Materials Lab Week 2 – Main and Cross

Effects of Infill Density, Print Speed, and Perimeter Width

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1. Introduction

This experiment aimed to investigate the effects of three controllable factors in 3D printing on the yield strength of printed parts. The factors examined were:

1. Infill density
2. Print speed
3. Perimeter width

Each factor was tested at two levels, a high and low setting. The experiment followed a full factorial design, resulting in 8 different combinations of the three factors. The standard used for tensile testing was ASTM D638-22 "Standard Test Method for Tensile Properties of Plastics".

The objective was to determine how these 3D printing parameters influence the mechanical properties of printed parts, with a focus on yield strength in this study. A Full Factorial Design of Experiments (DOE) systematically evaluates all possible combinations of input factors at defined levels (“low” and “high”) to understand their effects on a system. For three factors (A, B, and C), each having two levels, $2^3 = 8$ tests are required to test every combination of these factors. This approach ensures that the effects of each individual factor (main effects) as well as interactions between pairs or all three factors (cross effects) are accounted for.

2. Experimental Procedure

2.1 Preparation

Test specimens were 3D printed according to the dimensions specified in ASTM D638-22 for Type I specimens. A total of 8 different parameter combinations were printed, with each combination replicated 2 times for a total of 16 specimens.

The printing parameters varied were:

- Infill density: [Low-High]
- Print speed: [Low-High]
- Perimeter width: [Low-High]

All other printing parameters were held constant, including:

- Material: PETG filament
- Nozzle temperature
- Bed temperature
- Layer height

2.2 Tensile Testing

Tensile tests were conducted using an MTS Criterion universal testing machine with a 5 kN load cell. The procedure followed ASTM D638-22 with the following parameters:

- Test speed: 5 mm/min
- Gauge length: 50 mm
- Grip separation: 115 mm

Load and extension data were recorded throughout each test. The yield strength was determined by plotting the data and visually determining the region of plastic deformation. This method deviates from the recommended 0.02% method for determining yield stress.

3. Data and Equations

3.1 Three Case Full Factorial DOE Equations

Main Effect of Factor A ($\boldsymbol{\alpha_A}$) - Infill Density:

$$\alpha_A = \frac{y_1 + y_2 + y_3 + y_4 + y_5 + y_6 - y_7 - y_8}{8} \quad [1]$$

This equation measures how changes in infill density impact the yield stress, where a positive value indicates increasing the infill density has a positive effect on the yield stress where is the opposite it true as well.

Main Effect of Factor B ($\boldsymbol{\alpha_B}$) - Print Speed:

$$\alpha_B = \frac{y_1 + y_2 - y_3 - y_4 + y_5 + y_6 - y_7 - y_8}{8} \quad [2]$$

This equation measures how changes in print speed impact the yield stress, where a positive value indicates increasing the print speed has a positive effect on the yield stress where is the opposite it true as well.

Main Effect of Factor C ($\boldsymbol{\alpha_C}$) - Perimeter Width:

$$\alpha_C = \frac{y_1 + y_3 + y_4 - y_2 - y_5 - y_6 + y_7 + y_8}{8} \quad [3]$$

This equation measures how changes in perimeter width impact the yield stress, where a positive value indicates increasing the perimeter width has a positive effect on the yield stress where is the opposite it true as well.

Cross Effect of Factors A and B (α_{AB}) - Infill Density and Print Speed:

$$\alpha_{AB} = \frac{y_1 + y_2 - y_3 - y_4 - y_5 - y_6 + y_7 + y_8}{8} \tag{4}$$

This equation calculates the interaction effect between infill density and print speed. If α_{AB} is significant, it suggests that the effect of infill density on the outcome varies at different levels of print speed.

Cross Effect of Factors A and C (α_{AC}) - Infill Density and Perimeter Width:

$$\alpha_{AC} = \frac{y_1 - y_2 + y_3 - y_4 - y_5 + y_6 - y_7 + y_8}{8} \tag{5}$$

This equation calculates the interaction effect between infill density and perimeter width. If α_{AC} is significant, it indicates that the effect of infill density on the outcome depends on the perimeter width, or vice versa.

Cross Effect of Factors B and C (α_{BC}) - Print Speed and Perimeter Width:

$$\alpha_{BC} = \frac{y_1 - y_2 - y_3 + y_4 + y_5 - y_6 - y_7 + y_8}{8} \tag{6}$$

This equation calculates the interaction effect between print speed and perimeter width. If α_{BC} is significant, it indicates that the impact of print speed is dependent on the perimeter width.

Cross Effect of Factors A, B, and C (α_{ABC}) - Infill Density, Print Speed, and Perimeter Width:

$$\alpha_{ABC} = \frac{y_1 + y_2 + y_3 + y_4 - y_5 - y_6 - y_7 - y_8}{8} \quad [7]$$

This equation calculates the three-way interaction effect between infill density, print speed, and perimeter width. If α_{ABC} is significant, it suggests that the outcome depends on specific combinations of all three factors working together.

3.2 Data

The tabulated method of a three factors case is shown below.

Three Case Full Factorial DOE

A	B	C	AB	AC	BC	ABC	y_i
-1	-1	-1	1	1	1	-1	y_1
-1	-1	1	1	-1	-1	1	y_2
-1	1	-1	-1	1	-1	1	y_3
-1	1	1	-1	-1	1	-1	y_4
1	-1	-1	-1	-1	1	1	y_5
1	-1	1	-1	1	-1	-1	y_6
1	1	-1	1	-1	-1	-1	y_7
1	1	1	1	1	1	1	y_8

Table 1- Three Case Full Factorial DOE

The table below depicts the Yield strength of 2 samples for each test case where their plotted yield strengths are averaged and used in the equations above.

Yield Strength of Eight Combinations of Infill Density, Print Speed, and Perimeter Width

Sample	[+ + +]	[+ + -]	[+ - -]	[+ - +]	[- + +]	[- + -]	[- - +]	[- - -]
A	14.2	10.14	10.19	14.22	11.43	6.28	8.23	6.72
B	14.08	10.01	10.17	14.35	10.67	6.61	8.52	6.28
Avgerage	14.14	10.075	10.18	14.285	11.05	6.445	8.375	6.5

[mPa]

Table 2 - Tensile Test Yield Stress Data of 3 Case Full Factorial DOE

The table below displays the calculated alpha values from the seven equations above.

Main and Cross Effects Coefficients of Infill Density, Print Speed, and Perimeter Width

α_A	α_B	α_C	α_{AB}	α_{AC}	α_{BC}	α_{ABC}
3.795	2.18375	1.68625	1.1575	1.33875	-0.3	-0.595

Table 3 - Alpha Coefficients of Main and Cross Effects

4. Conclusion

The coefficients from the 3 case full factorial design of experiments indicate varied influence of infill density, print speed, and perimeter width on the target outcome. Infill density exhibits the strongest main effect with a coefficient of 3.795, suggesting that it has a significant positive impact on the result. Print speed and perimeter width also show positive impacts, though to a lesser extent, with coefficients of 2.18375 and 1.68625, respectively.

Among the interaction effects, the cross effect of infill density and print speed shows a positive but relatively minor impact (coefficient of 1.1575), indicating that the combination of high infill density and high print speed may slightly enhance the result beyond their individual contributions. The interaction between infill density and perimeter width and between print speed and perimeter width, also demonstrates positive effects.

The three-way interaction representing the combined effect of infill density, print speed, and perimeter width, shows a negative coefficient (-0.595). This suggests that when all three factors are at their higher levels, there might be diminishing returns or negative interactions impacting the result, implying a more complex relationship between these variables.