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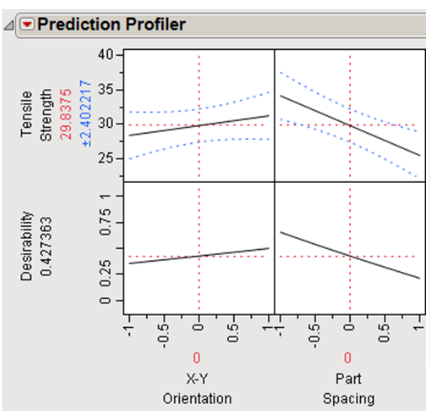
the tensile modulus. While the part spacing was the largest absolute main effect for both responses, the Z-orientation was the smallest absolute main effect for both.

4.3. Analysis of Variance (ANOVA)

Given that the Z-orientation parameter had the smallest absolute main effect, and appeared to be from the normal distribution for both the tensile strength and modulus (Figures 9 and 10), it was assumed to be statistically insignificant. This assumption permits the treatment of the performed three parameter and two level full-factorial design as a pseudo-replicated two parameter and two level full-factorial design (i.e., YXT to YZT and YZF to YXF were considered replicated experiments) [23]. By using this pseudo-replication, Analysis of Variance (ANOVA) could be performed on the two remaining effects (X-Y orientation and Part Spacing) and their interactions. ANOVA is a statistical technique in which the sum of squares and error terms are compared against an F-ratio statistic along with p-values to determine the statistical significance of the parameters.

Using SAS JMP, a statistical analysis software, experimental data was used in a "Fit Model" to define a two-level and two parameter full factorial design to perform an ANOVA. The DOE was modeled using a "Standard Least Squares" behavior. Each effect and interaction had its F-ratio calculated and compared against the critical F-ratio calculated at an alpha-value of 0.05. The ANOVA for Tensile Strength and Modulus is shown in Figure 11 and 12 below.



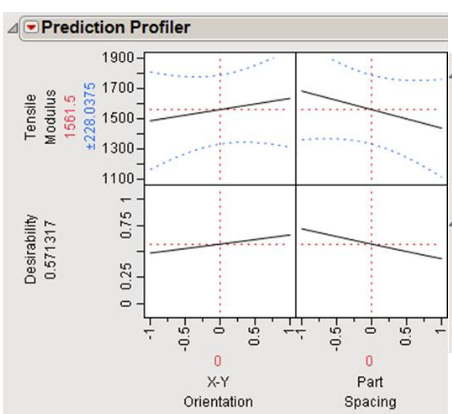
Parameter Estimates

Term	Estimate	Std Error	t Ratio	Prob>|t|
Intercept	29.8375	0.865213	34.49	<.0001*
X-Y Orientation	1.4125	0.865213	1.63	0.1779
Part Spacing	-4.3125	0.865213	-4.98	0.0076*
X-Y Orientation*Part Spacing	-0.9875	0.865213	-1.14	0.3174

Effect Tests

Source	Nparm	DF	Sum of Squares	F Ratio	Prob > F
X-Y Orientation	1	1	15.96125	2.6652	0.1779
Part Spacing	1	1	148.78125	24.8435	0.0076*
X-Y Orientation*Part Spacing	1	1	7.80125	1.3027	0.3174

Figure 11. Tensile Strength ANOVA



Parameter Estimates

Term	Estimate	Std Error	t Ratio	Prob>|t|
Intercept	1561.5	82.1329	19.01	<.0001*
X-Y Orientation	74	82.1329	0.90	0.4185
Part Spacing	-122.5	82.1329	-1.49	0.2101
X-Y Orientation*Part Spacing	-11.5	82.1329	-0.14	0.8954

Effect Tests

Source	Nparm	DF	Sum of Squares	F Ratio	Prob > F
X-Y Orientation	1	1	43808.00	0.8118	0.4185
Part Spacing	1	1	120050.00	2.2245	0.2101
X-Y Orientation*Part Spacing	1	1	1058.00	0.0196	0.8954

Figure 12. Tensile Strength ANOVA

4.4. Interpreting ANOVA

The ANOVA analysis of tensile strength provided an R-squared value of 0.88 and a RMSE of 2.45%, indicating an adequate correlation between the experimental data and the model suggesting the model is sufficient for prediction, due to minimal residuals and random noise. The factorial analysis in Figure 11's "Parameter Estimates" shows that the part spacing's was the largest absolute effect at 8.63 MPa, (which is approximately equal to the value from earlier analysis (Table 5). Its F-ratio of 24.8 is the only value that exceeds the critical F-ratio of 9.60 and its 0.0076 p-value is nearly an order of magnitude smaller than the 0.05 alpha value. Based on these two criteria, part spacing is the only statistically significant effect on the tensile strength.

