Process parameter optimization for tensile strength of 3D printed parts using response surface methodology

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Abstract Quality of 3D printed part is highly dependent on process parameters of 3D printer. In this study, authors investigated the effects of layer thickness and build orientation on tensile strength of part produced by a 3D printer. The experiments were conducted on ZCorp’s ZPrinter 450 by fabricating ZP150 powder’s dumbbell shaped test specimens. Box-Behnken Design (BBD) of response surface methodology (RSM) of design of experiment was used to obtain the number of experiments and results were analyzed using ANOVA and regression analysis methods. Optimization of the process parameters was done by one-way ANOVA in Minitab software. The results show that tensile strength decreases with increasing layer thickness. For orientation of the part in XY Plane, tensile strength increases with increasing rotation. For XZ and YZ plane tensile strength first decreases till 45° and then increases rapidly up to 90°.

1. Introduction
Additive manufacturing (AM), also known as rapid prototyping enables customers to fabricate physical models layer-by-layer directly from a computer-aided design (CAD) model in relatively shorter span of time compared to their conventional counterparts [1, 5, 6]. AM processes began to be established as standard approaches to product design and development recently [1, 2]. 3D printing is one of the most popular and effective processes among the several processes available in market today [3, 4, 6]. AM has widespread applications in various industries such as aerospace, armament, automotive, tool and mould making, architecture, building construction, dental, implants, prosthetics, surgical devices and aids, electronics, jewellery, furniture, specialty food, sports, textiles, toys and collectibles industry, etc. [7, 8, 9, 10, 13]. Box and Draper developed Response surface methodology (RSM) in 1987 to model the experimental responses; which was later used for modelling of numerical experiments differentiated with the type of error generated by the response. In RSM, randomization of the error is done. Design of experiments (DoE) is an important aspect of RSM with an objective to select the points where the response should be evaluated. A factorial experiment is an experimental strategy in which design variables are varied simultaneously, instead of one at a time.

2. Methodology
2.1 Fabrication of specimens
Test specimens were designed using Pro/E Wildfire 4.0 as shown in Figure 1(a) and saved into STL file format. Materialise’s Magics RP was used for the error removal in the STL format. Then the STL file was loaded into ZEDIT, proprietary software of ZCorp’s to prepare build volume and set the orientation of the part. Finally STL file was sliced and sent one slide at a time to ZPrinter 450 to fabricate the part layer by layer. A 3D printed specimen is shown in Figure 1 (b).

2.2 Measurement of tensile strength
The tensile strength (TS) of the specimens was measured using universal strength machine (USM) shown in Figure 2. The USM consists of hydraulic unit, high and low pressure gauge, set of compression pads, compression range high up to 13 kg/cm², low up to1600 gms/cm².
In this study, four parameters (factors) namely layer thickness, build orientation with respect to XY, XZ and YZ planes with three levels each were chosen. The process parameters along with their levels are shown in Table 1.

| Factor                        | Level       | 1          | 2          | 3          |
|-------------------------------|-------------|------------|------------|------------|
| Layer Thickness               | 0.0889 mm   | 0.0952 mm  | 0.1016 mm  |
| Orientation in XY plane       | 0°          | 45°        | 90°        |
| Orientation in XZ plane       | 0°          | 45°        | 90°        |
| Orientation in YZ plane       | 0°          | 45°        | 90°        |

For full factorial design of 4 parameters with 3 levels each (i.e. $3^4$), total 81 experiments are required to be conducted. However, conducting 81 experiments neither feasible nor economical viable. Fractional factorial design can be used in this case to draw out valuable conclusions from less number of experiments. Two steps are necessary while using Response Surface Methodology namely 1) defining an approximation function and 2) plan of Design of experiments. Planning of experiments has been done as per Box-behnken design in Minitab software.

