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APPLICATION OF DESIGN OF EXPERIMENT (TAGUCHI METHOD) ON ANALYSIS OF 3D PRINTING PARAMETERS

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Abstract
3D printing technology has developed quickly in the past decades and has been widely used in many areas, from models and hobby areas to construction objects like buildings and bridges. As one type of 3D printing method, Fused Deposit Modelling (FDM) can create 3D objects easily and so it become one of the most popular methods of additive manufacturing. In this paper, application of Taguchi method was exercised on six main printing parameters (layer thicknesses, Infill percentage, Raster angle, Infill speed, Infill pattern, and Nozzle temperature) to analyse the effective variable for selected objective properties (ultimate tensile strength, elastic modulus, mass and strength-to weight ratio). Using this method of experimental design, parameters with little influence can be determined for the next variation of experiment, thereby reducing the cost of experiment.

Key words: Design of Experiment, 3D printing, parameters, Taguchi method

1. Introduction

Additive Manufacturing (AM), also known as Rapid Prototyping (RP) or 3D printing, is a manufacturing method that differs in principle from traditional subtractive manufacturing. While traditional manufacturing has been around industry applications for many decades, 3D printing is a relatively new technology that has attracted much attention due to its advantages, such as the avoidance of tooling costs, reduction of material waste, and increased efficiency [1-3]. The process can fabricate parts layer by bayer then ccombine all layers to form a part that meets the requirements [4].

FDM is a popular 3D printing method for its low cost, high applicability, and ease of operation. It is commonly used to form low-melting-point polymer filaments, such as polylactic acid (PLA), acrylonitrile butadiene styrene (ABS), polycarbonate (PC), and polyamide (PA) [5].

The influence of process parameters(layer thickness, printing speed, orientation angles, infill pattern, and infill density) on properties of 3D printing products has been studied widely. For example studies by M. Rismalia et al. [6], and Shivani [7] have shown that higher infill density leads to higher ultimate tensile strength and yield strength, and the "concentric" infill pattern gives the highest properties. Optimization of three key parameters (infill pattern, build orientation, and infill percentage) in 3D printing of PLA and the effects of these parameters were analyzed using the Taguchi Methodology and analysis of variance. Layer thickness, raster angle, and build orientation were considered by Lokesh et al. [8, 9] and found that for 3D printing of ABS the maximum ultimate tensile strength observed was 46.65 MPa. Some references also consider product mass, processing time, and light-weight ratio [10], which showed that an orientation angle of 30° achieves the best trade-off among the studied variables. These values reduce the length and width dimensional variation and increase the ultimate tensile strength of the part without a significant increment of processing time and mass.
This paper aims to focus on studying the application of Taguchi method for analysing the influence of six parameters on different results as to make preliminary preparations for subsequent research to effectively reduce experimental attempts.

2. Taguchi method principle

The Taguchi method is belongs to the group of methds applied in design of experiment; it allows a minimum number of experiments to be applied (within the permissible limit of factors and levels) - to evaluate (formulate) output(s) in Design of Experiments in terms of inputs, two different ways are mainly used [11].

- Using **mean responses analysis** of the output(s), this is very basic but effective averaging method, most of the time yields good result.
- Second approach is using **Signal to Noise ratio (S/N)** approach, which requires using appropriate formulations for different scenarios for the objective(output), i.e. larger is better nominal is best or smaller is better.

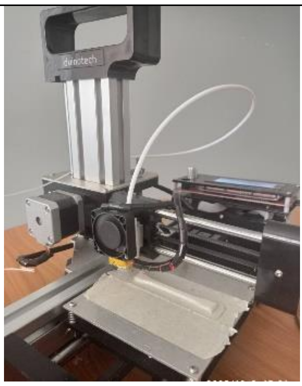
Mean responses analysis will be applied in this study, and average values of outputs will be calculated first. Then response table for mean effects will be obtained and can get effect of each factor on the outcome. Process of calculation and analysis will be shown in section 4.2.3.

3. Preparation of the Experiments

3.1 3D printer and materials

The specimens examined in this study were produced using a Mini 3D printer TL4076 and PLA filament. Table 1 provides an overview of the key features of the 3D printer and properties of PLA.

Table1 3D printer and materials

3D printer TL4076 (Duinotech)	PLA filament (Zhejiang flash forge 3d technology Co., Ltd)
Features: • 90 × 90 × 90 mm print area • Supports 1.75 mm filament • Non-heated bed suitable for printing with PLA • Comprehensive tool kit and spares	Properties: • Average filament diameter: 1.75 ± 0.5 mm • Recommended printing temperature: 195 - 230 °C • Recommended printing speed: 40 - 90 mm/s Color: clear
	

3.2 Process parameters

As mentioned earlier, parameters in the 3D printing process can significantly affect the printing outcomes. These parameters in this paper comprise layer thickness, printing angles, printing speed, raster angles, infill percentage, infill pattern, printing temperature, and orientation angles. To achieve the research objectives, some parameters were kept constant as indicated in Table 2, while others were considered as variable parameters for further investigation. Table 3 illustrates the variable parameters and their corresponding values.

