Critical Factors in Determining Tensile Properties of Parts Fabricated Through SLA

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Abstract **- The advantages of additive manufacturing (AM) come at a cost of a large number of process parameters, longer production times, and undesirable mechanical properties. The downsides are even more apparent as AM methods are increasingly being applied in industrial settings where strength is critical and time is often a limiting factor. This paper aims to investigate the effect of various time-dependent parameters, such as cure time and print orientation, on the ultimate tensile strength (UTS) of parts printed using SLA. Data from 9 treatments were collected through an efficient DoE, and the results analyzed with ANOVA. A reduced linear regression model was fitted to the data after discovering that cure time had a more significant effect on UTS than print orientation. The effect of cure time on UTS was then further investigated and compared to FormLab's documentation.**

Keywords - 3D Printing, SLA, ANOVA, Linear Regression, DoE, Surface Response Model

I. Introduction

A. Background

SLA (Stereolithography) is a widely used 3D printing technology that works by using ultraviolet light to solidify photopolymer resin and form very thin solid layers of plastic that then stack up to create a solid part in both "top-down" and "bottom-up" fashions. While SLA is among the most accurate forms of 3D printing, it is an expensive process due to the high cost of the UV-sensitive photopolymer resin.

As 3D printing gradually moves away from being simply a rapid prototyping method to an effective mass production method for industrial applications, more and more emphasis is placed on optimizing the mechanical properties of printed parts. SLA and, in general, 3D printing are particularly attractive in that part strength can depend not only on material intrinsic properties but various process parameters such as print orientation, print temperature, infill-density, and cure time, for example. In this study, therefore, we aim to investigate the effect of some of these factors on the mechanical properties of 3D-printed parts using ANOVA methods with data collected through an efficient DoE. Then we will discuss some areas for further exploration.

B. Objectives

The objective of this paper is to investigate how various process parameters affect the mechanical properties of 3D-printed parts in SLA. While we primarily aim to achieve high part strength by adjusting process parameters, we would also like to incorporate other effects from the perspective of process-related time and cost terms into our study.

II. Methodology

A. Input Factors

Based on the objectives of this study, the cure time and print orientation are chosen as input factors due to the belief that they would have the largest effect on part properties and largest contribution to time savings. Infill density was considered initially but discarded due to unclear documentation on the exact filling algorithm used in the FormLabs printers. Some other possible factors include orientations in other planes, print locations, and resin type, all of which may have an effect on part strength as well.

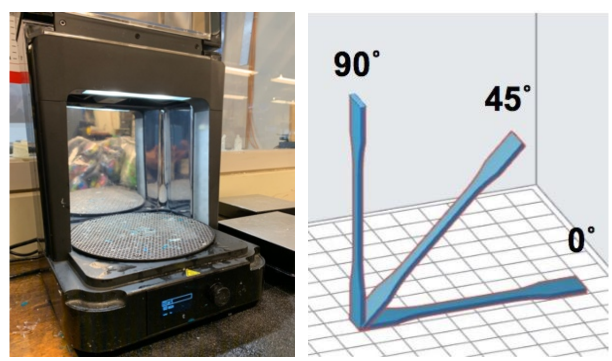


Figure 1: (left) Curing chamber with adjustable duration and temperature (right) Print orientations tested.

Print orientation is often the easiest way to save time on a print, but could also be the most critical factor in determining strength. Since the material is printed layer by layer in the z-direction, we expect the part to be weakest in the 90˚ orientation and strongest in the 0˚ orientation. The orientation is measured in the ZY-plane with respect to the X-axis shown in Figure 1.

Similar to print orientation, cure time presents another opportunity to save time. The assumption that cure time varies asymptotically to part strength led to the three chosen times in order to cover the largest range of response. The material used in the print is the proprietary resin from FormLabs named "Tough V5", which simulates the texture and many important properties of ABS plastics. This type of resin is often used to print engineering parts that withdraw high stress and strain, leading to our preference of using it for mechanical experiments. Figure 2 presents some prototypes printed from "Tough V5".

Figure 2: Parts printed with Form 2, Tough V5 resin [1].

B. *Hypothesis*

The following hypotheses are tested with ANOVA:

Ho: The cure time and print orientation have no effect on the tensile strength of the specimen.

Ha: At least one of the factors has a significant effect on the tensile strength of the specimen.

