# INFLUENCE OF PROCESS PARAMETERS ON THE MECHANICAL BEHAVIOUR AND PROCESSING TIME OF 3D PRINTING

**Ramu Murugan[1], Mitilesh R.N[2], Sarat Singamneni[3]**

[1,3] Department of Mechanical Engineering, Amrita School of Engineering, Coimbatore,
Amrita Vishwa Vidyapeetham, Pin 641112, India
[2] School of Engineering, Auckland University of Technology, Private Bag 92006, 1142 Auckland, New Zealand

Corresponding author: Ramu Murugan, m_ramu@cb.amrita.edu

***Abstract:*** 3D Printing technology has been extensity used to fabricate engineering components within a short span of time in small scale. The quality of parts being produced using 3D printing depends on the build parameters. This paper presents a study on the mechanical behaviour of 3D printed structures under the influence of build parameters such as build orientation, layer height, fill density, extrusion temperature and printing speed. Preliminary studies on the influence of build orientation were carried out by varying the y-axis orientation of the specimen and confirm that model built using y –axis orientation of $45^0$ yields better mechanical properties. The specimens were built using Poly Lactic Acid (PLA) material with different combination of the process parameters based on Taguchi's approach. The influence of the above parameters on the tensile strength, Young's modulus and printing time were analyzed and optimized.

***Key words:*** 3D Printing, Build parameters, Mechanical properties, Taguchi's DOE, ANOVA.

## 1. INTRODUCTION

Additive Manufacturing (AM) has started to get recognition worldwide, the reason being the flexibility to build models with a rigorous design. Compared to the traditional manufacturing, AM reduces the material consumption and reduces scrap. A lot of advancements are being done in order to achieve better mechanical properties of the end products and fabrication with multi-materials/ multi-colours(Sitthi-Amorn, et al.,2016). Most of the 3D printing processes are being used to develop prototypes and not been used to develop end products. In a real working environment, all objects are subjected to various complex stresses conditions. The main requirement when 3D printing systems are implemented for production is to develop reliable functional models at lower printing time. The main aim of this work is to develop 3D printed functional models that can be put into the application directly.

Build parameters that have an effect on the physical properties of 3D printed samples considered for the present study is given below:

- Printing orientation: This parameter describes the direction in which the 3D model is to be printed. Once the model is loaded onto the slicing software, the orientation of the model can be changed. The printer then prints the model in the selected orientation. This parameter has a significant impact on the strength of the material and the printing time.
- Layer height: Also known as the vertical resolution is the thickness with which the printer head prints a single sliced layer. Layer height is an important parameter as it governs the surface finish of the final model. Lower the layer height, higher the surface finish. However build time increases if we reduce the layer height.
- Fill density: Fill density/ Infill describe the density with which the material is filled within the outer shell of the model. The fill density varies from a 0% to a 100%. The 100% represents a solid block whereas the 0% represents an object with an outer shell. Mechanical strength increases with increase in fill density, but has longer build times.
- Printing speed: Printing speed describes the speed at which the printer head extrudes material onto the platform. Quality of the final print is inversely proportional to the printing speed. Hence an optimum printing speed gives a good quality product.
- Extrusion temperature: Extrusion temperature describes the temperature at which the material is to be extruded. If the printing is too hot, the print may not solidify quickly and may also have bad bridging. If the printing is too cold, adjacent layers may not stick properly causing the object to be weaker.

Few researchers have worked on the prediction of the influence of different process parameters in different ranges. Christiyan et al, (2016) had conducted tensile and flexure tests on ABS + hydrous magnesium silicate composite material in which parameters like layer height, printing speeds with a constant nozzle diameter and extrusion temperature was chosen. It was concluded that a lower layer height and a lower printing speed gave better bonding with the previous layer, which ultimately increases the strength of the model produced.

Fernandez et al., (2016) conducted mechanical tests with different pairs of infill patterns and found that the rectilinear pattern with 100% infill density had the best strength. It was also reported that there was a significant change in the tensile strength between fill densities of 50% and 100%.

Baich and Manogharan, (2015) analyzed the effect of infill patterns on a production grade FDM system and studied the relation between cost, time and the desired mechanical properties. They concluded that solid infill has greater strength performance than double dense infill at the same production cost.

