DESIGN OF EXPERIMENTS APPROACH FOR STATISTICAL CLASSIFICATION OF STEREOLITHOGRAPHY MANUFACTURING BUILD PARAMETERS: EFFECTS OF BUILD ORIENTATION ON MECHANICAL PROPERTIES FOR ASTM D-638 TYPE I TENSILE TEST SPECIMENS OF DSM SOMOS® 11120 RESIN

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Abstract

A statistical design of experiments (DOE) approach was used to determine if specific build orientation parameters impacted mechanical strength of fabricated parts. A single platform (10-inch by 10 inch cross-section) on the 3D Systems Viper si2 machine was designed to hold 18, ASTM D-638 Type I samples built in six different orientations (called Location) with three samples built for each location. The DOE tested four factors: Location, Position, Axis, and Layout. Each sample within a Location was labeled as Positions 1, 2, or 3 depending on the distance from the center of the platform with Position 1 being the closest to the center. Samples were fabricated parallel with the x-axis, y-axis, or 45^o to both axes (called Axis 1, 2, and 3, respectively) and were fabricated either flat or on an edge relative to the x-y plane (called Layout 1 and 2, respectively). The results from the statistical analyses showed that Axis, Location, and Position had no significant effect on UTS or E. However, Layout (or whether a sample was built flat or on an edge) was shown to have a statistically significant effect on UTS and E (at a 95% level of confidence). This result was not expected since a comparison of the average UTS for each Layout showed only a 1.2% difference (6966 psi versus 7050 psi for samples built flat and on an edge, respectively). Because of the small differences in means for UTS, the statistical differences between Layout most likely would not have been identified without performing the DOE. Furthermore, Layout was the only factor that tested different orientations of build layers (or layer-to-layer interfaces) with respect to the sample part, and thus, it appears that the orientation of the build layer with respect to the fabricated part has a significant effect on the resulting mechanical properties. This study represents one of many to follow that is using statistical analyses to identify and classify important fabrication parameters on mechanical properties for layer manufactured parts. Although stereolithography is the focus of this work, the techniques developed here can be applied to any layered manufacturing technology.

Keywords: rapid prototyping; stereolithography; design of experiments; tensile testing; WaterShed 11120

1. Introduction

As the rapid prototyping (RP) or layered manufacturing (LM) industry focuses on rapid manufacturing (RM) of end-use products, the machines that were originally designed to build prototypes may now be required to build functional end-use parts. In order to successfully accomplish this transition, the materials available for use in RP must provide the performance required for RM and the specific RP technology used for RM must be capable of providing repeatable and reproducible parts (with repeatable and reproducible performance dimensionally, mechanically, thermally, electrically, optically, etc.). Of the many additive manufacturing technologies available, stereolithography (SL) was the first technology commercialized in the 1980s and remains a very popular RP technology for building highly accurate parts with superior surface finish. The SL resin industry has also been making significant progress on improving the physical properties of photocrosslinkable resins, since these materials have traditionally performed poorly primarily in the area of impact strength. In addition to significant investment by the industry in new better-performing resins, many research groups have been exploring ways to improve performance of SL resins. Our group, for example, has been investigating dispersing multi-walled carbon nanotubes in SL resins to improve performance (Sandoval *et al.*, 2005 and Sandoval *et al*., 2006). Other groups have used electroplating to improve performance of SL-manufactured parts (Saleh *et al.,* 2004). Assuming current and/or future SL resins will provide the performance characteristics required for a particular RM application, the question reverts back to determining the variability introduced by the manufacturing process on performance.

When building RP parts, variability can be introduced in multiple ways. For example, research has shown varying mechanical performance as a result of different layer thicknesses (Chockanlingam *et al.,* 2006). If layer thickness introduces property anisostropy, the many factors associated with build orientation need to be explored. Issues associated with build orientation were explored by Hague *et al.* (2004) and Dulieu-Barton and Fulton (2000). In these studies, parts were built in a number of orientations and subjected to tensile testing. Both groups found differences in the tensile strength measurements for different orientations (less than 5% for Hague et al., 2004; and as much as 13% for the orientations tested by Dulieu-Barton and Fulton, 2000). Hague *et al.* (2004), for example, concluded that the 5% variation showed that SL produced what could be considered essentially isotropic parts for the orientations tested by them. We believe, however, it is important to classify the populations using statistical analyses, and as a result, this paper explores developing a statistical design of experiments approach for classifying differences in mechanical properties resulting from different build orientations. This study investigates a rather limited parameter space, but the techniques can be applied to statistically identify and classify differences in RP-manufactured parts with respect to virtually any parameter, and our group is embarking on a considerable effort to apply these techniques to classify a number of effects introduced by varying build orientations and parameters in SL. Furthermore, although SL is the focus of this work, the techniques developed and demonstrated here can be applied to any layered manufacturing technology.

2. Experimental Methods

Materials

A commercially available epoxy-based resin, WaterShed™ 11120 (DSM Somos®, Elgin, IL) was used to perform this investigation. WaterShed™ 11120 is a widely used multi-purpose resin, characterized by a low viscosity (~ 260 cps at 30 º C) with a density of ~1.12g/cm3 at 25 º C (Product Data Sheet, DSM Somos®). The epoxy-based resin is used for solid-state laser systems (354.7 nm laser wavelength) with a recommended critical exposure, Ec, of ~11.5 mJ/cm^2 and penetration depth, Dp, of ~6.5 mJ/cm^2. Using the recommended settings, a 3D System Viper si2 SL machine manufactured all test specimens presented here.

