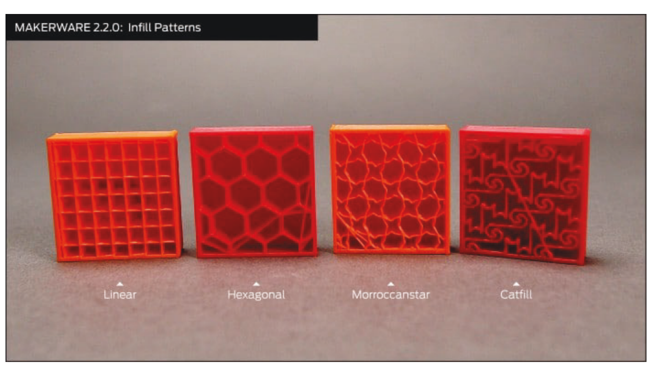

Figure 2: Makerbot Replicator Infill Pattern Options for the Makerbot Replicator
Source: https://www.makerbot.com/stories/news/makerware-2-2-0-more-features/

Table 3. Makerbot replicator default settings under model properties

Setting	Default value
Layer height	0.20 mm
Infill layer height	0.20 mm
Number of shells or extruded outlines	2
Roof and floor thickness	0.80 mm
Coarseness	0.00010 mm

The raft category in the Makerbot software permits to turn on and off the option of using rafts. The default values when the raft option is selected are: (1) raft-model spacing, that is the vertical distance between the raft and the model, (0.29 mm) and (2) raft margin, that is how far the raft extends from the edges of the object, (4.0 mm). Other options that can be manipulated on the raft panel are the spacing of base, interface and surface layers of the draft. Because the specimens printed in this study didn't require supports, we skip listing the default settings for the supports and bridging panel options. Under the extruder panel category the options available are presented in Table 4. All the settings and default values mentioned in this section are available at Makerbot custom settings (Makerbot, 2009c).

Table 4. Makerbot replicator default settings under extruder panel category

Setting	Default value
Filament diameter	1.77 mm
Filament retraction distance	1.0 mm
Filament retraction speed	50 mm/s
Filament restart speed	30 mm/s
Filament extra restart distance	0.1 mm
Extra restart speed	30 mm/s
Ooze distance (i.e. amount of oozed plastic used after the extrusion stops before the end of a move)	0.1 mm
Minimum ooze path length (this is to turn off the oozing on very short movements)	0.1 mm

__Design Factors or Independent Variables in the DOE__

Many factors such as the layer height, extruder nozzle speed, extruder nozzle temperature, infill pattern, print bed (i.e. platform) temperature, and infill rate may affect the tensile strength of an additive manufactured part in the Makerbot Replicator. In Torres *et al.*, (2015) it is mentioned that layer height has been shown of high importance for strength and that the extruder nozzle temperature and the number of perimeter layers affect strength values while extruder speed doesn't. In Torres *et al.*, (2015), it is also mentioned about the effect of the duration of postprocess annealing in strength.

In this study, infill rate (i.e. infill density), extruder nozzle temperature, and number of shells were finally chosen as the three design factors in the DOE. Infill rate relates to the density of the internal support structure of the manufactured object. The higher the infill rate the denser the object but more filament is used, and the printing time will increase. Number of shells corresponds to the number of extruded outlines to form the perimeter that defines the shape of the layer. Every object must have at least on shell; more shells increase the strength and weight of the object but also the print time. Table 5 presents the values considered for the two levels of each one of the factors studied using coded and uncoded units. Table A.1 in Appendix 1 presents the 24 experimental runs performed in the DOE using coded units for the levels of the factors. Thus, in the table in Appendix 1 a value of +1 for the level of a factor indicates that the factor is set at its high level and a value of -1 indicates that it is set at its low level. The value for the factors in coded units can be easily translated to uncoded units using Table 5.

Table 5. Levels for the factors included in the DOE

	Values for each of the factors in uncoded units		
Level value in coded units	Extruder Temperature (*T*)	Infill Density (*I*)	Number of Shells (*NS*)
1 (High)	215ºC	100%	4
-1 (Low)	190ºC	70%	2

The model and printing settings available in the Makerbot Desktop software, discussed in the previous section and not listed in Table 5, correspond to potential design factors that we decided to maintain constant at the default values in the DOE reported in this paper. The effect of held-constant factors and allowed-to-vary design factors, such as variations in the quality of the filament used, are assumed to be small in this DOE. In addition, the following three factors fall in the category of DOE nuisance factors. They are: (1) controllable (i.e. those that can be set to a particular level by the experimenter, such as the temperature of the printing lab), (2) uncontrollable but measurable ones (i.e. humidity of the lab) and (3) pure noise factors (i.e. those that vary naturally and in an uncontrollable way such as wear and tear of the equipment).