The tensile modulus ANOVA has an R-squared value of 0.43 but a RMSE of 232% which indicates that large residuals and a very large amount of noise exists in the data, suggesting that the model is not very adequate to predict the data. Figure 12's "Parameter Estimates" show that the part spacing had the largest absolute effect at 122 MPa, which is not approximately equal to the value found in earlier factorial analysis (Table 6). This discrepancy is due to the interaction effect between the part spacing and Z-orientation, which is confounded with the part spacing in this ANOVA. While part spacing's F-ratio of 2.22 does exceed the critical F-ratio of 1.02, further analysis reveals that its 0.210 p-value is greater than the alpha value. Despite having a large F-ratio, part spacing and other effects are not statistically significant due to p-values greater than the alpha value, indicating a higher risk of Type I error.

5. DISCUSSION

5.1. Analysis of Results

Synthesizing the experimental data presented in Section 4, the following results are identified:

- Part dimensions aligned in the X-Y plane were fabricated 200-400 μm larger than designed (Table 3). This suggests that Z-orientation can affect the accuracy of a part's thicknesses and widths. This result is not surprising given that the Z-resolution of the PJD-3DP process (32-60 mm layer thickness) is better than the X-Y printing resolution (600 dpi). This is result is unique to the PJD-3DP process as most AM processes have poor dimensional accuracy for features aligned along the Z-axis due to the discretized nature of the layer-by-layer approach.
- XY and YX parts did not show any statistically significant effects on material performance. The authors' hypothesis that YX oriented parts would be weaker due to jetting from discretized nozzles was found to be incorrect. XY and XZ parts were, on average, stronger; however, the results were not statistically significant.
- Parts oriented in the Z-plane did not show any statistically significant improvements in material performance. The authors' hypothesis that parts with XZ and YZ orientation would be stronger due to an increase in the number of layers (and thus lead to increased curing due to "print-through", as noted for SL in [17]) was incorrect. Specimens with widths along the Z-axis were, on average, stronger; however the results were not statistically significant.

- Part spacing in the X-Y plane showed statistically significant effects on material performance. As hypothesized by the authors, parts printed closer together in the X-Y plane were stronger than parts printed further apart. This increase in material properties is hypothesized to be related to the manner in which the PJD-3DP indiscriminately patterns UV light during processing. Thus, when printing multiple parts that span multiple print paths, UV irradiation from the printing-block can over-cure parts in paths adjacent to the current printing path.

5.2. Sources of Experimental Error

The weakness of DOE is that there are no immediately replicated results to verify and validate the completed DOE. While ANOVA helps eliminate unnecessary variables, its success is based on the quality and precision of the collected data, in which replication would provide the best insurance for determining the consistency of the data. Full-factorial DOE's provide the highest quality and resolution in an experiment but considering each combination of parameter level can be time-consuming and lead to excessive use of resources. While a pseudo-replication can enable ANOVA for two parameters (Section 4.4), this assumption removes a parameter which provides less precision and insight as to how the original three parameters truly interacted together. For example, while factorial analysis did not suggest that Part Spacing and Z-orientation had statistical significance, they had a practical significance in that their interaction was the largest absolute effect on the tensile modulus.

In addition to error in statistical techniques, the lifetime of parts (i.e., time between print start and tensile test) was not consistent between experiments. This is important because time is suspected to be a potential cause of polymer aging and degradation [21]. In addition, differences of relative humidity between experiments and testing were not explicitly controlled; humidity can affect mechanical properties since polymers are hygroscopic and could have softened surfaces due to ambient moisture [24]. Finally, it is noted that a potential source of differentiation between the measured values with that specified by Objet could be due to their use of ASTM D638-03 and D638-04 [25], which might have different test specimens and conditions for testing and/or the authors' use of "Digital Material" mode instead of "High Quality" mode during sample fabrication.

6. CLOSURE

The purpose of this study was to analyze variability in the mechanical properties of parts created by the PolyJet Direct 3D Printing process due to changes in process parameters. The authors employed a design of experiments to identify changes in part tensile strength and tensile modulus due to changes in X-Y orientation, Z-orientation, and part spacing in the X-Y plane. ANOVA revealed that part spacing had a statistically significant effect on mechanical properties; specifically, parts printed closer together were stronger than those printed farther apart.

Future studies will further investigate the effect of part spacing on mechanical properties. The authors will explore the hypothesis that the PJD-3DP process is over-curing parts across multiple print paths. An AM process wherein part quality is affected by its layout on the build platform could have significant impact on a designer's ability to predict part performance – in effect, part properties would be inconsistent across various build platforms (due to part count and/or size).

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