Table 2 Printing parameters that are kept constant and their values

Parameters	value	Parameters	value
First layer height	0.2 mm	Specimen thickness	3 mm
Horizontal shells solid layer Top/ bottom	3 layers	Nozzle diameter	0.35 mm
Specimens thickness	3 mm		

This paper focuses on application of Taguchi method on investigating six parameters: printing layer thickness, infill percentage, raster angles, infill speed, infill pattern, and nozzle temperature, as presented in Table 3.

Table 3 Factors and their levels

Factors	layer thicknesses (mm)	Infill percentage (%)	Raster angle (°)	Infill speed (mm/s)	Infill pattern	Nozzle temperature (℃)
Level1	0.2	30	0	30	Rectilinear	200
Level2	0.4	90	45	70	Concentric	220

3.3 Specimens and design

According to ISO 527-2-2012 (International standard, plastics Determination of tensile properties Part 2: Test conditions for moulding and extrusion plastics) [12], determined geometric model of the 3D printing specimens as shown in Fig. 1.

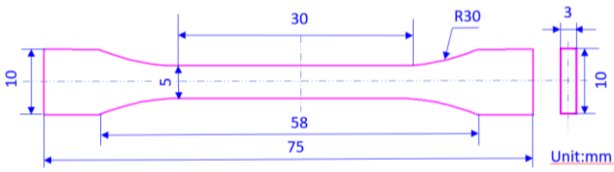
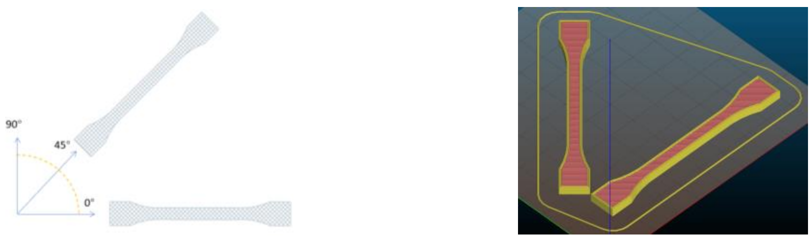


Fig. 1 Size of the 3D printing specimens

In this paper, the raster angle is a studied parameter, and in different raster angle the infill results are different, as shown in Fig. 2.



(a) schematic diagram (b) preview in Slic3r

Fig. 2 Specimens with different raster angles selected for the experimental trials

4 Experimental procedure for part forming and material properties testing

4.1 Experiments for specimens printing

To obtain the experiment specimens, there are three basic steps should be followed.

- Step 1 3D model creation

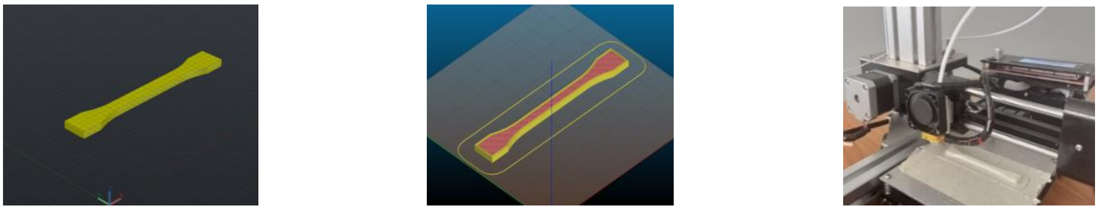
AutoCAD software is used to create the specimen's model, as shown in Fig. 3(a). The size is shown in Fig. 1. Then use the export function to get the STL. format file, which can be recognized by Slic3r for further operation.

- Step 2 Gcode file

Slic3r[13]is use to create the Gcode file, which can be read by the 3D printer. All the parameters in section 2.2 are set here. Fig. 3(b) shows the model after the printing setting.

- Step 3 3D printing

The 3D printer TL4076 start printing when insert the SD card with the Gcode file created in last step. The printed specimen on the bed is shown in Fig. 3(c).



(a) specimen's model (b) model after setting (c) printed specimen

Fig. 3 Steps to print the specimens

4.2 Experiments

4.2.1 Experimental equipment

Two tests are carried out in this paper, which are the tensile testing and the measurement of the specimen's mass. To get the mechanical properties of the specimens, Electronic ensometer, Model PC-2000 is used, as shown in Fig. 4. GF-6000 Precision Toploading Balance quantified the mass of each specimen, as shown in Fig. 5. ISO 257-2 standard is used for the tensile testing, which defines 1 mm/min strain rate.