Akande et al., (2015) studied the significance of different process parameters like layer thickness, fill density, and speed of deposition on the mechanical properties of samples. Tensile, flexural, and impact test specimens were performed based on standard methods and on a new test jig to evaluate the strength parts made of FFF. These results were then compared with the conventional testing methods.

Lanzotti et al., (2015) studied the mechanical properties of 3D printed Polylactic Acid (PLA) by varying the layer thickness, printing orientation and the number of shell. The range of layer thickness was chosen between 0.1 mm and 0.2 mm. The optimum combinations were predicted for maximizing the ultimate tensile strength and maximizing strain.

In another study, the influence of three responses such as tensile, flexural and impact strength on parameters such as layer thickness, orientation, raster angle, raster width and air gap were studied (Rajkumar, 2010). It was concluded that increasing the number of layers accumulates residual stress due to increase in heating and cooling cycles. This may lead to distortion, inter-layer cracking and fabrication failure.

Ahn et al., (2002) analyzed the properties of ABS parts fabricated by the FDM 1650. Design of Experiment (DOE) approach was adoped by choosing the process parameters as raster orientation, air gap, bead width, colour, and model temperature. Tensile strengths and compressive strengths of these specimens were measured and compared with that of the injection moulded FDM ABS P400 material.

Mahmood et al., (2017) synthesized the parameters analyzed in previous studies, and selected a list of 13 controllable factors, which may affect the mechanical behaviour. They have used Taguchi's method of Design of Experiment to obtain the optimized parameter value.

Fernandez et al., (2016) studied the influence of layer thickness, air gap, raster width, contour width and raster orientation on surface roughness and tensile strength. It was concluded with the analysis of variance and S/N ratios that air gap influenced the most. Taguchi technique simplifies the experimental plan and helps in study of effects of different parameters.

Arunachalam et al., (1997) have applied this technique and have compared super abrasive process with the existing hole finishing process. Similarly, Anitha et al., (2001) has applied this technique to analyze the effect of process parameters like road width, build layer thickness and speed of deposition on the surface roughness of the end product.

Only few researchers have performed the optimization of process parameters considering build time as one of the primary response. This research paper focuses on the optimization of the build parameters; build orientation, layer height, fill density, print speed and extrusion speed to achieve maximum tensile strength and minimum build time.

## 2. EXPERIMENTAL PROCEDURE

### 2.1 Fabrication of test specimen

The tensile test specimen conforming to ASTM D638 I (Figure 1) was used to determine the tensile behavior of the 3D printed samples. CAD models of the standard test specimens were built using Autodesk Inventor software and were exported as stereolithography (.STL) file, as it is widely supported by most of the 3D printers. The slicer program in 3D printing systems slices the model horizontally into a series of layers and generates G-codes and M-codes. These codes are fed into the printer's hardware which builds the entire model in subsequent layer.

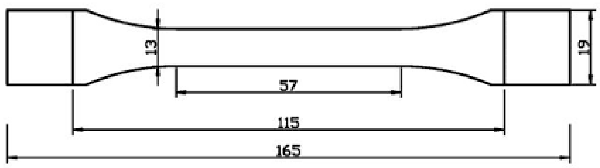



Fig.1. Tensile test specimen as per ASTM D638 I (All dimensions in mm)

### 2.2 Selection of process parameters

Design of experiment is a tool used for maximizing the amount of information gained from a study while minimizing the amount of data required, which, in this case, is minimizing the number of test specimens. The plan of experiments was mainly done to study the factors which are influential in affecting the mechanical properties (tensile strength, Young's modulus) and printing time. Initially, specimens were built along the edges by fixing the z-orientation at 45º and varying the y-orientation by 10°, 45° and 50°. The 10° and 50° orientations were chosen as this was the minimum and maximum possible orientations that the printer was capable of printing the specimen. The fill density, extrusion temperature, printing speed and layer height were kept constant. The experiment

revealed that the specimen with the y-orientation of 45° had the best mechanical properties viz tensile strength.
The specimen was built with it y-axis orientation fixed at 45°. According to the Taguchi design, a L9 orthogonal array was developed with three levels of layer height, extrusion temperature, printing speed and fill density. The process parameters with its levels and L9 orthogonal array used for the study are given in Table 1 and Table 2 respectively.