The rationale for the hypothesis is to identify if either of the two factors are important to an α = 0.05 significance level. Further analysis can then be carried out on a reduced model knowing that some factors or their interactions may be insignificant.

C. *Experimental Design*

A set of experiments are performed to investigate how various process parameters affect the mechanical properties of printed parts, and thus how to determine appropriate time-saving print methods without significantly losing desired mechanical properties. In this study, particularly, the ultimate tensile strength (UTS) is the primary mechanical property that is analyzed.

Process parameters, i.e. print orientation and cure time, are defined as input factors A and B of our experiments, respectively, while UTS is the output. Instead of studying the impact of input factors on a one-by-one approach, multiple input factors are changed and investigated at the same time using Design of Experiment (DoE), where they are set to three main levels, with 0˚, 45˚, 90˚ for print orientation and 20, 40, 60 minutes for cure time shown in Table 1.

Table 1: The different levels of cure time (Factor A) and print orientation (Factor B) tested.

Level	Factor A	Factor B
0	20 min	0˚
1	40 min	45˚
2	60 min	90˚

In DoE, treatments are defined as combinations of set levels of various input main factors. The means of multi-level factor combinations are calculated and compared in order to study their individual and interaction effects on the output of experiments. A face-centered, full factorial design was used and the resulting DoE table shown in Table 2.

Table 2: DoE table of the 3^2 full factorial design used during experimentation.

	1	A	B	AB	A^2	B^2	A^2B	B^2A	A^2B^2
y_1	1	-1	-1	1	1	1	-1	-1	1
y_2	1	-1	0	0	1	0	0	0	0
y_3	1	-1	1	-1	1	1	1	-1	1
y_4	1	0	-1	0	0	1	0	0	0
y_5	1	0	0	0	0	0	0	0	0
y_6	1	0	1	0	0	1	0	0	0
y_7	1	1	-1	-1	1	1	-1	1	1
y_8	1	1	0	0	1	0	0	0	0
y_9	1	1	1	1	1	1	1	1	1

Three batches of test specimens are printed with the three defined print orientations. The test specimens, sorted by print orientation, are then cured 20, 40, 60 minutes, respectively as shown in Figure 3. Due to time constraints, the specimens are printed in two FormLabs SLA printers with the same specifications. The 0˚ and 90˚ orientations are printed in the same printer, while the 45˚ orientation is printed in a different printer. The curing temperature is set at 60 degree Celsius. 5 replicates are done at each of the 9 treatment levels (Table 3).

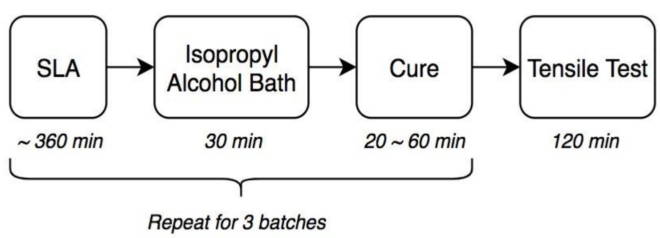


Figure 3: Experimental procedure outlining the printing, cleaning, curing and testing completed.

After the data is collected for each of the samples, Analysis of Variance (ANOVA) is used to test how significant each of the factors is in affecting the UTS of the parts. After performing ANOVA, several quadratic regression models are fitted to the data and a response surface is created based on the best regression model in order to find the optimal operating points that maximize UTS.

Table 3: The nine treatment levels used in the experiment.

Treatments	Orientation	Cure Time
1	0°	20 mins
2	0°	40 mins
3	0°	60 mins
4	45°	20 mins
5	45°	40 mins
6	45°	60 mins
7	90°	20 mins
8	90°	40 mins
9	90°	60 mins

D. Specimen and Measurement

The geometry of the specimen is determined by the ISO 527-2 standard [2] as shown in Figure 4. Type 1BB was chosen in order to fit 15 replicates in one build of Form 2, which has a build area of 6 in^3.

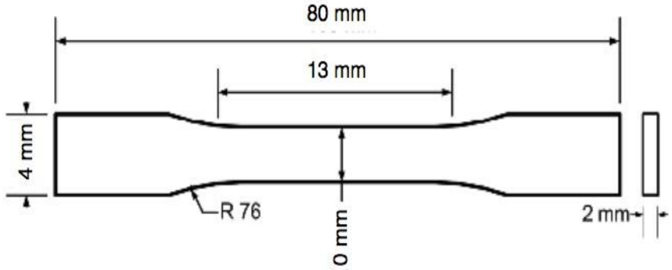


Figure 4: Geometry of test specimen (top). Photo of a specimen (bottom).