Methods

ASTM D-638 Type I tensile test specimens (ASTM, 2005) as shown in Figure 1 and Table 1 were manufactured for this study. The thickness of 0.13-inches applies to molded plastics and was used here. A separate study showed that the Viper si2 was a capable process for producing repeatable and reproducible parts using the ASTM tolerances shown in Table 1 (these results are provided separately in Quiñones *et al.*, 2006).

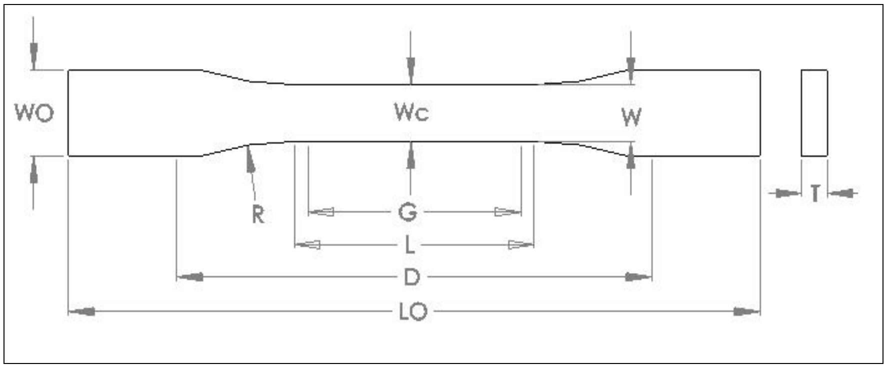


Figure 1. ASTM D-638 Type I tensile test specimen.

Table 1. ASTM D-638 Type I tensile test specimen dimensions and tolerances.

Dimensions (in)	Type I	Tolerances
W, (Wc) - Width of narrow section	0.5	± 0.02
L - Length of narrow section	2.25	± 0.02
WO - Width overall	0.75	+ 0.25
LO - Length overall	6.5	no max
G - Gage length	2	± 0.01
D - Distance between grips	4.5	± 0.2
R - Radius of fillet	3	± 0.04
T - Thickness	0.13	± 0.02

The layout of build orientations tested in the DOE is provided in Figure 2 and the levels for each factor are shown in Table 2. A single platform (10-inch by 10 inch cross-section) on the 3D Systems Viper si2 machine was designed to hold 18, ASTM D-638 Type I samples and the experimental design tested four factors, called Location, Position, Axis, and Layout. The 18 total samples were divided into six platform Locations with three samples per each Location. Each sample within a Location was labeled as Positions 1, 2, or 3 depending on the distance from the center of the platform with Position 1 being the closest to the center. Samples were fabricated parallel with the x-axis, y-axis, or 45^o to both axes (called Axis 1, 2, and 3, respectively) and were fabricated either flat or on an edge relative to the x-y plane (called Layout 1 and 2, respectively). This layout enabled a single platform to produce 18 samples with 3 replicates for each factor. A single build was used in the DOE to remove any batch to batch variations and aging effects. As will be described in the results, there were sufficient samples in this approach to make statistical conclusions.

Table 2. Specific factors with levels tested in DOE.

Location	Position	Axis		Layout	
1	1	x	1	Flat	1
2	2	y	2	Flat	1
3	3	xy	3	Flat	1
4	1	x	1	On Edge	2
5	2	y	2	On Edge	2
6	3	xy	3	On Edge	2

The test specimens were drawn using SolidWorks as shown in Figure 2, and then converted to stl file format. The stl file was processed with 3D Lightyear, sliced into standard 0.004-inch thick layers, and built using the Viper si2 (laser power of ~45 mW) with the resin manufacturer's recommended build parameters. The build time for the 18 test specimens was 9 hours. Once finished, the samples were removed from the platform, cleaned with isopropyl alcohol, and post-cured inside an ultraviolet oven for 30 minutes on each side. After post-curing, any remaining support material was removed by hand. Prior to pulling the test specimens on an Instron 5866 tensile testing machine (using a 10 kN static load cell with a cross-head test speed of 0.2 in/min), each sample was measured to ensure the samples were manufactured within the ASTM specifications.