Table 1. Process parameters and their respective levels.

| Level | Layer height [mm] | Extrusion temperature [°C] | Fill density [%] | Printing speed [mm/s] |
|---|---|---|---|---|
| 1 | 0.2 | 200 | 60 | 80 |
| 2 | 0.25 | 210 | 70 | 100 |
| 3 | 0.3 | 220 | 80 | 120 |

Table 2. $L_9$ orthogonal array of process parameters

| Specimen | Layer height [mm] | Extrusion temperature [°C] | Fill density [%] | Printing speed [mm/s] |
|---|---|---|---|---|
| 1 | 0.2 | 200 | 60 | 80 |
| 2 | 0.2 | 210 | 70 | 100 |
| 3 | 0.2 | 220 | 80 | 120 |
| 4 | 0.25 | 200 | 70 | 120 |
| 5 | 0.25 | 210 | 80 | 80 |
| 6 | 0.25 | 220 | 60 | 100 |
| 7 | 0.3 | 200 | 80 | 100 |
| 8 | 0.3 | 210 | 60 | 120 |
| 9 | 0.3 | 220 | 70 | 80 |

The commercial statistical software Minitab gave the L9 orthogonal array based on the input of factors and their respective levels. The following table depicts the specimens that were to be fabricated according to the array. The 3D printer used to build the specimens is of Flashforge make with its technical given in Table 3.

Table 3. 3D printer specifications

| | |
|---|---|
| Device's Build Volume (L x W x H) | (139.7 x 139.7 x 139.7) mm |
| Precision positioning on X | 0.011mm |
| Precision positioning on Y | 0.011mm |
| Precision positioning on Z | 0.0025mm |
| Technology | Fused Deposition Modeling |
| Compatible materials | Poly Lactic Acid (PLA) |
| Nozzle Diameter | 0.4mm |
| Filament Diameter | 1.75mm |
| Layer Thickness | (0.1 – 0.5)mm |
| Slicing software | Flashprint |

## 3. RESULTS AND DISCUSSION

### 3.1. Tensile testing

Mechanical testing on the specimens was conducted on a Tinius Olsen H25KT Universal Testing Machine (Figure 2). The tensile test specimen built as per ASTM D638 Type I, shown in Figure 3. Results of the tensile test are given in Table 4 and are shown in Figure 4.


Fig. 2. 25kN Universal testing machine used for the mechanical tests

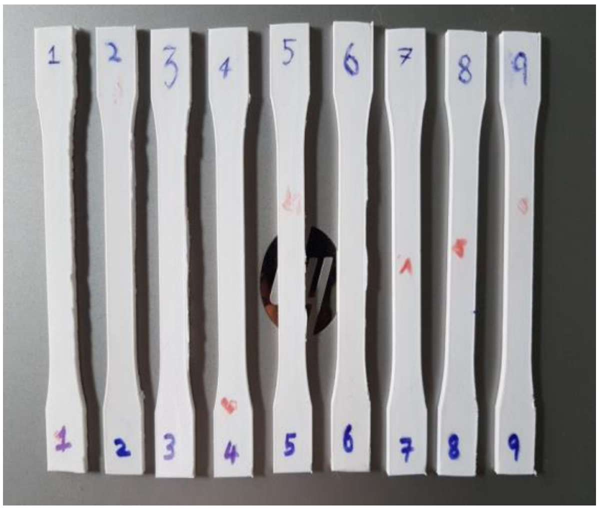



Fig. 3. Fabricated tensile test specimen

Table 4. Results for tensile tests

| Specimen | Tensile strength [N/mm$^2$] | Elongation at break [%] | Elastic modulus [GPa] | Breaking stress [N/mm$^2$] |
|---|---|---|---|---|
| 1 | 19.05 | 3.320 | 0.635 | 19.032 |
| 2 | 20.6 | 5.160 | 0.710 | 20.192 |
| 3 | 22.55 | 5.000 | 0.780 | 22.235 |
| 4 | 18.08 | 4.480 | 0.644 | 18.000 |
| 5 | 20.82 | 5.136 | 0.700 | 20.817 |
| 6 | 20.22 | 4.640 | 0.695 | 20.216 |
| 7 | 16.4 | 4.600 | 0.630 | 16.019 |
| 8 | 16 | 4.800 | 0.625 | 15.673 |
| 9 | 18.69 | 4.580 | 0.660 | 18.635 |