Tensile tests were performed on the specimens using the Instron 5969, which has a 50kN rated load cell with 0.1% resolution (Figure 5). Each sample was pulled at a constant speed of 5mm/min until failure. While switching the specimens, care was taken to ensure similar conditions between each run, such as sufficient lateral gripping force to prevent slip, minimal preload, and straight orientation. A single operator was made to operate the machine to reduce measurement variance as much as possible. The specimen was observed to break near the center as expected. However, some broke closer to the grip, possibly due to surface imperfections as a result of incomplete removal of support structures.

The force profile over time was also recorded on the Instron, from which UTS, Young's Modulus, and Yield Strength were derived with given inputs of the specimen geometry. While our focus is on the UTS,

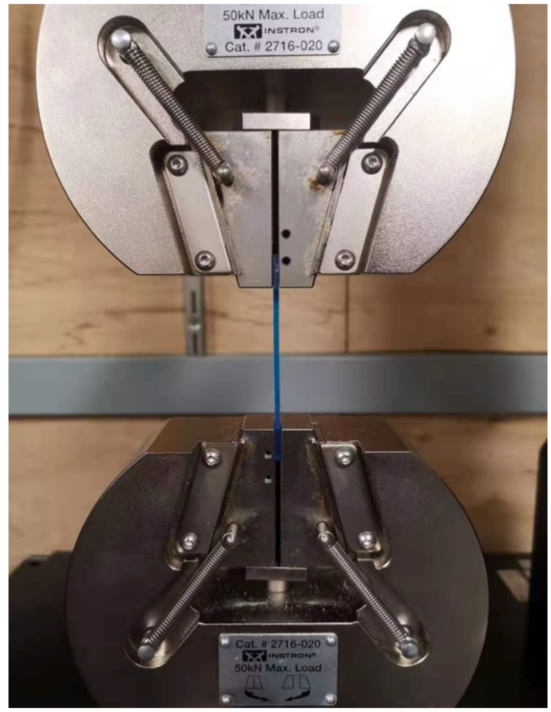


Figure 5: Experimental testing set-up on the Instron. Data collected with BlueHill software.

III. Results & Analysis

A. Raw Data Charts

As the Instron pulled the specimen, the load and extension were recorded and plotted. Figure 6 shows the raw data plot for the specimens in treatment 2 (0˚ orientation, 40-minute cure time).

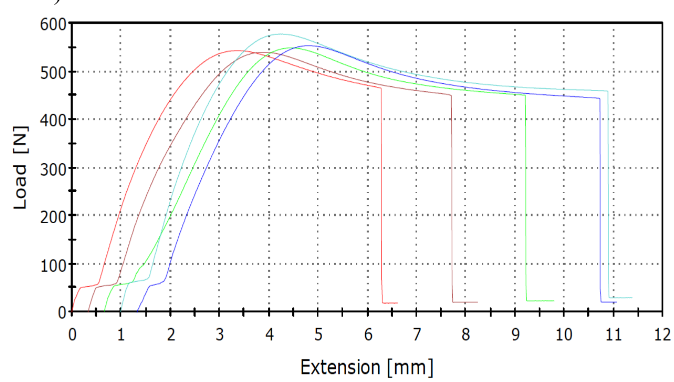


Figure 6: Raw data from the Instron tensile test of treatment 2 plotted using BlueHill 3 Testing Software. The peaks in the data all occur around the same point. The specimens did not show a lot of variation in ultimate tensile strength within the treatment level. The plastic region of the graph varied across specimens and the breaking point occurred at different extensions.

B. SPC Charts

The initial data was plotted on a run chart to observe trends and determine if the printing process executed was in control. Figure 7 shows the data plotted with control limits in JMP. The data stays within the control limits and does not break any of the Western Electric rules [3]. As shown in the chart, there is some variability from part to part, but there do not seem to be any major trends that cause concern of the process being out of control.