The Experimental Unit

The cross-sectional dogbone specimen used as the experimental unit in the DOE is depicted in Figure 3 on next page. It was designed with the software Solidworks (Solidworks, 2002) in accordance to the ASTM D638 -14 standard for Type 1 test specimens (ASTM, 2014). The specimen has an overall length of 165 mm (6.5"), an overall width of 19 mm (0.75"), a thickness of 7 mm (0.28"), a length of the narrow section of 57 mm (2.25"), a width of the narrow section of 13 (0.50"), and radiuses of fillet (i.e. grip radiuses) of 76 mm (3.00"). More than 12,800 ASTM standards are used by companies and consumers to have confidence in the things they buy and use (ASTM, 1996). The ASTM standards impact product quality, consumers' health and safety and facilitate product commercialization.

Response Variable for the DOE

The response variable for the implemented DOE is the ultimate tensile strength (UTS). The preferred procedure to acquire tensile strength measurements is from the stress-strain curve. The purpose of the curve is to indicate the mechanical strengths of structures by emphasizing the computations of stress and strain. UTS is the maximum strength an object can resist prior encountering failure. Stress can be computed as:

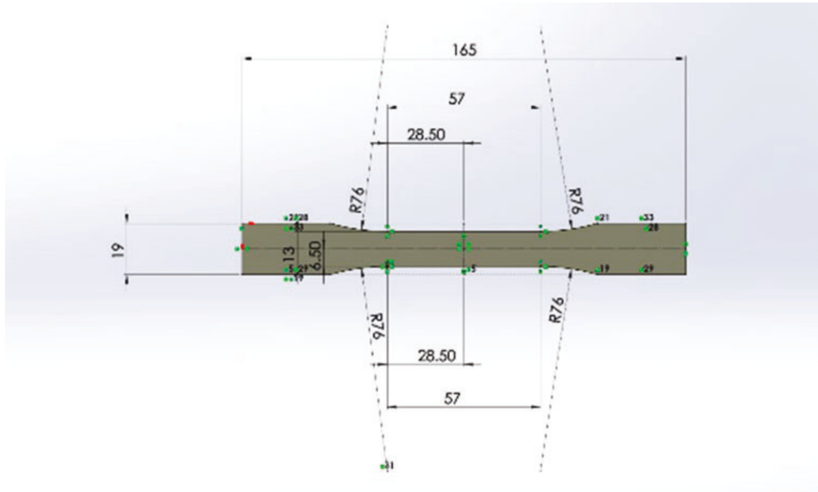

Figure 3: Dimensioned Dogbone Specimen used as Experimental Unit in the DOE

$$\sigma = \frac{F}{A} \quad (1)$$

In formula (1), σ indicates stress and it is normally expressed in megapascals (MPa) in the International System of Units, or in pounds-force per square inch (psi) if following the customary units used in the United States. F represents the load (i.e. amount of tensile force) applied in Newtons (N) or pounds-force (lb_f), A is the initial cross-sectional area in the gage length segment of the specimen in square meters (m^2) or square inches (in^2).

Procedure to Collect the Response Variable: Tensile Strength

Tensile strength tests were performed to the 24 dogbone specimens printed. The tensile test is one of the mechanical stress-strain tests that provides information about tensile strength, yield strength and ductility of a material. It is a good way to ascertain mechanical properties of polymers such as the PLA plastic. It is also the most common mechanical test performed in experiments due to its feasibility to perform. The tensile strength test is performed perpendicular to the cross-sectional area of the gage and the direction of the applied force goes away from the specimen. Some of the universal tensile machines (UTM) and software available in the market for doing the tensile strength test are presented in (ADMET, 2019).

As mentioned in the previous section, UTS is the maximum stress, measured as the uniaxial force per unit area, that a material can withstand before it breaks when subject to tension (i.e. elongation). It reflects how strong the material is. UTS demonstrates the point where the specimen is encountering permanent deformation and failure under tension by resisting a tensile load hanging from the upper and lower shoulders.

The UTS data was collected using the MTS 810 Servo Hydraulic Universal Testing Machine (UTM) from MTS Corporation available at the Advanced Composites Lab (ACL) in the Ingram School of Engineering at Texas State University (Advanced Composites Lab, 2008) and following the ASTM D638 -14 standard (ASTM, 2014). The model of the machine is the 810 system FlexTest SE Controller-Plus. The machine has great flexibility to test a variety of materials such as plastics, aluminum, composites and steel. The machine crosshead speed was of 1mm/min and an extensometer was used. The temperature and humidity of the lab were 23° and 50%, respectively. The specimens were no pretreated in any way.

In the data collection phase of the DOE, the dogbone specimen was loaded onto the machine and firmly positioned by its shoulders. The tensile grips are required for the specimen to stay in place as shown in Figure 4a. A tensile load is applied, and an extensometer is connected to the specimen to record the tensile strain or to compute the difference in elongation. Computing the gage's length before the test is important because permanent deformation and failure are to be determined. The machine separates the tensile grips at a constant speed in opposite directions. This constant rate of speed is chosen in accordance with the shape and standard dimensions of the specimen. The stress-strain data provided by the test is collected through a computer system and a software that the machine has available. Figure 4b shows some of the dogbone specimens after the tensile strength test.