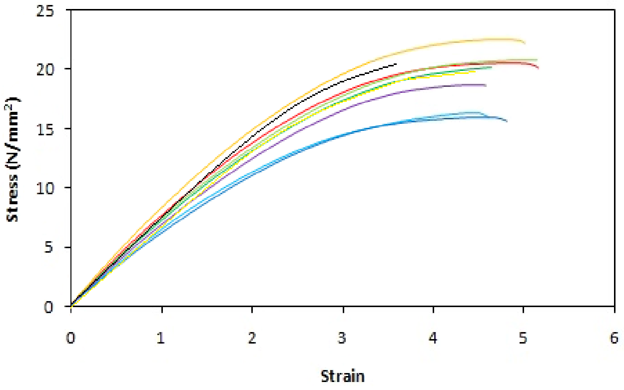



Fig. 4 Stress-Strain curves for tensile tests on different samples

The maximum values of ultimate tensile strength, % elonation and elastic modulus for the 3D printed specimen is found to 22.6MPa, 5.16 and 0.78GPa respectively. This means that higher the fill density, faster the printing speed and less the layer height more the strength will be. The influence of built parameters on the response parameters were identified using Taguchi's analysis.

### 3.2 Statistical analysis results – Taguchi's DOE

Results obtained from the tensile tests of the specimen built according to L9 Taguchi's orthogonal array are analysed using the MINITAB software. The Signal-to-Noise(S/N) ratio provided the qualitative performance characteristics from the results of mechanical tests.

Table 5 Signal to Noise response for the mechanical properties

| Layer height, [mm] | Extrusion temp, [$^0$C] | Fill density, [%] | Print speed, [mm/s] | Signal to Noise response, [db] | | |
|---|---|---|---|---|---|---|
| | | | | Ultimate tensile strength, [MPa] | Print time, [s] | Elastic modulus, [MPa] |
| 0.2 | 200 | 60 | 80 | 25.6 | -43.5 | -3.9 |
| 0.2 | 210 | 70 | 100 | 26.3 | -43.6 | -3.0 |
| 0.2 | 220 | 80 | 120 | 27.1 | -43.5 | -2.2 |
| 0.25 | 200 | 70 | 120 | 25.1 | -43.3 | -3.8 |
| 0.25 | 210 | 80 | 80 | 26.4 | -43.8 | -3.1 |
| 0.25 | 220 | 60 | 100 | 26.1 | -43.1 | -3.2 |
| 0.3 | 200 | 80 | 100 | 24.3 | -42.2 | -4.0 |
| 0.3 | 210 | 60 | 120 | 24.1 | -41.5 | -4.1 |
| 0.3 | 220 | 70 | 80 | 25.4 | -42.0 | -3.6 |

Based on these Signal-to-Noise responses, the effect of process parameters on the ultimate tensile strength, printing time and elastic modulus were studied. tensile strength and, The S/N responses were set as larger is better for tensile strength  and Young's modulus, whereas for printing time it was set as smaller is better. Table 5 presents the S/N response of specimens as per design of experiments. The factors that have contributed to individual built parameter can be noted based on higher value of Signal-to-Noise response.

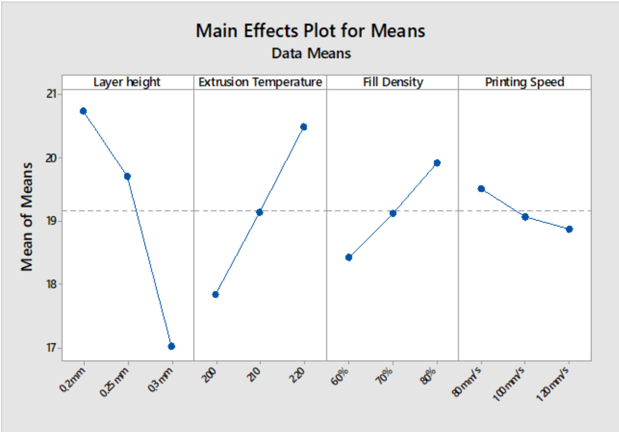
The different levels of process parameters are ranked based on the ultimate strength (Table 6), using S/N ratio. Depends on the ranking of the process parameters, it is inferred that layer height is a dominant parameter on the ultimate tensile strength followed by extrusion temperature, fill density and printing speed. By analyzing the S/N ratio, optimum conditions for printing models with maximum tensile strength can be noted.