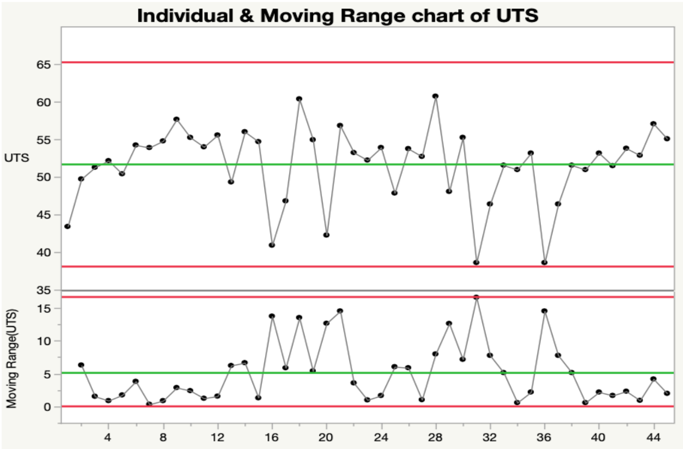


Figure 7: The UTS of the 45 replicates plotted on a run chart. The grand mean is represented by the green line, while the lower and upper control limits are represented by the red lines. None of the points fall outside of the control limits or break any of the WECO rules for control charts. The process appears to be in statistical control.

The UTS of each of the five replicates for each treatment was recorded. The average UTS for the samples in each treatment were calculated and recorded (Table 4).

Table 4: The average UTS of all five replicates in each of the nine treatments.

Treatments	Average UTS (MPa)
1	49.39
2	55.17
3	53.92
4	49.06
5	52.81
6	54.10
7	46.94
8	48.14
9	54.06

C. Normality Assumption

Before performing ANOVA on the main effects and interaction effects, the normality assumption was checked by plotting the normal probability plots shown in Figure 8. Since the printing was done in three batches at different orientations, the normality assumption was examined in these three sets of data. Evidently, the dataset exhibits some deviation from the normal distribution, possibly due to the lack of sufficient data. While the following ANOVA was still carried out with the normality assumption, it is worth noting that the process may not be entirely normally distributed.

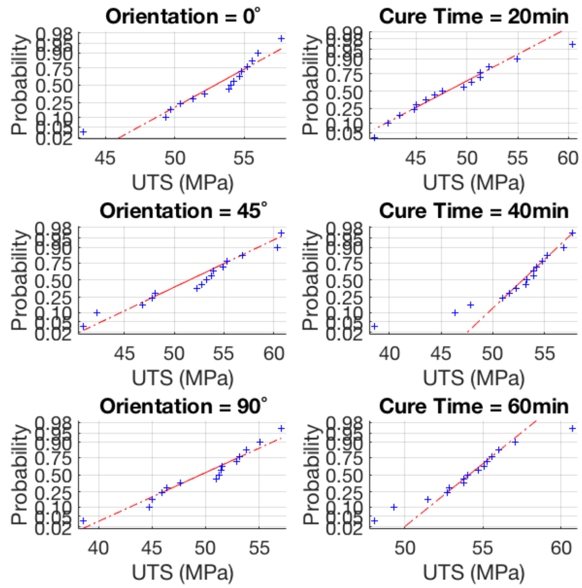


Figure 8: Normal probability plots of the replicates in groupings of orientation and cure times.

D. ANOVA

After investigating the normality assumption and discovering that the process was in control through an SPC chart, an ANOVA was performed on the main effects of print orientation and cure time using Excel. The interaction effect of these two factors was also analyzed in this ANOVA. The average of the UTS found at each treatment level is used in the ANOVA due to the low variance of the specimens within the treatment levels. The results of the ANOVA are shown in Table 5. The ANOVA showed that cure time had a significant effect on the UTS of the SLA-printed part at the $\alpha = 0.05$ significance level. With this, we reject the null hypothesis that neither of the factors has a significant effect on the UTS. The results of the ANOVA showed that print orientation did not have a significant effect on the UTS of the parts at the $\alpha = 0.05$ significance level. Furthermore, the interaction effect between print orientation and cure time is insignificant. Given the layer-by-layer method that SLA printing uses, we predicted the print orientation would be significant. The results of the ANOVA conflict with our initial predictions.

Table 5: ANOVA performed on the effect of cure time and print orientation and their interaction effect. Cure time had a statistically significant effect on UTS as indicated by a p-value of less than 0.05.