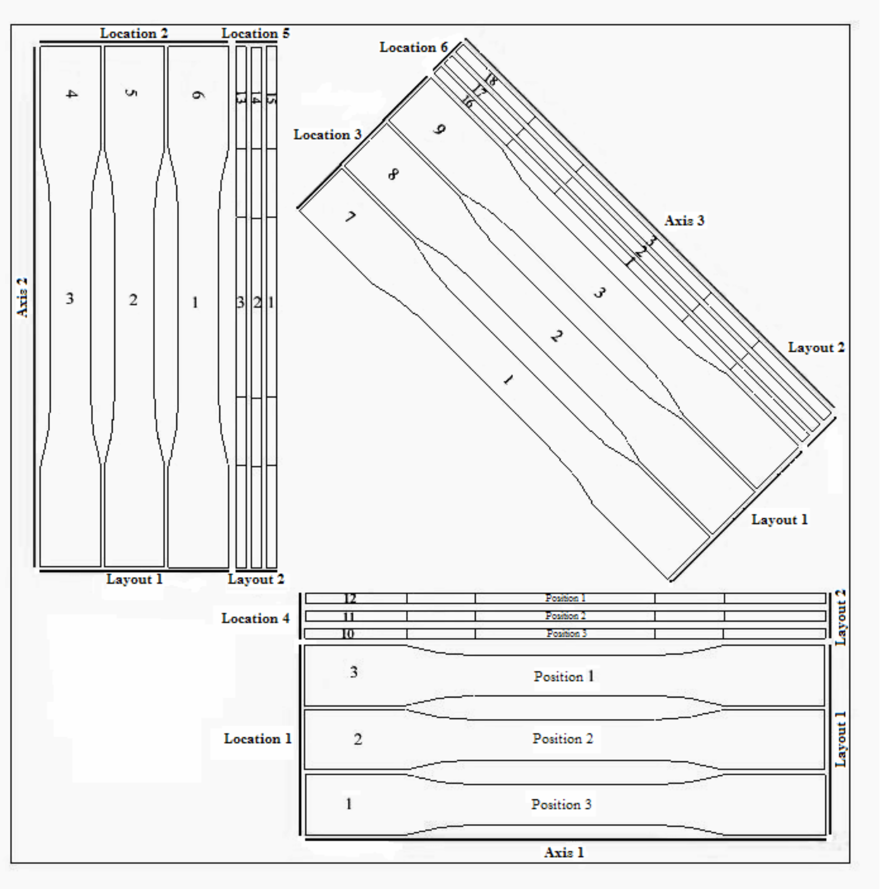


Figure 2. Layout of the Viper si2 build platform illustrating 18 samples in 6 different orientations with 3 replicates for each orientation.

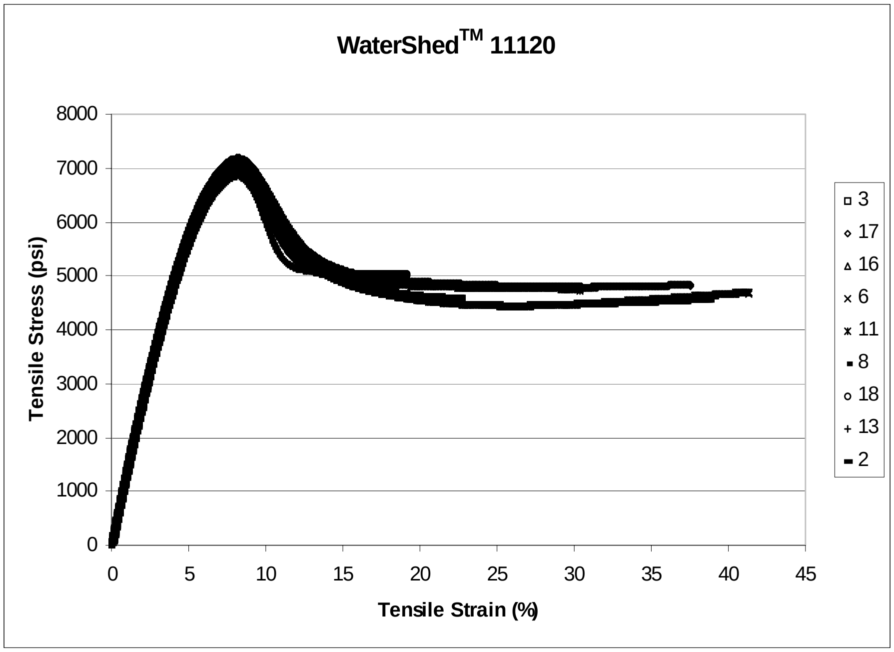
3. Tensile Test Results

Mechanical Testing

The 18 samples shown in Figure 2 were subjected to tensile testing (in random order) using an Instron 5866 tensile testing machine and Ultimate Tensile Stress (UTS, in psi), Elongation at Break (EB, in %), Fracture Stress, (FS, in psi), and Young's Modulus (E, in psi) were measured and recorded. The results are shown in Table 3 and Figure 3. The minimum standard deviations for the measurements occur for UTS and E, as expected, and thus, these measurements are used in the statistical analyses in the following sections.

Table 3. Tensile testing results.

Specimen	Ultimate Tensile stress (UTS) (psi)	Elongation at Break (Standard) (%)	Fracture Stress (Standard) (psi)	Modulus (E-modulus) (psi)
1	7015	16	4908	121223
2	6904	39	4561	120890
3	7071	23	49	121722
4	6925	25	4569	121215
5	6973	46	4772	121897
6	6992	41	4695	123737
7	6954	23	4777	121711
8	6842	36	4540	119534
9	7021	17	4841	121008
10	6980	13	5063	121844
11	7029	30	4754	123678
12	7023	15	4981	125496
13	7006	14	5081	123914
14	7077	10	6377	122100
15	7080	10	6253	120311
16	7029	15	4991	124551
17	7182	38	4837	124917
18	7040	19	5027	123657
Mean	7008	24	4727	122411
Standard Deviation	76	12	1273	1698