The graphical representation of S/N response and mean of means of process parameters are shown in Figure 5. The mean of means plot provides the trend in which the different process parameters affect the tensile strength. From the Signal-to-Noise response, the optimum values of process parameters for maximum tensile strength were noted as Layer height = 0.2mm, Extrusion temperature = 220°C, Fill density = 80% and Printing speed = 80mm/s.

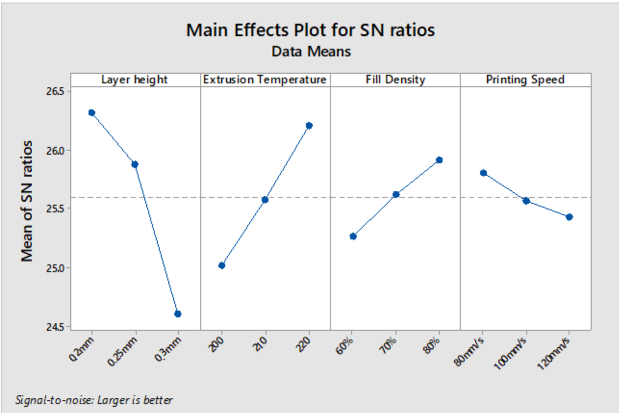
Table 6. Ranking of S/N ratio parameters for maximum tensile strength

| Level | Layer height [db] | Extrusion temperature [db] | Fill density [db] | Printing speed [db] |
|---|---|---|---|---|
| 1 | 26.31 | 25.01 | 25.27 | 25.80 |
| 2 | 25.88 | 25.58 | 25.62 | 25.56 |
| 3 | 24.60 | 26.20 | 25.91 | 25.43 |
| Delta | 1.71 | 1.19 | 0.64 | 0.37 |
| Rank | 1 | 2 | 3 | 4 |

Similarly, the process parameters were ranked based on the printing time with the help of S/N response is presented in Table 7 and the graphical representation of S/N response and mean of means of process parameters are shown in Figure 6. The mean of means plot provides the trend in which the process parameter affect the printing time. From the Signal-to-Noise response, the optimum values of process parameters for printing time were obtained as Layer height = 0.3mm, Extrusion temperature = 220°C, Fill density = 60% and Printing speed = 120mm/s.

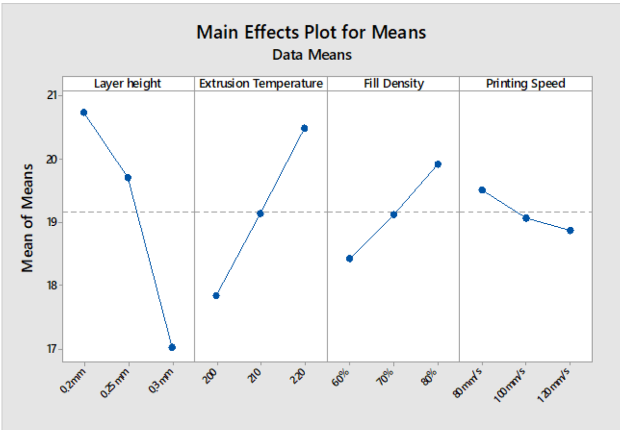



a.