Source of Variation	SS	df	MS	F	P-value	F crit
Cure Time	238.440	2	119.220	6.329	0.00441	3.259
Orientation	77.948	2	38.974	2.069	0.141	3.259
Interaction	67.815	4	16.953	0.900	0.474	2.633
Within	678.110	36	18.836			
Total	1062.31	44				

E. Regression Analysis

To identify the quantitative relationship between the response (UTS) and predictor variables (cure time and print orientation), we fit a regression model to our data using JMP. Equation 1 was used to fit the regression model. After the data was fit to the regression, the coefficients and p-values were recorded for each of the coefficients in the model. The β_8 term was not used in the regression because the effects were assumed to be negligible at this level. The results of the initial regression model are shown below in Table 6.

$$\hat{y} = \beta_0 + \beta_1 x_1 + \beta_2 x_2 + \beta_3 x_1 x_2 + \beta_4 {x_1}^2 + \beta_5 {x_2}^2 + \beta_6 {x_1}^2 x_2 + \beta_7 x_1 {x_2}^2 + \beta_8 {x_1}^2 {x_2}^2 \quad \text{(Eq. 1)}$$

Table 6: The coefficients and their corresponding p-values from the regression modelled from Equation 1.

	Coefficients	P-value
β_0	52.521	0.004
β_1	-3.514	0.056
β_2	2.521	0.077
β_3	0.649	0.206
β_4	-0.724	0.256
β_5	-0.793	0.236
β_6	0.391	0.489
β_7	2.935	0.081

An ANOVA was also performed on the regression model to determine the significance of the model. As shown in Table 7, the model has a 0.101 P-value, indicating that the regression is not statistically significant, assuming $\alpha = 0.05$.

Table 7: Results of ANOVA testing for significance of the regression modelled from Equation 1. The regression does not show statistical significance.

	df	*SS*	*MS*	*F*	*Significance F*
Regression	7	76.651	10.950	57.631	0.101
Residual	1	0.190	0.190		
Total	8	76.841			

To explore further, three reduced regression models were fitted to the data with decreasing number of regression coefficients. These three different model forms were screened for goodness-of-fit and significance of regression by calculating the R^2 and P-value using JMP, as shown in Table 8.

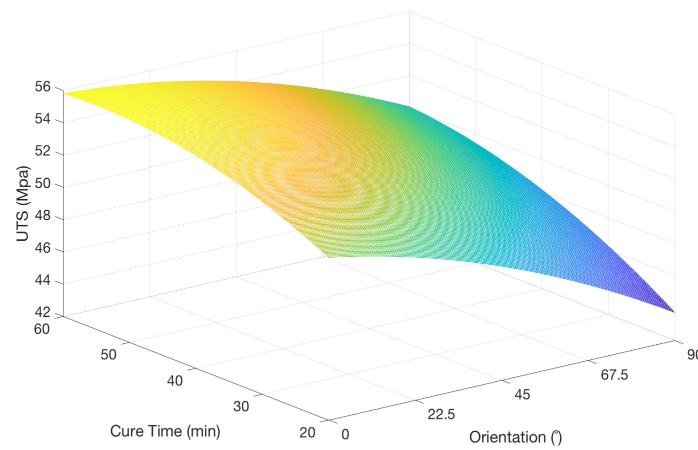
Similar to the results found in ANOVA, the regression coefficients for the higher order terms are in general not significant due their associated large P-value. It is also important to note that the R^2 value is not a suitable indicator by itself in determining the goodness of fit. Comparing to the second model, the first model has a higher R^2 value but is clearly less significant due to the larger P-value, indicating the possibility of overfitting.

Table 8: The equations of the three reduced factor regressions and their corresponding R^2 and p-values. The second and third regressions are statistically significant. The first equation has the highest R^2 value but does not exhibit statistical significance.

Model	R^2	P-value
$y = \beta_0 + \beta_1 x_1 + \beta_2 x_2 + \beta_3 x_1 x_2 + \beta_4 {x_1}^2 + \beta_5 {x_2}^2 + \beta_6 {x_1}^2 x_2 + \beta_7 x_1 {x_2}^2$	0.998	0.101
$y = \beta_0 + \beta_1 x_1 + \beta_2 x_2 + \beta_3 x_1 x_2 + \beta_4 {x_1}^2 + \beta_5 {x_2}^2 + \beta_7 x_1 {x_2}^2$	0.995	0.015
$y = \beta_0 + \beta_1 x_1 + \beta_2 x_2 + \beta_3 x_1 x_2$	0.815	0.028