### 3 Results and Analysis

By applying RSM approach, number of experiments was reduced to 27 from 81 as shown in Table 2. As per the plan total 27 specimens were fabricated on ZPrinter450 using ZP150 powder. Tensile strength of all the specimens was measured using USM and shown in Table 2. The detail analysis of the results was done using Analysis of Variance (ANOVA) method and Regression Analysis of the data.

| S. No. | Layer thickness | XY plane | XZ plane | YZ plane | Tensile strength | S. No. | Layer thickness | XY plane | XZ plane | YZ plane | Tensile strength |
|--------|-----------------|----------|----------|----------|------------------|--------|-----------------|----------|----------|----------|------------------|
| 1      | 0.1016          | 0        | 45       | 45       | 1.69             | 15     | 0.0952          | 0        | 45       | 90       | 4.60             |
| 2      | 0.0889          | 90       | 45       | 45       | 3.33             | 16     | 0.0952          | 90       | 45       | 90       | 4.70             |
|   | 0.1016 | 0.0952 | 0.0889 | 0.1016 | 0.0952 | 0.0889 | 0.1016 | 0.0952 | 0.0889 | 0.1016 |
|---|-------|-------|-------|-------|-------|-------|-------|-------|-------|-------|
| 3 | 90    | 45    | 45    | 3.10  | 17    | 45    | 45    | 3.20  | 17    | 45    |
| 4 | 0     | 0     | 0     | 3.91  | 16    | 0     | 0     | 2.60  | 16    | 0     |
| 5 | 45    | 90    | 0     | 4.46  | 19    | 0.0889| 45    | 90    | 3.97  | 19    |
| 6 | 0.0952| 45    | 90    | 4.71  | 20    | 0.1016| 45    | 90    | 3.30  | 20    |
| 7 | 0.0952| 45    | 90    | 4.89  | 21    | 0.0952| 0     | 0     | 4.20  | 21    |
| 8 | 0.0889| 45    | 0     | 4.11  | 22    | 0.0952| 90    | 0     | 3.71  | 22    |
| 9 | 0.1016| 45    | 0     | 4.29  | 23    | 0.0952| 90    | 0     | 3.60  | 23    |
| 10| 0.0889| 45    | 90    | 3.70  | 24    | 0.0952| 90    | 45    | 3.10  | 24    |
| 11| 0.1016| 45    | 90    | 2.50  | 25    | 0.0952| 45    | 45    | 3.09  | 25    |
| 12| 0.0952| 0     | 45    | 3.00  | 26    | 0.0952| 45    | 45    | 3.20  | 26    |
| 13| 0.0952| 90    | 45    | 4.20  | 27    | 0.0952| 45    | 45    | 3.10  | 27    |
| 14| 0.1016| 90    | 0     | 4.37  | 28    | 0.0952| 45    | 45    | 3.20  | 28    |

3.1 Graphical analysis

**Tensile strength V/s XY plane V/s Layer thickness:** From the Figure 3, it is clear that tensile strength decreases with an increase in layer thickness and increases with an increase in angle of orientation in XY plane. This may be due to the fact that at lower layer thickness, the sprayed binder penetrates better in vertical and lateral directions leaving behind less unoccupied space between powder particles, resulting less porosity and higher strength. While part is at 0° orientation (length along x-axis), binder gets deposited along the length of part requiring less number of strokes to bind the full layer. At 45° to 90° position, effective length of binder stroke decreases and number of strokes increases which results in increased binder saturation time which ultimately leads to higher tensile strength. The optimal value of tensile strength in XY plane is obtained when the layer thickness is kept near 0.0889 and the angle in XY plane is near 45°.

![Figure 3](image3.png)

**Figure 3. Plot between tensile strength vs XY plane, Layer thickness**

**Tensile strength V/s YZ plane V/s Layer thickness:** From the Figure 4, it can be seen that with an increase in layer thickness, tensile strength initially increases slightly up to 0.095 mm and significantly decreases after that. With increasing angle of orientation in YZ plane, there will be slight decrease in tensile strength initially then it increases up to 90°. This may be because when part is at 0° orientation,

![Figure 4](image4.png)

**Figure 4. Plot between tensile strength vs YZ plane, Layer thickness**
it is in flat position and less number of binder layers is required. The number of binder layers increases with increasing angle up to 90° (part is rotated about x-axis, yz-face being parallel to YZ plane) which probably provide specimen added tensile strength. So, the combined effect of both the parameters, we can see that the optimal value of tensile strength in YZ orientation is obtained when the layer thickness is kept near 0.0889 and angle in YZ plane be kept in between 0-45 degrees nearer to lower value.