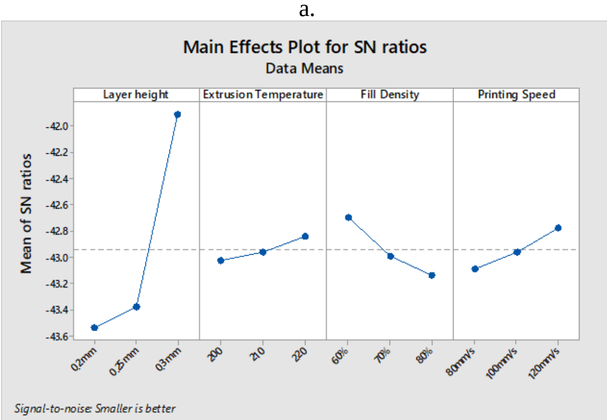



b.

Fig. 5. Main effects: a. Mean of mean plot of tensile strength; b. S/N response of tensile strength




a.




b.

Fig.6. Main effects: a. Mean of mean plot of printing speed; b. S/N response plot of printing speed

Table 7. Ranking of process parameters based on S/N ratio for printing speed

| Level | Layer height [db] | Extrusion temperature [db] | Fill density [db] | Printing speed [db] |
|---|---|---|---|---|
| 1 | -43.54 | -43.03 | -42.69 | -43.09 |
| 2 | -43.38 | -42.97 | -43.00 | -42.96 |
| 3 | -41.91 | -42.84 | -43.14 | -42.77 |
| Delta | 1.63 | 0.19 | 0.45 | 0.32 |
| Rank | 1 | 4 | 2 | 3 |

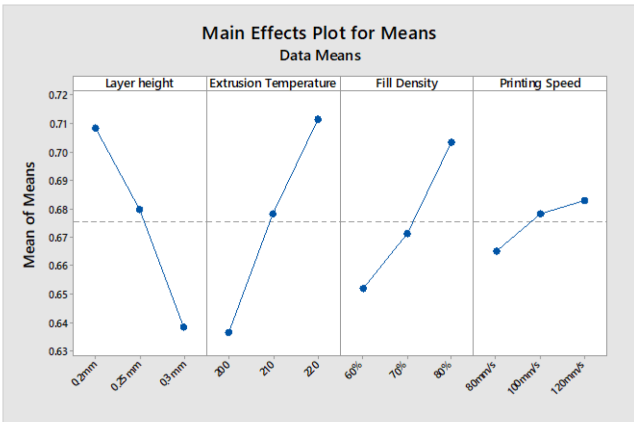
S/N analysis for elastic modulus is presented in Table 8 and illustrated in Figure 7. The Graphical representation of S/N response and mean of means of process parameters are shown. The mean of means plot provides the trend in which the process parameters affect the elastic modulus. From the Signal-to-Noise response, the optimum values of process parameters were obtained as Layer height = 0.2mm, Extrusion temperature = 220°C, Fill density = 80% and Printing speed = 120mm/s.

Table 8. Rank of process parameters based S/N ratio for elastic modulus

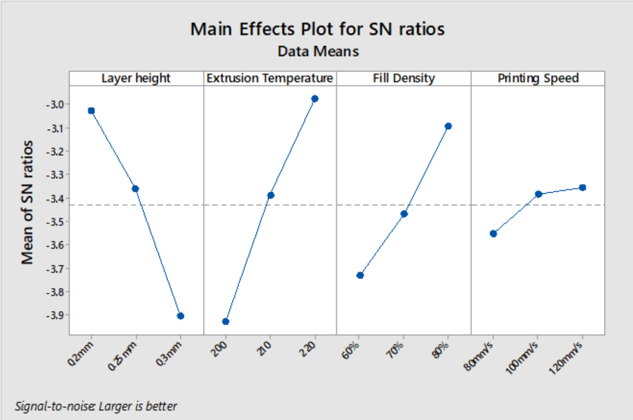
| Level | Layer height [db] | Extrusion temperature [db] | Fill density [db] | Printing speed [db] |
|---|---|---|---|---|
| 1 | -43.54 | -43.03 | -42.69 | -43.09 |
| 2 | -43.38 | -42.97 | -43.00 | -42.96 |
| 3 | -41.91 | -42.84 | -43.14 | -42.77 |
| Delta | 1.63 | 0.19 | 0.45 | 0.32 |
| Rank | 1 | 4 | 2 | 3 |

### 3.3 Analysis of variance

The independent dominant factor affecting the ultimate tensile strength, printing time and elastic modulus can be found from the results obtained from ANOVA.




a.




b.