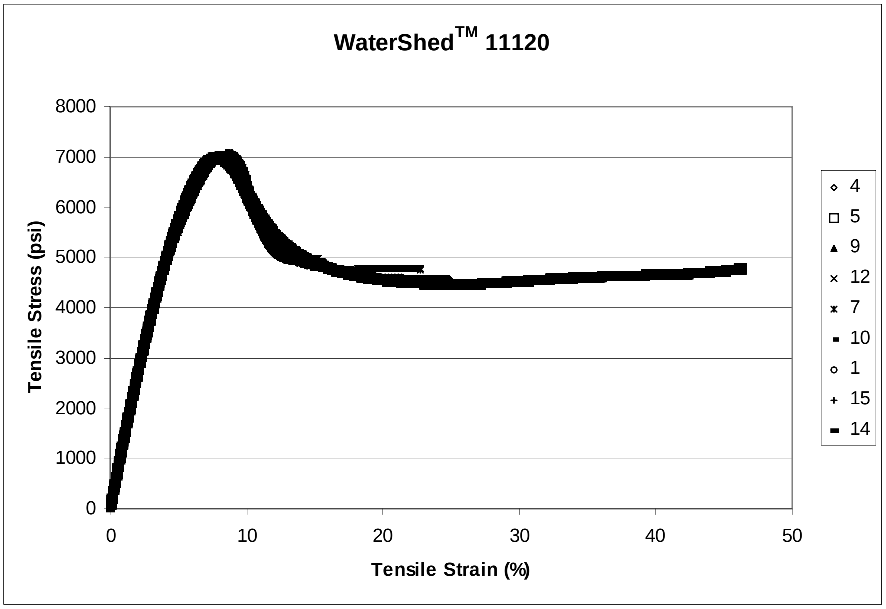


Figure 3. Stress vs. strain results (Data split into two figures for visual clarity). Top: The first nine random specimens tested, and Bottom: The second nine random specimens tested.

4. Experimental Design

Using the results from the tensile testing as shown in Table 3 and Figure 3, the statistical analyses were performed. The following section describes and provides rationale for the experimental design and presents the experimental results and concomitant statistical analysis. The key assumptions underlying the adequacy of the statistical models are then presented.

The tensile strength completely randomized experiment on ASTM Type I specimens involved the study of the effects of three factors (Axis, Layout, and Position) on ultimate tensile strength (UTS) and Young's modulus (E). This preliminary investigation was focused on answering the following questions:

What effects do the geometric configuration factors (*i.e.*, Axis, Position, and Layout) have on tensile strength (ultimate tensile strength - UTS and Young's modulus – E) for an ASTM Type I specimen?

Is there a geometric configuration that would give uniformly higher tensile strength for an ASTM Type I specimen?

In each complete replication of the experiment, all possible combinations of the levels of the factors (3 for Axis, 2 for Layout, and 3 for Position) were investigated. All 18 parts were made from the same build (batch). Therefore, a three-factor factorial model was first developed, using Axis, Position and Layout as factors with UTS and E as dependent variables. The three-factor analysis of variance model is provided in Equation 1.

$$y_{ijkl} = \mu + \tau_i + \beta_j + \gamma_k + \left(\tau\beta\right)_{ij} + \left(\tau\gamma\right)_{ik} + \left(\beta\gamma\right)_{jk} + \left(\tau\beta\gamma\right)_{ijk} + \varepsilon_{ijkl} \quad \begin{cases} i = 1,2,3 \\ j = 1,2,3 \\ k = 1,2 \\ l = 1 \end{cases} \qquad \mathbf{1}$$

where τ represents Position factor with 3 levels, β the Axis factor with 3 levels, and γ the Layout factor with 2 levels constituting 3x3x2 = 18 complete cases made in random order. Note that ε the random error component, has a single level corresponding to a single replicate per cell due the destructive nature of the tensile strength testing.

Location was studied independently of other factor since it is a linear combination due to physical restrictions. For example, Locations 1, 2, and 3 only correspond to Layout 1, while Locations 4, 5, and 6 correspond to Layout 2. Without loss of continuity, future investigation may involve a nested or hierarchical design, with the corresponding levels of the Location factor under the levels of factor Layout under a two-staged nested design. In the meantime, the one-factor ANOVA model is provided in Equation 2.

$$y_{ij} = \mu + \tau_i + \varepsilon_{ij} \quad \begin{cases} i = 1,2,3,4,5,6 \\ j = 1,2,3 \end{cases} \qquad \mathbf{2}$$

In each of three (j) complete replications of the experiment, all possible combinations of the 6 Location levels (i) were investigated. Again all 18 parts were made from the same build (batch).

4.1 Experimental Results

Tables 4 and 5 present the experimental results for Position, Axis and Layout by UTS and E, respectively.

Table 4. Results for UTS by orientation.

	Layout					
	1			2		
	Axis			Axis		
Position	1	2	3	1	2	3
1	7071.3	6991.8	6954.2	7022.8	7080.3	7029.5
2	6903.7	6972.7	6841.5	7028.9	7076.6	7182.4
3	7014.9	6924.8	7021.5	6980.2	7005.7	7040.3

Table 5. Results for E by orientation.

	Layout					
	1			2		
	Axis			Axis		
Position	1	2	3	1	2	3
1	121722.1	123736.8	121710.7	125495.8	120311.0	124550.6
2	120890.3	121897.1	119533.5	123678.5	122100.2	124916.9
3	121222.7	121214.8	121007.8	121844.4	123914.1	123656.7

Tables 6 and 7 show the mean UTS and E, respectively, for each level of the factors. It also shows the standard error of each mean, which is a measure of its sampling variability. The rightmost two columns show 95.0% confidence intervals for each of the means.

Table 6. Least squares means for UTS with 95.0 percent confidence intervals.