Similarly Figure 5 shows the results for Tensile strength V/s XZ plane, Layer thickness.

![Figure 5. Plot between Tensile strength vs XZ plane, Layer thickness](image)

**Tensile strength V/s YZ plane V/s XZ Plane:** From the graph shown in Figure 6, it can be observed that with an increase in angle of orientation in XZ plane, tensile strength will decrease initially and then increase slightly. With an increase in angle in the YZ plane, again a parabolic nature of the curve is obtained. So, the optimal value of tensile strength in YZ orientation is obtained when the angle in XZ and YZ orientation will be kept between 45-90 degrees nearer to higher value. Similarly Figure 7 shows the results for Tensile strength V/s YZ plane, XY Plane.

![Figure 6. Plot between Tensile strength vs YZ plane, XZ](image)

![Figure 7. Plot between Tensile strength vs XY plane, YZ](image)

### 3.2 Regression Analysis

The ANOVA table for the investigation is shown in Table 3.
Table 3. Analysis of variance for tensile strength

| Source     | DF | Seq SS   | Adj SS   | Adj MS   | F      | P      |
|------------|----|----------|----------|----------|--------|--------|
| Regression | 14 | 15.0221  | 15.02209 | 1.07301  | 30.48  | 0.0    |
| Linear     | 4  | 5.4021   | 5.40211  | 1.35053  | 38.37  | 0.0    |
| Square     | 4  | 8.5913   | 8.59134  | 2.14783  | 61.02  | 0.00   |
| Interaction| 6  | 1.0286   | 1.02865  | 0.17144  | 4.87   | 0.010  |
| Residual error | 12 | 0.4224 | 0.42241 | 0.03520 |
| Lack of fit | 10 | 0.4157 | 0.41567 | 0.04157 | 12.35 | 0.77 |
| Pure error  | 2  | 0.0067  | 0.00673  | 0.00337  |
| Total       | 26 | 15.4445  |          |          |

R-Sq = 97.3%  R-Sq(adj) = 94.1%

Table 4. Standard deviation at all 3 levels

| Level | N | Mean | Standard deviation |
|-------|---|------|--------------------|
| 0     | 3 | 4.433| 2.043              |
| 45    | 3 | 3.433| 2.281              |
| 90    | 3 | 5.400| 0.819              |

Pooled standard deviation = 1.830
All pairwise comparisons among levels of YZ plane
Individual confidence level = 97.80%
Following regression equation is obtained by the analysis of the data:

\[
3.133 - 0.414p + 0.299q + 0.168r + 0.40s - 0.566p^2 + 0.199q^2 + 0.427r^2 + 0.810s^2 + 0.379(p \star q) - 0.170(p \star r) - 0.018(p \star s) - 0.002(q \star r) - 0.275(q \star s) - 0.091(r \star s)
\]

where, \(p\) = layer thickness, \(q\) = angle in XY plane, \(r\) = angle in XZ plane, \(s\) = angle in YZ plane. This equation gives optimized value for all the process parameters which will yield the best possible tensile strength at any orientation and at any value of layer thickness. Table 4 shows the standard deviation of the values at all 3 levels.

4. Conclusions
Response surface methodology of design of experiment is used to get optimum level setting of the process parameters for 3D printing process. All the 27 specimens have been fabricated on ZPrinter450 in Zp150 powder. The tensile strength of each specimen is measured by USM and results have been analysed using ANOVA and regression analysis. The contribution of the layer thickness and the build orientation on tensile strength of the part has been shown in Figure 9. Tensile strength increases with decreasing thickness of layers and its influence is around 9.362%. For different orientation of part in XY Plane, tensile strength decreases with increasing orientation angle; however, the rate of decrease is higher till 45°. For different orientation in XZ and YZ Planes, tensile strength decrease initially till 45° then increases rapidly up to 90°. Contribution of build orientation in affecting tensile strength is 90.638%.
Figure 8. Influence of process parameters on tensile strength

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