F. Surface Response Model

The results of the regression showed that there may be some quadratic factor influence on the effects of cure time and print orientation on UTS. In order to observe this quadratic effect further, we plotted the surface response of the second equation in Table 8, corresponding to Equation 2. The surface response (Figure 10) shows a clear maximum when cure time is maximized and orientation is minimized. This surface is consistent with the observations from the data and showed non-linearity with respect to both cure time and orientation. The curve appears to be flattening as it approaches its maximum.



$$\hat{y} = 52.8 - 3.5x_1 + 2.5x_2 + 0.6x_1x_2 - 1.2{x_1}^2 - 1.2{x_2}^2 + 0.4{x_1}^2 x_2 + 2.9 x_1 {x_2}^2 \quad \text{(Eq. 2)}$$

Figure 10: Surface response of UTS with respect to print orientation and cure time as defined by Equation 2. A clear maximum is seen at the maximum cure time and minimum print orientation angle. The surface appears to decrease in slope as it approaches this maximum.

IV. Discussion

Given the layer-by-layer printing mechanism of SLA printing, we anticipated to see a significant effect of the print orientation on UTS. Similarly, because curing the parts strengthens the bonds of the material, we anticipated an increase of UTS in the part as the cure time increased.

Looking at the average UTS of the replicates from each treatment, the print orientation does not seem to have an effect on the UTS. The averages, with the exception of treatments 2 and 3, do show that the average UTS of the replicates increases as the cure time increases.

The ANOVA further proves these observations from the raw data. The ANOVA revealed that the cure time has a significant effect on UTS with a p-value of 0.004. On the other hand, the ANOVA showed that print orientation did not have a significant effect on the UTS of the parts, with a p-value of 0.141. In this experiment, we used an $\alpha = 0.05$ significance level to determine if factors were significant or not. The p-value of the print orientation factor is not small enough to say that it has absolutely no effect on the UTS of the printed samples. The lessened effect of print orientation in SLA-printed parts compared to FDM parts could be a result of the difference in bonding between the layers. The layers in FDM are mechanically bonded, while in SLA the layers are chemically bonded. These chemical bonds could prevent the part from being sensitive to changes in print orientation. Because print orientation does not have a significant effect on the strength of the parts, printing in the orientation that uses the least material to print support should be considered as a cost cutting and time saving procedure.

The ANOVA also evaluated the interaction effects between print orientation and cure time. We hypothesized that the interaction effect would be minimal because the processes seem to be fairly independent. We calculated a p-value of 0.474 for the interaction effect using the ANOVA. This high value of the p-value conclusively proves that the interaction between cure time and print orientation does not have an effect on UTS.

After looking at the results from the ANOVA, we wanted to look deeper into the effects of each of the factors and how they influence the UTS of a SLA-printed part. A regression was fit to the data to analyze the significance of the coefficients, and therefore learn more about how the factors influenced the response of the part. After fitting the regression, the p-values of the coefficients were calculated and summarized in Table 6. The most significant coefficient, aside from β_0, was $\beta_1$with a p-value of 0.056. β_1 corresponds to the cure time factor. This value does not pass an $\alpha = 0.05$ test, but we used these results to determine which of the coefficients were more significant than others so we could eliminate coefficients that had lesser effects from the next regression. The p-value for $\beta_2$was 0.077, which also does not pass an $\alpha = 0.05$ test, but it is a much lower p-value relative to the other p-values in the table. $\beta_2$corresponds to the print orientation factor. Given the insignificance of the print orientation and its interaction with cure time in the ANOVA, we did not expect that any of the interaction effects would have low p-values. β_7 had a p-value of 0.081 so we included this term in our reduced models.

After performing the ANOVA and the regression with all of the coefficients, we created three reduced regression models. While the first of the models had the highest R^2 value, the second model had the highest p-value. Equation 2 was the most significant out of the three reduced models. This equation included β_7, which had one of the higher p-values in the full factor regression model.

The surface response model was created using Equation 2 and showed results consistent with the observations from the statistical analysis performed on the data. The curve in the surface reaches a maximum when cure time reaches its maximum value and orientation is at its minimum value. The surface does, however, seem to be flattening out as it approaches this maximum. This could suggest that the parts response to cure time and orientation is asymptotic.

Because orientation was not found to be significant in affecting the parts UTS tensile strength, we focused on looking into the parts response to cure time. The average UTS from each of the cure times is plotted below in Figure 11. The blue markers are representative of the data collected during the inspection. These data points appear as if they could be linear. The average UTS for the parts cured for 60 minutes looks as if it could be breaking the linear trend; however, without more data it is hard to determine if it is or is not linear with confidence.