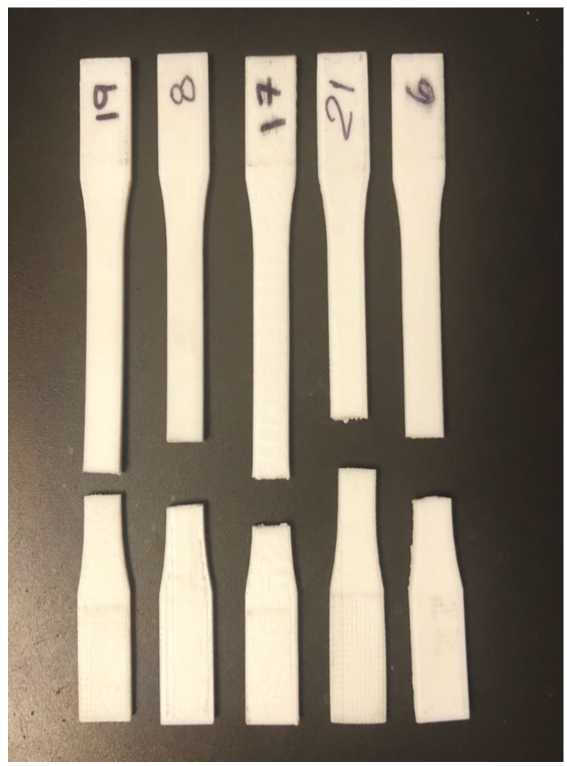

Figure 4: (a) A dogbone specimen being loaded for testing (b) Several dogbone specimens after the tensile strength test.

Results

The dogbone specimens were printed so that the length dimension was along the *x*-axis and the width dimension was along the *y*-axis. An ANOVA model was run for the times to print. This ANOVA does not show that the time to print is significantly affected by any of the 3 factors studied in the DOE.

Stress-Strain Curves

Figure 5 shows the stress-strain graph for run 15 (i.e. the one that corresponds to experimental standard order number 17). It corresponds to the dogbone specimen that showed the lowest UTS in the DOE. The UTS is the maximum point in the curve. Stress was measured in megapascals (MPa). Strain is the deformation measured as the change in length divided by original length. It is measured in mm/mm. The experimental setting that corresponds to this run is: extruder nozzle temperature (low), infill density (low) and number of perimeter shells (low). This result is somehow expected since this setting has all factors at the low level. The stress-strain curve also permits to find the Young's modulus of elasticity. It is the ratio of stress to strain in the linear part of the graph. The Young modulus can be used to determine how stiff a material is. Stiff materials have high Young modulus. The relationship between stress and strain is given by equation (2)

$$S = Y\epsilon \tag{2}$$

where, σ corresponds to the uniaxial stress, Y is the Young's modulus and ε is the stain.