Level	Count	Mean	Stnd. Error	Lower Limit	Upper Limit
GRAND MEAN	18	7007.94			
Position					
1	6	7024.83	29.5885	6960.37	7089.3
2	6	7001.17	29.5885	6936.7	7065.63
3	6	6997.83	29.5885	6933.37	7062.3
Layout					
1	9	6966.33	24.1589	6913.7	7018.97
2	9	7049.56	24.1589	6996.92	7102.19
Axis					
1	6	7003.67	29.5885	6939.2	7068.13
2	6	7008.83	29.5885	6944.37	7073.3
3	6	7011.33	29.5885	6946.87	7075.8

Table 7. Least squares means for E with 95.0 percent confidence intervals.

Level	Count	Mean	Stnd. Error	Lower Limit	Upper Limit
GRAND MEAN	18	122411.0			
Position					
1	6	122921.0	636.302	121535.0	124308.0
2	6	122169.0	636.302	120783.0	123556.0
3	6	122144.0	636.302	120757.0	123530.0
Layout					
1	9	121437.0	519.539	120305.0	122569.0
2	9	123385.0	519.539	122253.0	124517.0
Axis					
1	6	122476.0	636.302	121089.0	123862.0
2	6	122196.0	636.302	120809.0	123582.0
3	6	122563.0	636.302	121177.0	123949.0

4.2 Multifactor Analysis – Position, Axis, Layout

A multifactor ANOVA for the dependent variables UTS and E, respectively, by levels of the Position, Axis and Layout factors is first presented. Various tests and graphs to determine which factors have a statistically significant effect on the dependent variables were performed, as well as tests for significant interactions amongst the factors.

The multifactor ANOVA for UTS and E, summarized in Tables 8 and 9, respectively, decomposes the variability of the dependent variable (UTS and E) into contributions due to the various factors. All *F*-ratios are based on the residual mean square error. Further, Type III sums of squares was utilized since it allows for the contribution of each factor to be measured after having removed the effects of all other factors.

Table 8. Analysis of variance for UTS - Type III sums of squares.

Source	Sum of Squares	Df	Mean Square	F-Ratio	P-Value
MAIN EFFECTS					
A:Position	2600.44	2	1300.22	0.25	0.7846
B:Layout	31166.7	1	31166.7	5.93	0.0314
C:Axis	183.444	2	91.7222	0.02	0.9827
RESIDUAL	63034.3	12	5252.86		
TOTAL (CORRECTED)	96984.9	17			

Table 9. Analysis of variance for E - Type III sums of squares.

Source	Sum of Squares	Df	Mean Square	F-Ratio	P-Value
MAIN EFFECTS					
A:Position	2.34239E6	2	1.1712E6	0.48	0.6289
B:Layout	1.70742E7	1	1.70742E7	7.03	0.0211
C:Axis	441793.0	2	220897.0	0.09	0.9137
RESIDUAL	2.91514E7	12	2.42928E6		
TOTAL (CORRECTED)	4.90098E7	17			

Tables 10 - 15 apply a multiple comparison procedure to determine which means are significantly different from which others for UTS and E by Position, Axis and Layout, respectively. The bottom half of the output shows the estimated difference between each pair of means. Within each column, the levels containing X's form a group of means within which there are no statistically significant differences. The method used to discriminate among the means is Fisher's least significant difference (LSD) procedure. With this method, there is a 5.0% risk of calling each pair of means significantly different when the actual difference equals 0.

Table 10. Multiple range tests for UTS by Position.

Method: 95.0 percent LSD

Position	Count	LS Mean	LS Sigma	Homogeneous Groups
3	6	6997.83	29.5885	X
2	6	7001.17	29.5885	X
1	6	7024.83	29.5885	X

Contrast	Difference	+/- Limits
1 - 2	23.6667	91.1713
1 - 3	27.0	91.1713
2 - 3	3.33333	91.1713

Table 11. Multiple range tests for E by Position.

Method: 95.0 percent LSD

Position	Count	LS Mean	LS Sigma	Homogeneous Groups
3	6	122144.0	636.302	X
2	6	122169.0	636.302	X
1	6	122921.0	636.302	X

Contrast	Difference	+/- Limits
1 - 2	752.0	1960.65
1 - 3	777.833	1960.65
2 - 3	25.8333	1960.65

There are no statistically significant differences between the mean values of UTS and E from one level of Position to another at a level of confidence of 95%, as depicted in Figures 4a and 4b.

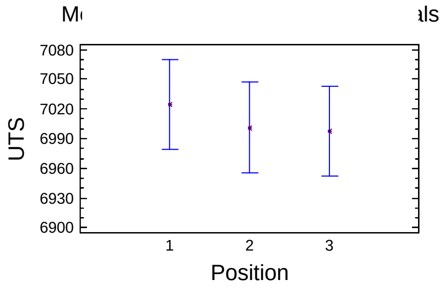


Figure 4a. Means and 95% LSD, UTS by Position intervals.

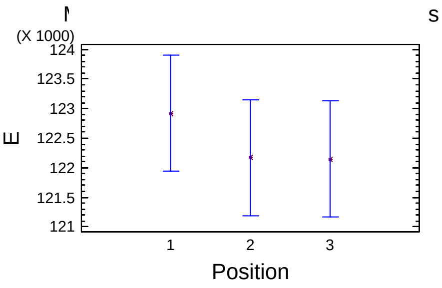


Figure 4b. Means and 95% LSD, E by Position intervals.

Table 12. Multiple range tests for UTS by Axis.