Fig.7. Main effects: a. Mean of mean plot of elastic modulus; b. S/N response plot of elastic modulus

Table 9. ANOVA for ultimate tensile strength with $R^2$ of 100%

| Source | DF | Adj. SS | Adj. MS | F-value | P-value | P (%) |
|---|---|---|---|---|---|---|
| Extrusion temperature | 1 | 10.48 | 10.481 | 8384.7 | 0.008 | 28.76 |
| Layer height | 2 | 21.93 | 10.97 | 8773.3 | 0.007 | 60.18 |
| Fill density | 2 | 3.380 | 1.690 | 1352.0 | 0.019 | 9.27 |
| Printing speed | 2 | 0.652 | 0.326 | 260.83 | 0.044 | 1.78 |
| Error | 1 | 0.001 | 0.001 | | | 0.04 |
| Total | 8 | 36.45 | | | | 100 |

Table 10. ANOVA for printing time with $R^2$ of 99.79%

| Source | DF | Adj. SS | Adj. MS | F-value | P-value | P (%) |
|---|---|---|---|---|---|---|
| Extrusion temperature | 1 | 13.50 | 13.500 | 4.96 | 0.269 | 1.02 |
| Layer height | 2 | 1194.9 | 597.444 | 219.47 | 0.048 | 90.18 |
| Fill density | 2 | 76.22 | 38.111 | 14.00 | 0.186 | 5.75 |
| Printing speed | 2 | 37.56 | 18.778 | 6.90 | 0.260 | 2.83 |
| Error | 1 | 2.72 | 2.722 | | | 0.20 |
| Total | 8 | 1324.9 | | | | 100 |

Table 11. ANOVA for elastic modulus with R2 of 99.82%

| Source | DF | Adj. SS | Adj. MS | F-value | P-value | P (%) |
|---|---|---|---|---|---|---|
| Extrusion temperature | 1 | 0.008513 | 0.008513 | 227 | 0.04 | 41.4 |
| Layer height | 2 | 0.0074 | 0.0037 | 98.9 | 0.07 | 36.1 |
| Fill density | 2 | 0.0042 | 0.0020 | 54.32 | 0.1 | 19.82 |
| Printing speed | 2 | 0.0005 | 0.0003 | 6.97 | 0.26 | 2.55 |
| Error | 1 | 4e-5 | 0.38e-4 | | | 0.19 |
| Total | 8 | 0.0206 | | | | 100 |

The tables 9, 10 and 11 depict the ANOVA results with a significance level of $\alpha$=0.05 or 95% of confidence interval. The parameter which has their p-value less than 0.05 is considered to be a statistically dominant contributor. The tables 9, 10 and 11 presents the predicted ANOVA for ultimate tensile strength, printing time and elastic modulus.
Based on tables 9 and 10, it is inferred that layer height has the highest influence of p = 60.18% and 90.18% on the ultimate tensile strength and elastic modulus respectively, followed by extrusion temperature, fill density and printing speed. From table 10, infers that layer height has the highest influence with p = 90.18% on the printing time.
Table 11 infers that extrusion temperature has the highest influence with p = 41.4% on the elastic modulus. Thus extrusion temperature is the important parameter that is needed to be controlled followed by layer height, fill density and printing speed. The maximum error in the predicted is found to be 0.18%.

## 4. CONCLUSION

The main aim of this research article is to predict the feasibility of using 3D printed models as functional models with better strength and less printing time. Since functional models are subjected to complex load conditions, combined stress may be induced in it. In order to accommodate the combined stress induced in practical situations, the printing orientation was varied between $0^0$ and $90^0$ during initial analysis. The tensile specimens were built as per ASTM standard, by fixing the z-orientation and varying the y orientation. The tests revealed the y-orientation of 45° gave the best ultimate tensile strength. Similarly, the influence of other parameters like layer height, extrusion temperature, fill density and printing speed were studied based on $L_9$ orthogonal array. The influence of process parameters on the different response parameters (ultimate tensile strength, elastic modulus and printing time) obtained based on ANOVA and S/N ratio. It was observed that layer height influence majorly for ultimate tensile strength and printing time, whereas, extrusion temperature influences much for the elastic modulus.

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