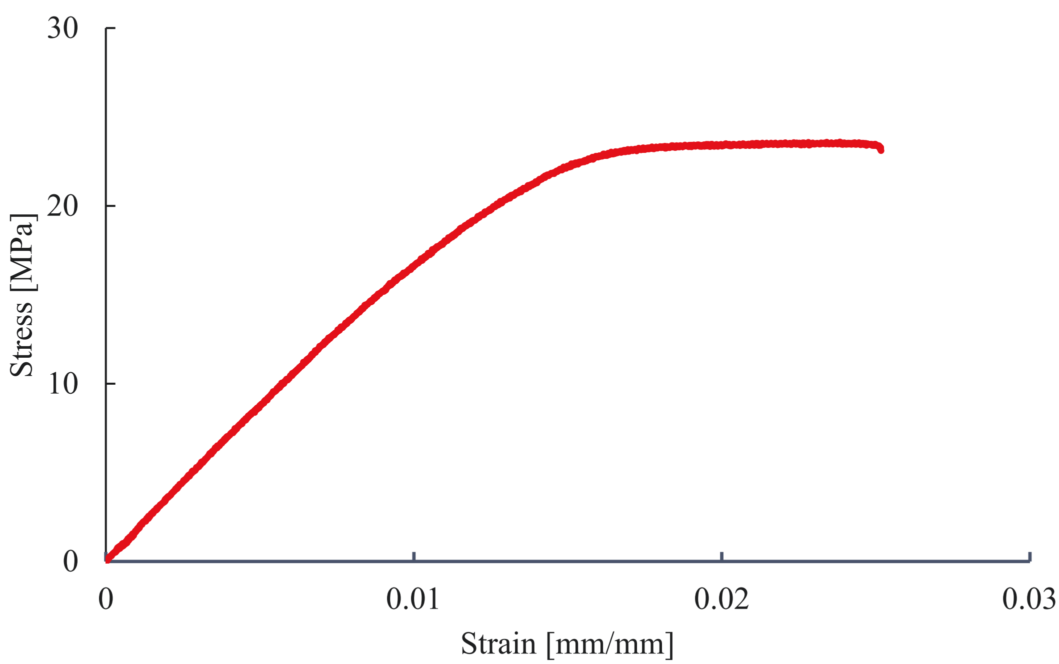

Figure 5. Stress vs Strain Curve for the Specimen with the Lowest UTS

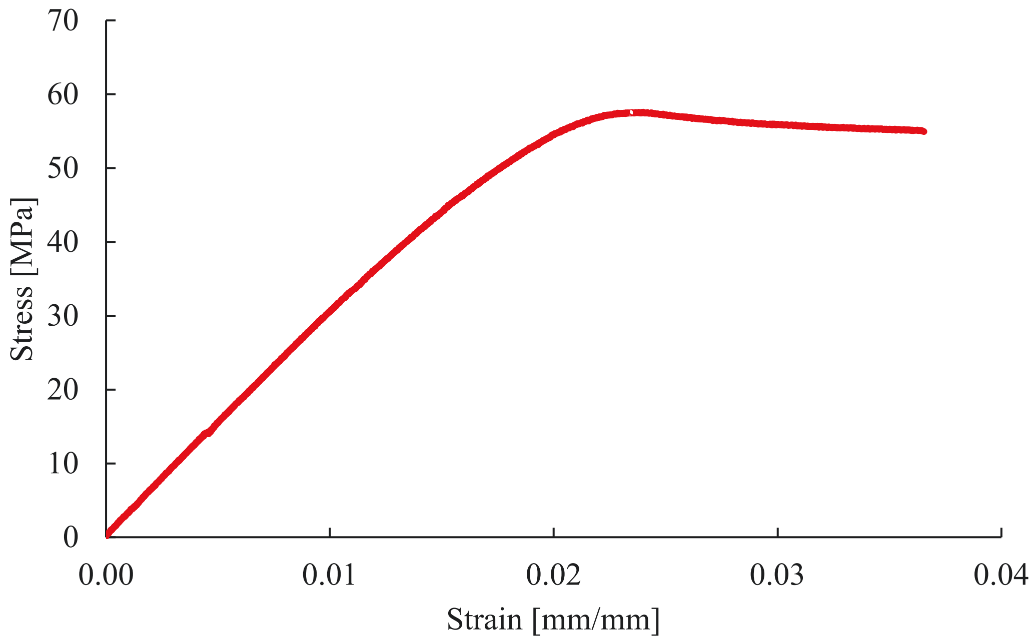

Figure 6. Stress vs Strain Curve for the Specimen with the Highest UTS

Figure 6 above shows the stress-strain graph for run 21 (i.e. the one that corresponds to experimental standard order number 12). It corresponds to the dogbone specimen that showed the highest UTS in the DOE. The experimental setting for this sample is: extruder nozzle temperature (low), infill density (high) and number of perimeter shells (low). This result is somehow encouraging from the point of view of time and energy consumption because extruder nozzle temperature and number of perimeter shells were set in the low levels, but the infill density was set at the high level.

The software used to generate and analyze the DOE is Minitab (Minitab, 2019). Figure 7 on next page shows the Pareto chart of standardized effects for the tensile strength response variable at a significance level α=0.05. It shows the absolute values of the standardized effects of the factors and their interactions from the largest to the smallest one. The x-axis corresponds to the absolute value of the standardized value of the effect and the y-axis lists the factors and their interactions. The value of the critical value for the t-statistics to test the null hypothesis that the effect of each factor is 0 at a significance level $\alpha = 0.05$ is equal to 2.12. Such critical value is represented by the dashed vertical line. Effects located to the left of the line are non-significant. Figure 7 on next page shows that extruder temperature and infill density are the only significant factors that affect the tensile strength. The figure also shows that none of the factor interactions are significant.

Authors in Torres *et al.*, (2015) mentioned that number of perimeter layers significance was well established. However, this study doesn't confirm that such factor is significant. Our results agree with (Torres *et al.*, 2015) regarding the significance of using a high value for extruder temperature. In Torres *et al.*, (2015) the authors suggested also a high temperature value of 230ºC that is above the default value for the Makerbot Software.