Fig. 4 Electronic tensometer, Model PC-2000

Fig. 5 GF-6000 Precision Balance

4.2.2 Design of experiments

Taguchi methodology will be used in this study. It is one of experimental methodologies used to find the minimum number of experiments to be performed within the permissible limit of factors and levels[13]. Taking 6-factor analysis in this paper as an example, if a full factorial experimental design is used, at least 64 experiments are required, while with the Taguchi method, 8 experiments can be achieved.

To make it more understandable, the Taguchi Array selector and the Taguchi DOE are both shown in Table 3. *A~F* means the different factors and 1and 2 means the level1 and level 2 in Table 4.

Table 4 Taguchi Array selector and the Taguchi DOE

Run	Taguchi Array selector						Taguchi DOE					
	A	*B*	*C*	*D*	*E*	*F*	Layer thicknesses (mm)	Infill percentage (%)	Raster angle (°)	Infill speed (mm/s)	Infill pattern	Nozzle temperature (℃)
1	1	1	1	1	1	1	0.2	30	0	30	Rectilinear	200
2	1	1	1	2	2	2	0.2	30	0	70	Concentric	220
3	1	2	2	1	1	2	0.2	90	45	30	Rectilinear	220
4	1	2	2	2	2	1	0.2	90	45	70	Concentric	200
5	2	1	2	1	2	2	0.4	30	45	30	Concentric	220
6	2	1	2	2	1	1	0.4	30	45	70	Rectilinear	200
7	2	2	1	1	2	1	0.4	90	0	30	Concentric	200
8	2	2	1	2	1	2	0.4	90	0	70	Rectilinear	220

4.2.3 Experiment Results

The experiment results include ultimate tensile strength (*UTS*), elastic modulus, mass and Strength-to weight ratio. Fig. 6 shows the Fractures formed on the specimen after the tensile test and experimental results are shown in Table 5.

Fig. 6 Specimens before and after tensile testing

Table 5 The experimental results

	UTS (MPa)	Elastic modulus (GPa)	Mass (g)	Strength - to weight ratio (MPa/g)
1	24.99	1.823	1.38	18.11
2	27.98	1.832	1.41	19.84
3	33.20	2.786	1.62	20.50
4	34.69	3.609	1.71	20.29
5	30.59	2.178	1.49	20.53
6	26.11	2.637	1.51	17.29
7	33.58	3.177	1.72	19.52
8	32.83	3.189	1.69	19.42

5 Analysis and discussion

5.1 Analysis about UTS

To determine the influence of each parameters on the results, main responses analysis will be used in this part, and main effects graphs for means will indicate the higher level of influence on the output. The calculation process will be given take ultimate tensile strength as an example, and the calculation process of other results will be omitted. Response tables for mean effects and mean effects graphs will be supplied for every parameter.

In order to make the following statement clearer, A~F are used to represent each parameter, as shown in Table 4. *Y* in Table 6 refers to the ultimate tensile strength, and there are 8 values of *Y* (*Y*1~*Y*8).

Table 6 Taguchi design total effects of processing parameters on UTS

Parameters	#	1 (Level1)		2 (Level2)	
Layer thicknesses	*A*	$A_1 = (Y_1+Y_2+Y_3+Y_4)/4$ $A_1 = (24.99+27.98+33.20+34.69)/4 = 30.22$	30.22	$A_2 = (Y_5+Y_6+Y_7+Y_8)/4$ $A_2 = (30.56+26.11+33.58+32.83)/4 = 30.78$	30.78
Infill percentage	*B*	$B_1 = (Y_1+Y_2+Y_5+Y_6)/4$ $B_1 = (24.99+27.98+30.59+26.11)/4=27.42$	27.42	$B_2 = (Y_3+Y_4+Y_7+Y_8)/4$ $B_2 = (33.20+34.69+33.58+32.83)/4=33.58$	33.58
Raster angle	*C*	$C_1 = (Y_1+Y_2+Y_7+Y_8)/4$ $C_1 = (24.99+27.98+33.58+32.83)/4=29.85$	29.85	$C_2 = (Y_3+Y_4+Y_5+Y_6)/4$ $C_2 = (33.20+34.59+30.59+26.11)/4=31.15$	31.15
Infill speed	*D*	$D_1 = (Y_1+Y_3+Y_5+Y_7)/4$ $D_1 = (24.99+33.20+30.59+33.58)/4=30.59$	30.59	$D_2 = (Y_2+Y_4+Y_6+Y_8)/4$ $D_2 = (27.98+34.69+26.11+32.83)/4=30.40$	30.40
Infill pattern	*E*	$E_1 = (Y_1+Y_3+Y_6+Y_8)/4$ $E_1 = (24.99+33.20+30.59+32.83)/4=29.28$	29.28	$E_2 = (Y_2+Y_4+Y_5+Y_7)/4$ $E_2 = (27.98+34.69+30.59+33.58)/4=31.71$	31.71
Nozzle temperature	*F*	$F_1 = (Y_1+Y_4+Y_5+Y_8)/4$ $F_1 = (24.99+34.69+30.59+32.83)/4=30.78$	30.78	$F_2 = (Y_2+Y_3+Y_6+Y_7)/4$ $F_2 = (27.98+33.20+26.11+33.58)/4=30.22$	30.22