In order to further investigate the plateau of the surface model as it reached its maximum, we looked at the specifications of the resin used during experimentation. FormLabs specifies that the UTS of the Tough V5 resin is 55 MPa after the part has been cured for 120 minutes [4], denoted by the red ‘x’ in Figure 11. The curve appears to flatten out, showing non-linear behavior between cure time UTS. This flattening of the curve suggests that there is an optimal point for curing because the compromise of strength from not curing for longer begins to become smaller in the region between 60 minutes and 120 minutes.

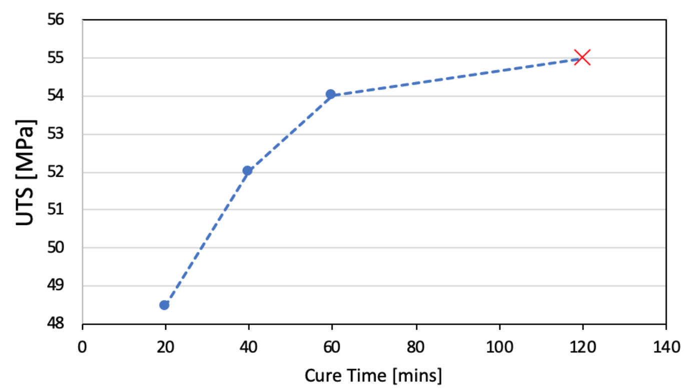


Figure 11: UTS plotted as a function of cure time. The data collected in the experiment is denoted by the blue markers. The red ‘x’ is FormLabs specification for UTS of a Tough V5 resin part that has been cured for 120 minutes. The addition of this data point shows that the relationship between cure time and UTS may not be purely linear.

After we found that cure time was significant, we wanted to explore how cure time affects other mechanical properties of the specimens printed. We examined the elastic modulus of the parts and the results are shown below in Figure 12. The relationship between cure time and elastic modulus should be further investigated. The graphs below do not show a clear trend, the slope varies and the data does not follow a linear trend in all of the graphs.

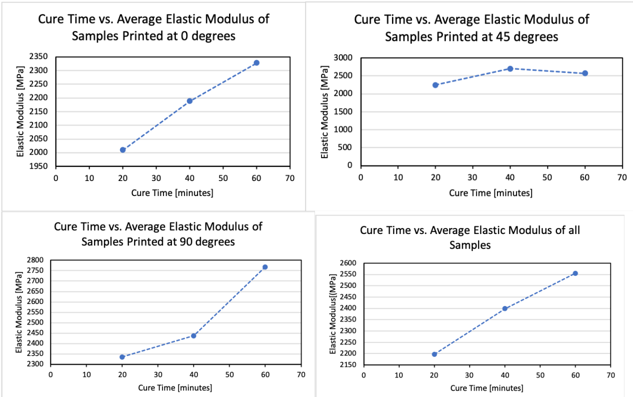


Figure 12: The average elastic modulus of the specimens at each of the cure times grouped by print orientation. The bottom left graph shows the average of all of the data points at each cure time, independent of print orientation. There is a clear increase in the elastic modulus as cure time increases in all of the graphs except the 45˚ orientation (top right).

In future work, more data should be collected for the cure time region between 60 minutes and 120 minutes to better classify the printed parts' response to a longer cure time. Once more data is collected in this region, and for all of the cure times examined in this study, cure time can be optimized to maximize part strength while minimizing the time the part spends in the curing machine.

V. Conclusion

In this study, we investigated the effect of two time-dependent process parameters, cure time and print orientation, on the UTS of SLA-printed parts. Three main levels are used for experiment design, 20, 40 and 60 minutes, and 0˚, 45˚ and 90˚ for cure time and print orientation, respectively. The combination of each level of both parameters created 9 treatments, in which five replicates were tested for each. The results are analyzed with ANOVA, revealing that the effect of print orientation is not significant for SLA printing process, which conflicts with our initial predictions. A reduced linear regression model is then fitted, the results of which indicate possible quadratic factor influence on the effects of cure time and print orientation on UTS, leading to a subsequent plot of the response surface. A clear maximum is observed from the response surface at maximized cure time and minimized print orientation. Since the latter proved insignificant, we conclude that cure time has notable effects on the UTS of SLA-printed parts and serves as an important optimization target to consider between maximization of part strength and minimization of cure time.

VI. Acknowledgements

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VII. References

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