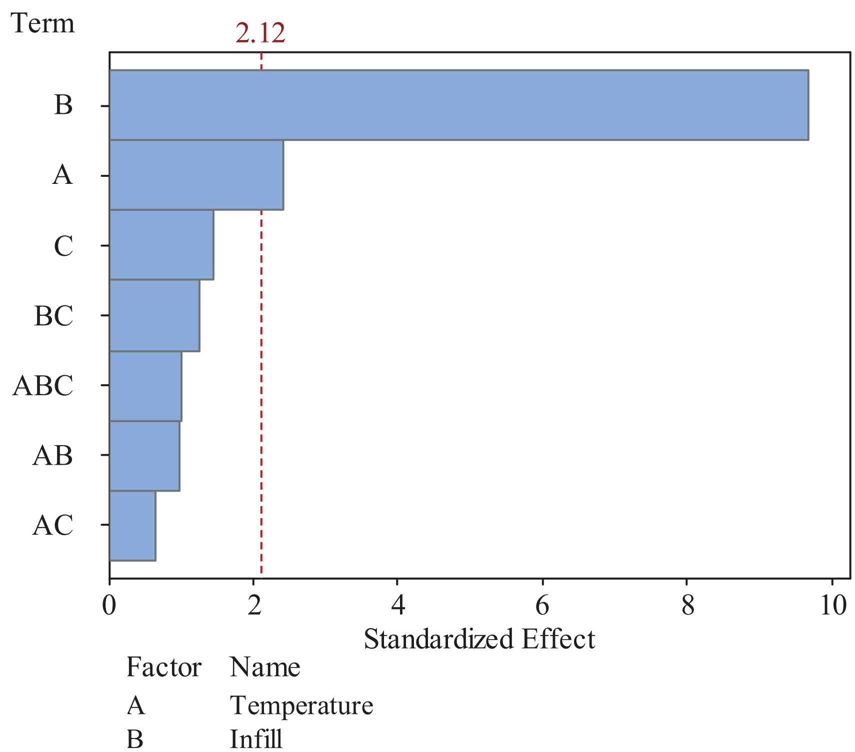

Figure 7: Pareto Chart of Standardized Effects for Response Variable: UTS ($\alpha = 0.05$)

Table A2.1 in Appendix 2 presents the Minitab ANOVA table for the DOE. The model *p*-value is very small (less than 0.0000) indicating that the model is significant. Table A2.2 shows that the model has an adjusted R^2 of 86.46%. It means that about 87% of the variability in the UTS is explained by extruder temperature, infill density, number of shells and the two and three-way interactions of those factors. Because the number of shells and the two and three-way interactions resulted non-significant, a new ANOVA model was requested to Minitab in which only temperature and infill were considered as factors. Table A3.1 in Appendix 3 presents the ANOVA table for this new model. Table A3.2 shows that about 80% of the variability in the UTS is explained by temperature and infill density since the model has an adjusted R^2 of 80.10%. Figure A3.1 in Appendix 3 shows the Pareto chart of standardized effects for the tensile strength as response variable in the model with only two factors. Figure A3.1 shows that both effects are significant since the end located to the right of the red line.

Figure 8 on next page shows the residual plots for the ANOVA model that includes only temperature and infill rate. Residuals can be thought of as observed values of the noise error (Montgomery, 2017). The normal probability plot and the histogram are used to test the assumption of normality of the residuals. These plots show that the residuals are relatively normal and have a mean close to zero. Run number 15 (standard order number 17), one of the two runs where temperature, infill rate and number of shells were set at low level, had a large residual of -11.09

that corresponds to a standardized residual of -2.72. The other run at the same low levels of the factors had a standardized residual of -1.63. Those residuals are large but still are not greater than 3 or 4 standard deviations to be considered as outliers.

The residuals vs. fits plot is helpful to validate the assumption of constant variance of the residuals. In the graph, there is a slight but not severe tendency for the variance of the residuals to become larger for those observations where the tensile strength ended low. However, excluding run number 15 with the large residual of 11.09 this tendency is practically not present. The plot of residuals vs. experimental order doesn't show any patterns that violate the randomness assumption for the residuals. The non-existence of patterns on the residuals vs. order graph was validated also trough performing run tests under the control chart for individuals option in Minitab.

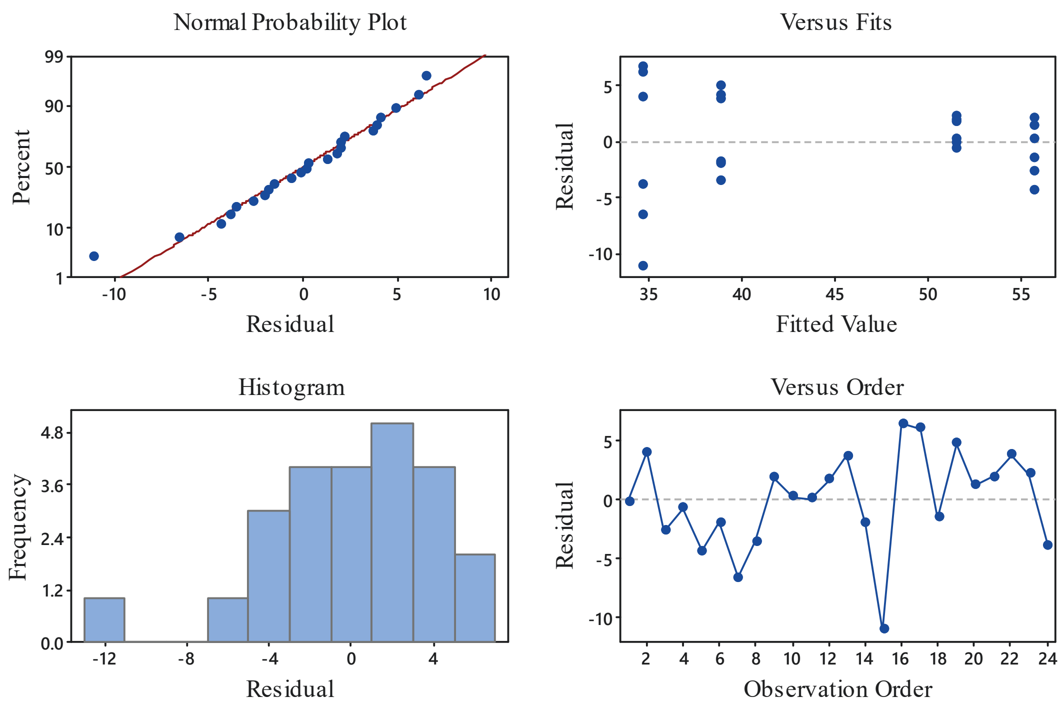

Figure 8: Residual Plots for the ANOVA Model with Temperature and Infill Rate as only Factors and UTS as Response Variable