Method: 95.0 percent LSD

Axis	Count	LS Mean	LS Sigma	Homogeneous Groups
1	6	7003.67	29.5885	X
2	6	7008.83	29.5885	X
3	6	7011.33	29.5885	X

Contrast	Difference	+/- Limits
1 - 2	-5.16667	91.1713
1 - 3	-7.66667	91.1713
2 - 3	-2.5	91.1713

Table 13. Multiple range tests for E by Axis.

Method: 95.0 percent LSD

Axis	Count	LS Mean	LS Sigma	Homogeneous Groups
2	6	122196.0	636.302	X
1	6	122476.0	636.302	X
3	6	122563.0	636.302	X

Contrast	Difference	+/- Limits
1 - 2	279.833	1960.65
1 - 3	-87.5	1960.65
2 - 3	-367.333	1960.65

There are no statistically significant differences between the mean values of UTS and E from one level of Axis to another at a level of confidence of 95%, as depicted in Figures 5a and 5b.

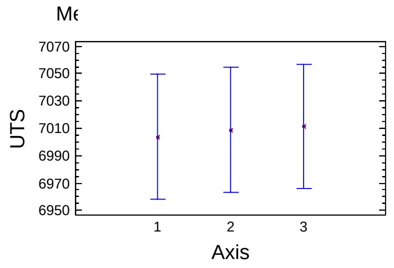


Figure 5a. Means and 95% LSD, UTS by Axis intervals.

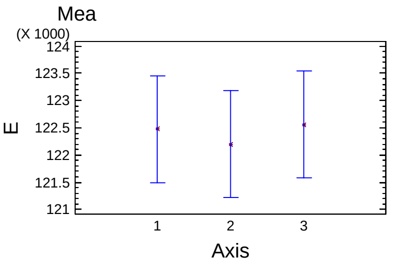


Figure 5b. Means and 95% LSD, E by Axis intervals.

Table 14. Multiple range tests for UTS by Layout.

Method: 95.0 percent LSD

Layout	Count	LS Mean	LS Sigma	Homogeneous Groups
1	9	6966.33	24.1589	X
2	9	7049.56	24.1589	X

Contrast	Difference	+/- Limits
1 - 2	*-83.2222	74.4411

** denotes a statistically significant difference.*

Table 15. Multiple range tests for E by Layout.

Method: 95.0 percent LSD

Layout	Count	LS Mean	LS Sigma	Homogeneous Groups
1	9	121437.0	519.539	X
2	9	123385.0	519.539	X

Contrast	Difference	+/- Limits
1 - 2	*-1947.89	1600.86

** denotes a statistically significant difference.*

An asterisk has been placed next to 1 pair in both preceding tables, indicating that there are statistically significant differences between the mean values of UTS and E from one level of Layout to another at a level of confidence of 95%, as depicted in Figures 6a and 6b.

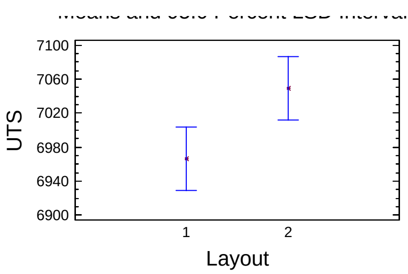


Figure 6a. Means and 95% LSD, UTS by Layout intervals.

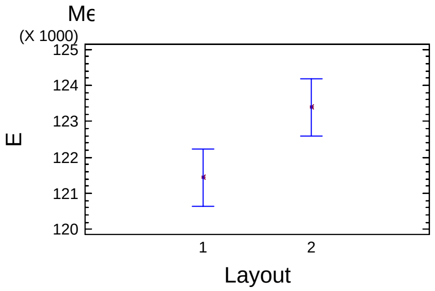


Figure 6b. Means and 95% LSD, E by Layout intervals.

Tables 16 and 17 summarize the significance of factor levels versus UTS and E, respectively, at a level of confidence of 95%. Layout (P-value ~ 0.0314 for UTS and ~0.0211 for E) was the only orientation that had a statistically significant effect on the respective dependent variables at the 95.0% level of confidence. The physical significance of this result is that the individual build layers (x-y plane) is the same for Axis, Location, and Position. Layout is the only factor that has individual layers in a different orientation with respect to the test samples. It is also important to note that the vertical orientation (where the L for the Type I sample is built vertically) was not tested and based on these results, we would expect a difference for this orientation as well. This experiment is left for future work.

Table 16. Significance summary of UTS by factor at the 95% level of confidence.

Factor		**Axis**			***Layout***		**Position**		
		1	***2***	***3***	***1***	***2***	***1***	***2***	***3***
Axis	**1**		**N**	**N**					
	2			**N**					
	3								
Layout	***1***					***Y***			
	2								
Position	**1**							**N**	**N**
	2								**N**
	3								

Table 17. Significance summary of E by factor at the 95% level of confidence.

Factor		**Axis**			***Layout***		**Position**		
		1	***2***	***3***	***1***	***2***	***1***	***2***	***3***
Axis	**1**		**N**	**N**					
	2			**N**					
	3								
Layout	***1***					***Y***			
	2								
Position	**1**							**N**	**N**
	2								**N**
	3								

4.3 One Factor Analysis – Location

Various tests and graphs to determine which Location levels have a statistically significant effect on the dependent variables UTS and E were performed, as well as tests for significant interactions amongst the levels of Location. As shown in the results for UTS and E in Tables 18 and 19, 3 replicates for each of the 6 levels of Location for a total of 18 observations per dependent variable were run.