Figure 9 makes evident that setting the number of perimeter shells in low (-1) or in high (1) level does not significantly change the UTS at the levels considered for infill. When infill rate is at the low level (-1) regardless the value for the number of shells (-1 or 1), the medians for the corresponding UTS's represented by the horizontal lines inside the box plots remain almost equal. A similar case happens when the infill rate is at the high level (+1)

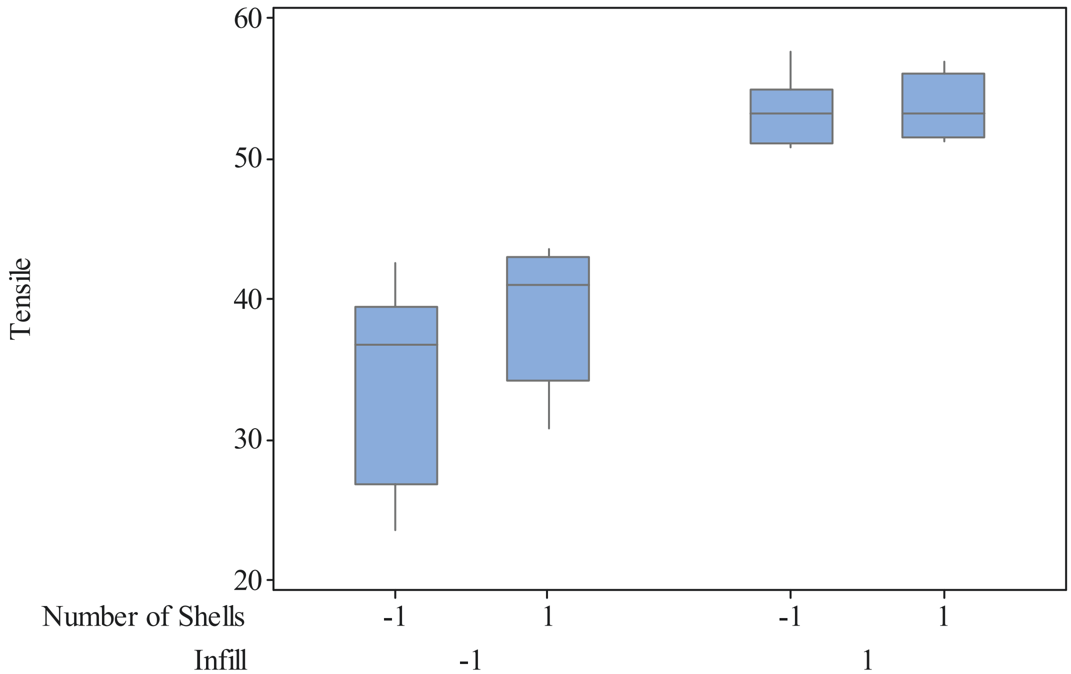

Figure 9: Boxplots for UTS vs. Number of Shells and Infill Rate

Optimization Model

Temperature and infill rate are factors that can be easily set in the Makerbot replicator to any value. Thus, it is desirable to get an empirical model that describes the relationship among tensile, extruder temperature and infill rate. The model will let to predict the UTS at any value for temperature and infill range within the ranges studied. To accomplish this objective, a linear regression model with constant intercept was requested to Minitab. Table A3.3 in Appendix 3 shows the regression model coefficients. The table shows that all coefficients, including the intercept, are significant. The regression model equation in coded units is given by equation (3) where T is the extruder temperature, I is the infill rate and ε is the error term of the regression model.

$$UTS = 45.146 + 2.082T + 8.376I + \varepsilon \qquad (3)$$

From (3) it is observed that the model predicts that the settings that maximize the UTS are: extruder temperature (215 ºC) and infill density (100%). We also use equation (3) to formulate a linear optimization model (*OM*) to find the values for temperature (*T*) and infill rate (*I*) that result in a pre-specified UTS. The model is presented immediately below this paragraph. The optimization model was solved with the Excel Solver (Frontline Systems, 2019). The optimization model prescribes that, for instance, to obtain a desired UTS of 45 MPa, the temperature of the extruder must be set as 203 ºC (i.e. 202.4 ºC) and the infill density must be 85% (i.e. 84.8%).

$$OM : Max\ z = UTS = 45.146 + 2.082T \qquad (4)$$

s.t.

$$190 \le T \le 215 \quad (5)$$

$$0.70 \le I \le 1.00 \quad (6)$$

$$T,\ I \ge 0 \quad (7)$$

Validation Runs

To validate if the settings found by the optimization model (*OM*) result in 3D printed dogbone specimens with a UTS of 45 MPa, we proceeded to manufacture ten specimens using the prescribed extruder temperature and infill density settings. The number of shells was set to 4, since there is not significant difference in printing time when 2 or 4 shells are used, and the tensile strength test was performed on the specimens. Figure 10 shows that the confidence interval for the median UTS of these 10 observations is (41.3925 MPa, 44.6154 MPa). The interval is centered on 42.9530 MPa and the mean is represented by the small circle above the median (horizontal line inside the box). The box plot shows that the 95% confidence interval for the median is relatively precise and at least does not fall out of the interquartiles range. This result indicates that even if the sample was small it wasn't too small to obtain meaningful estimates for the confidence interval for the median. Figure 10 also shows that the validation runs fell slightly below the 45 MPa target with a maximum deviation of about -8.88%. This deviation can be acceptable for some but not all practical applications. Further experimentation with the factor levels around the chosen values is desirable.

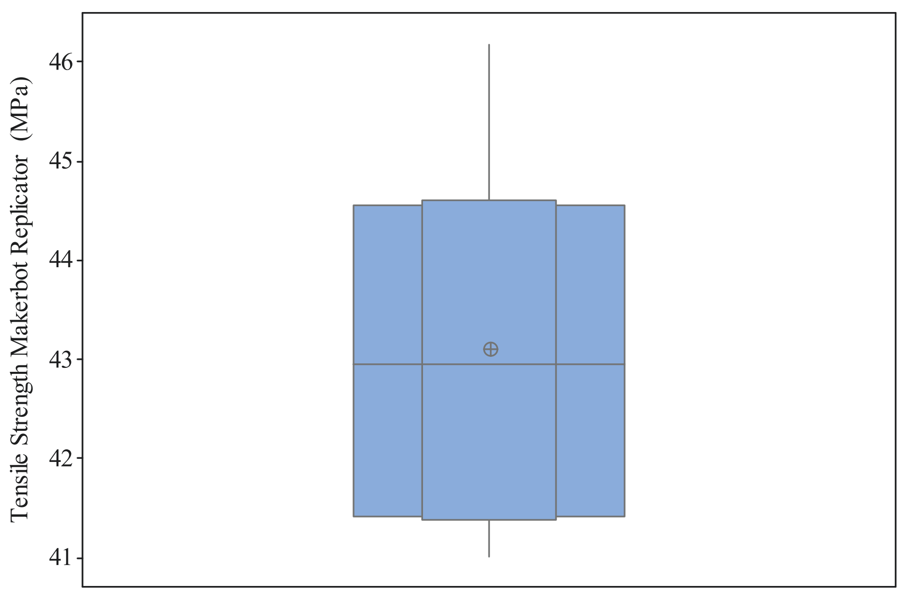

Figure 10: Boxplot of the UTS gotten on the validation experiment

Conclusions and Future Research

This preliminary research indicates that the ultimate tensile strength (UTS) of PLA products manufactured in the Makerbot replicator can be maximized if extruder temperature and infill percentage of the manufactured part are set at the highest levels studied. The research also shows that the number of shells is a factor that does not significantly affect the tensile strength. Based on the desired final applications for the 3D printed PLA products or parts, the regression model found in this study helps to predict with a relatively good accuracy the settings for extruder temperature and part infill percentage that achieve a predetermined UTS. It was exemplified with the validation run.

Future works are: (1) to test the PLA material using the ASTM D790 Flexural Testing Standards, (2) to identify a product to be printed using the FDM technique and study all those mechanical properties that are the most relevant to its application and (3) to extend the DOE to 3D printed products to be produced in a new 3D printing machine located also in the AMA lab that may use several materials besides PLA.

Finally, it may be useful to use Solidworks to implement a Finite Element Analysis (FEA) and compare the results from DOE and FEA. FEA is a computerized method to predict how a product reacts to forces, vibrations, heat, fluid flow, and other physical effects. In the product development process, FEA is used to predict the product behavior once it is used (Autodesk, 2019). FEA divides an object into a thousand to hundreds of thousands finite elements and mathematical equations help predict the behavior of each element.

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Appendix 1.