Table 18. Results for UTS by Location.

	Observations		
Location	1	2	3
1	7071.3	6903.7	7014.9
2	6991.8	6972.7	6924.8
3	6954.2	6841.5	7021.5
4	7022.8	7028.9	6980.2
5	7080.3	7076.6	7005.7
6	7029.5	7182.4	7040.3

Table 19. Results for E by Location.

	Observations		
Location	1	2	3
1	121722.1	120890.3	121222.7
2	123736.8	121897.1	121214.8
3	121710.7	119533.5	121007.8
4	125495.8	123678.5	121844.4
5	120311.0	122100.2	123914.1
6	124550.6	124916.9	123656.7

Tables 20 and 21 show the mean UTS and E, respectively, for each level of the factors. It also shows the standard error of each mean, which is a measure of its sampling variability. The rightmost two columns show 95.0% confidence intervals for each of the means.

Table 20. Summary statistics for UTS by Location.

Location	Count	Average	Variance	Stnd. dev.	Minimum
1	3	6996.67	7224.33	84.9961	6904.0
2	3	6963.33	1192.33	34.5302	6925.0
3	3	6939.0	8179.0	90.4378	6842.0
4	3	7010.67	714.333	26.727	6980.0
5	3	7054.33	1754.33	41.8848	7006.0
6	3	7083.67	7282.33	85.3366	7029.0
Total	18	7007.94	5705.0	75.5314	6842.0

Location	Maximum	Range	Stnd. Skewness	Stnd. kurtosis
1	7071.0	167.0	-0.654409	
2	6992.0	67.0	-0.820978	
3	7021.0	179.0	-0.513244	
4	7029.0	49.0	-1.15567	
5	7080.0	74.0	-1.21768	
6	7182.0	153.0	1.20189	
Total	7182.0	340.0	-0.0543025	1.14912

Table 21. Summary statistics for E by Location.

Location	Count	Average	Variance	Stnd. dev.	Minimum
1	3	121278.0	175352.0	418.751	120890.0
2	3	122283.0	1.70187E6	1304.56	121215.0
3	3	120751.0	1.23437E6	1111.02	119534.0
4	3	123673.0	3.3343E6	1826.01	121844.0
5	3	122108.0	3.24545E6	1801.51	120311.0
6	3	124375.0	420132.0	648.176	123657.0
Total	18	122411.0	2.88293E6	1697.92	119534.0

Location	Maximum	Range	Stnd. skewness	Stnd. kurtosis
1	121722.0	832.0	0.413122	
2	123737.0	2522.0	0.859076	
3	121711.0	2177.0	-0.696667	
4	125496.0	3652.0	-0.00929374	
5	123914.0	3603.0	0.0147187	
6	124917.0	1260.0	-0.800305	
Total	125496.0	5962.0	0.486497	-0.805102

There is more than a 3 to 1 difference between the smallest standard deviation and the largest. This may cause problems since the analysis of variance assumes that the standard deviations at all levels are equal, and the error term is normal and identically distributed (NID). A variance check presented in the Model Adequacy section indicates that there is not a statistically significant difference amongst the standard deviations at the 95.0% confidence level. Nevertheless, we choose to err on the conservative side in this case where the normality assumption may not be valid and utilize an alternative to the *F*-test procedure presented in Equation 2. The non-parametric Kruskal-Wallis test (Kruskal and Wallis, 1952) is thus utilized to compare medians rather than means.

The y_{ij} observations are first ranked in ascending order, and each observation is then replaced by its rank (R_{ij}), with the smallest observation assigned a rank = 1. In case of ties the average rank is assigned to each tied observation. If $R_i = \sum$ (the ranks in the i^{th} treatment or Location), then the test statistic is shown in Equation 3, where $n_i = 3$ (the number of observations in the i^{th} Location) and $N = 18$ (total number of observations).

$$H = \frac{1}{S^2}\left[\sum_{i=1}^{6}\frac{R_i^2}{n_i} - \frac{N(N+1)^2}{4}\right] \tag{3}$$

S^2, the variance of the ranks, is given in Equation 4, and barring ties the test statistic H is presented in Equation 5.

$$S^2 = \frac{1}{N-1}\left[\sum_{i=1}^{6}\sum_{j=1}^{3}R_i^2 - \frac{N(N+1)^2}{4}\right] \tag{4}$$

$$H = \left[\frac{12}{N(N+1)}\sum_{i=1}^{6}\frac{R_i^2}{n_i}\right] - 3(N+1) \tag{5}$$

Tables 22 and 23 present the results of the Kruskal-Wallis test for UTS and E by Location, respectively, where the null hypothesis is that the medians of the dependent variables within each of the 6 levels of Location are the same. Since the *P*-values are greater than or equal to 0.05 in both cases, there is not a statistically significant difference amongst the medians at the 95.0% confidence level for either dependent variable. Figures 7a and 7b display the box and whisker plot for the medians for UTS and E, respectively.

Table 22. Kruskal-Wallis test for UTS by Location.

Location	Sample Size	Average Rank
1	3	8.66667
2	3	5.0
3	3	5.0
4	3	9.83333
5	3	13.6667
6	3	14.8333
Test statistic = 9.17906,	P-Value = 0.102132	

Table 23. Kruskal-Wallis test for E by Location.

Location	Sample Size	Average Rank
1	3	5.66667
2	3	9.66667
3	3	4.0
4	3	13.3333
5	3	9.33333
6	3	15.0
Test statistic = 9.46784	P-Value = 0.0917969	

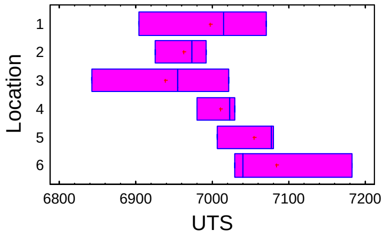
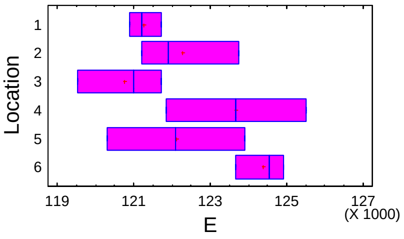
	

Figure 7a. Box and whisker plot, UTS by Location intervals.	**Figure 7b. Box and whisker plot, E by Location intervals.**

4.4 Model Adequacy

In all models generated no indications were present to assume that the fundamental conditions for the models were violated, based on the following analyses:

- The normal probability plots do not reveal violations of the normal and identically distributed (NID) error term.
- The residuals are structure less; that is, the plot of residuals versus fitted values of the dependent variables did not reveal any obvious patterns.
- Standardized residuals were approximately normal with mean = 0 and unit variance – no residual was greater than 2 standard deviations, and thus outliers did not seriously distort the ANOVA.
- The residual plots showed no significant tendencies, and thus no correlation between residuals.
- No 2-factor interactions in the models were present.

The four statistics displayed in Tables 24-26 test the null hypothesis that the standard deviations of the dependent variable (UTS and E) within each of the levels of each of the factors, respectively, are the same (Montgomery, 1997). Of particular interest are the *P*-values. Since the smallest of the *P*-values is greater than or equal to 0.05, there is not a statistically significant difference amongst the standard deviations at the 95.0% confidence level. As a result, the important assumption that the variance of the observations did not change significantly as the magnitude of the observation changed is upheld. It should be noted that the measuring instruments were calibrated before each test.

Table 24. Variance check – UTS by Factor.

Factor→	**Position**		**Layout**		**Axis**	
Test	Result	P-Value	Result	P-Value	Result	P-Value
Cochran's C	0.492	0.71	0.580	0.65	0.643	0.11
Bartlett's	1.044	0.60	1.013	0.65	1.220	0.25
Hartley's	3.012		1.384	N/A	3.853	N/A
Levene's	1.154	0.33	0.489	0.49	0.632	0.54

Table 25. Variance check – E by Factor.

Factor→	**Position**		**Layout**		**Axis**	
Test	Result	P-Value	Result	P-Value	Result	P-Value
Cochran's C	0.421	0.85	0.698	0.27	0.473	0.60
Bartlett's	1.067	0.63	1.082	0.27	1.059	0.67
Hartley's	2.310		2.239	N/A	2.314	
Levene's	0.704	0.51	1.210	0.28	0.868	0.43

Table 26. Variance check – UTS and E by Location.

Variable→	**UTS**		**E**	
Test	Result	P-Value	Result	P-Value
Cochran's C	0.310	0.93	0.324	0.81
Bartlett's	1.494	0.54	1.546	0.49
Hartley's	11.449	N/A	19.018	N/A
Levene's	0.435	0.81	0.704	0.63

Conclusions

A statistical design of experiments (DOE) approach was used to determine if specific build orientation parameters impacted mechanical strength of fabricated parts, measured in the statistical analysis using ultimate tensile strength (UTS) and Young's modulus (E). A single platform (10-inch by 10 inch cross-section) on the 3D Systems Viper si2 machine was designed to hold 18, ASTM D-638 Type I samples in six different orientations (called Location) with three replicates for each Location. Four factors were tested in the DOE: Location, Position, Axis, and Layout. Each sample within a Location was labeled as Positions 1, 2, or 3 depending on the distance from the center of the platform. Samples were fabricated parallel with the x-axis, y-axis, or 45^o to both axes (called Axis 1, 2, and 3, respectively) and were fabricated either flat or on an edge relative to the x-y plane (called Layout 1 and 2, respectively). The results from the statistical analyses showed that Axis, Location, and Position had no significant effect on UTS or E. However, Layout (or whether a sample was built flat or on an edge) was shown to have a statistically significant effect on UTS and E (at a 95% level of confidence). Physically, this result can be explained by the orientation of individual layers (or layer-to-layer interfaces) with respect to the part, since Axis, Location, and Position all had identical sample layer interfaces. That is, Layout was the only factor that tested different orientations of layer interfaces with respect to the test samples (samples built flat versus those built on an edge produced orthogonal layer interfaces with respect to the part). Without performing the DOE, the statistical differences between Layout most likely would not have been identified (since a comparison of the average UTS for each Layout showed only a 1.2% difference). Should one conclude that building a part flat or on an edge produces parts with essentially isotropic properties (based on the 1.2% difference in the means of UTS for the samples), this conclusion would be statistically incorrect. As a result of this work, it appears that the orientation of the individually fabricated layers (or the layer interfaces) with respect to the part produces samples with statistically different mechanical properties (UTS and E in this case). This study did not include a test of samples built vertically (where the major axis of the part is built vertically or in the z direction of the machine). Based on the present work, we would expect vertically built samples to have UTS and E properties that are statistically different from samples built flat and on an edge. Testing this hypothesis statistically will be left for future work.

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