Table A1: Runs performed in the 2^3 with 3 replicates implemented DOE

Run order	*Standard Order*	*Temperature*	*Infill*	*Number of Shells*
1	15	-1	1	1
2	14	1	-1	1
3	16	1	1	1
4	3	-1	1	-1
5	4	1	1	-1
6	18	1	-1	-1
7	1	-1	-1	-1
8	22	1	-1	1
9	19	-1	1	-1
10	24	1	1	1
11	7	-1	1	1
12	11	-1	1	-1
13	10	1	-1	-1
14	2	1	-1	-1
15	17	-1	-1	-1
16	5	-1	-1	1
17	13	-1	-1	1
18	20	1	1	-1
19	6	1	-1	1
20	8	1	1	1
21	12	1	1	-1
22	9	-1	-1	-1
23	23	-1	1	1
24	21	-1	-1	1

Appendix 2:

Table A2.1: ANOVA Table for the DOE

Source	DF	Adj SS	Adj MS	F-Value	P-Value
Model	7	1897.64	271.09	15.11	0.000
Linear	3	1825.88	608.63	33.92	0.000
Temperature	1	104.05	104.05	5.80	0.028
Infill	1	1683.80	1683.80	93.83	0.000
Number of Shells	1	38.03	38.03	2.12	0.165
2-Way Interactions	3	53.99	18.00	1.00	0.417
Temperature*Infill	1	17.56	17.56	0.98	0.337
Temperature*Number of Shells	1	7.54	7.54	0.42	0.526
Infill*Number of Shells	1	28.89	28.89	1.61	0.223
3-Way Interactions	1	17.77	17.77	0.99	0.334
Temperature*Infill*Number of Shells	1	17.77	17.77	0.99	0.334
Error	16	287.13	17.95		
Total	23	2184.76			

Table A2.2: ANOVA Model Summary

S	R-sq	R-sq(adj)	R-sq(pred)
4.23620	86.86%	81.11%	70.43%

Appendix 3:

Table A3.1: ANOVA Table for the Tensile Considering Only Temperature and Infill as Factors

Source	DF	Adj SS	Adj MS	F-Value	P-Value
Model	2	1787.9	893.93	47.30	0.000
Linear	2	1787.9	893.93	47.30	0.000
Temperature	1	104.1	104.05	5.51	0.029
Infill	1	1683.8	1683.80	89.09	0.000
Error	21	396.9	18.90		
Lack-of-Fit	5	109.8	21.96	1.22	0.343
Pure Error	16	287.1	17.95		
Total	23	2184.8			

Table A3.2: Model Summary

S	R-sq	R-sq(adj)	R-sq(pred)
4.34748	81.83%	80.10%	76.27%

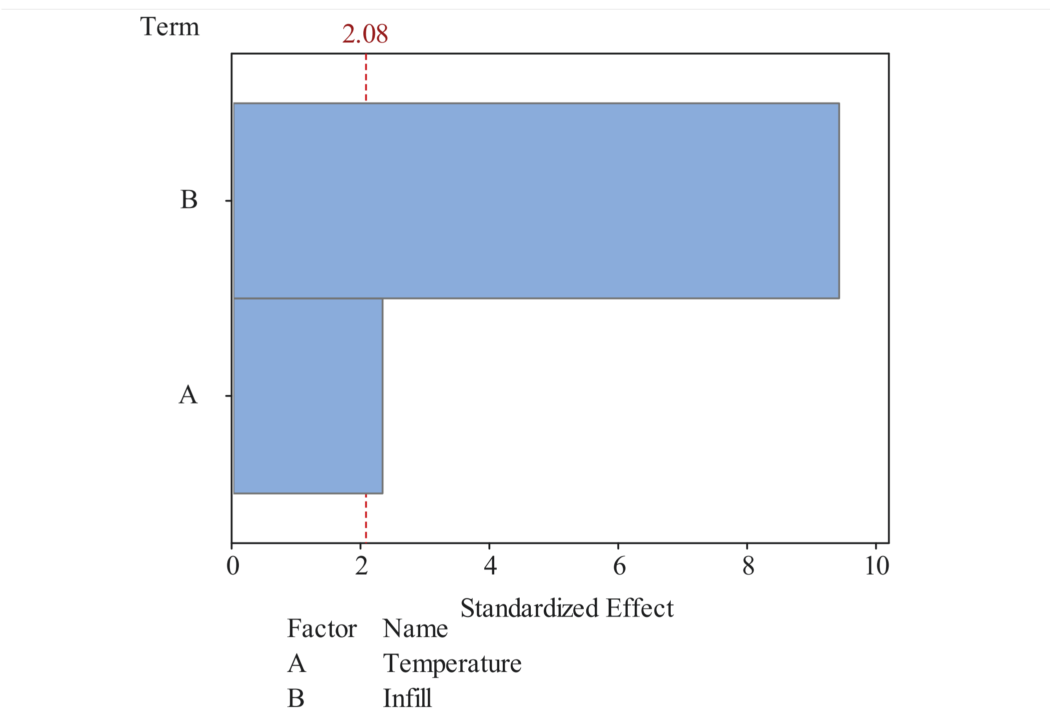

Figure A3.1: Pareto Chart of Standardized Effects for Response Variable: UTS (α = 0.05) for the ANOVA model with Temperature and Infill Rate as Factors

Table A3.3: Regression Model Coefficients

Term	Effect	Coef	SE Coef	T-Value	P-Value	VIF
Constant		45.146	0.887	50.87	0.000	
Temperature	4.164	2.082	0.887	2.35	0.029	1.00
Infill	16.752	8.376	0.887	9.44	0.000	1.00

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