Then the results can be re-arranging into the classic form of response table for means format, and the relationship between inputs and output can be seen more clearly in rank order, as shown in Table 7.

Table 7 Response table of processing parameters on UTS for mean effects

	A	*B*	*C*	*D*	*E*	*F*
Level1	30.22	27.42	29.85	30.59	29.28	30.78
Level2	30.78	33.58	31.15	30.40	31.71	30.22
|Delta|	0.56	6.16	1.30	0.19	2.43	0.56
%Delta	5	55	11.61	1.70	21.70	5
Rank	4	1	3	6	2	4

The rank reveals the most important parameter on *UTS*, and the highest level of is *B*, infill percentage. The mean effects graphs can be obtained, as shown in Fig. 6, including the trend of effects of parameters on *UTS*. That is with the increase of infill percentage *UTS* increase significantly. Higher layer thickness and raster angle lead to a higher result, but the influence is not obvious. With the increase of nozzle temperature, there is a slight decrease for *UTS*. The result also showed that infill pattern can influence *UTS*, and it might be given more attention in the following study.
After the comparison of the mean effects, an optimum design can obtained for *UTS*, which is: $A_2B_2C_2D_1E_2F_1$. Thus, UTS_{max} can be calculated by equation1and 1, and the theoretical UTS_{max} is 36.11 MPa. Where *T* is the average value of *Y*, and can be calculated by equation 2.

$$UTS_{max} = T + (A_2 - T) + (B_2 - T) + (C_2 - T) + (D_1 - T) + (E_2 - T) + (F_1 - T) \quad (1)$$

$$T = (Y_1 + Y_2 + Y_3 + Y_4 + Y_5 + Y_6 + Y_7 + Y_8)/8 \quad (2)$$

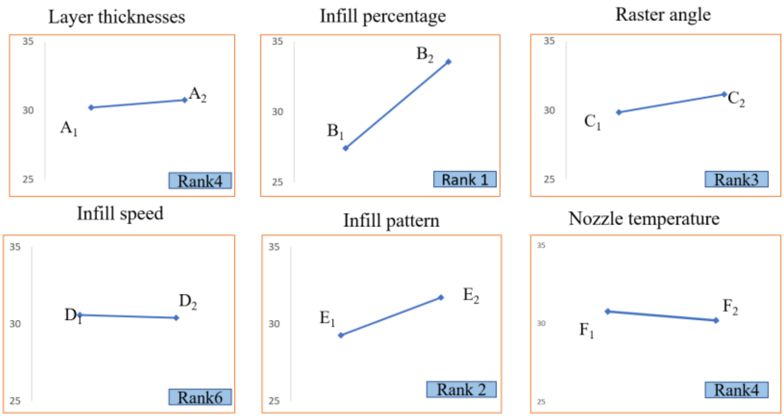


Fig. 6 The mean effects graphs on *UTS*

5.2 Analysis for other properties

Other three properties need to be analysis in the experiment results, elastic modulus, Mass and Strength-to weight ratio. The above described analysis steps can be followed for other experimental results (elastic modulus, mass and strength-to weight ratio), and the results are shown in 5.2.1-5.2.3.

5.2.1 Influence on elastic modulus

Table 8 shows the Response table of processing parameters on elastic modulus for effects. Then the highest level of influence on the modules is *B*, infill percentage, and the lowest influence is infill pattern. Fig. 7 shows the trend of effects of parameters on elastic modulus, and the optimum design input parameters for elastic modulus is: $A_2B_2C_2D_2E_2F_1$.

Table 8 Response table of processing parameters on elastic modulus for effects

	A	*B*	*C*	*D*	*E*	*F*
Level1	2.513	2.118	2.505	2.491	2.609	2.7
Level2	2.795	3.19	2.802	2.817	2.699	2.608
|Delta|	0.282	1.072	0.297	0.326	0.09	0.092
%Delta	13.06	49.65	13.76	15.106	4.17	4.26
Rank	4	1	3	2	6	5

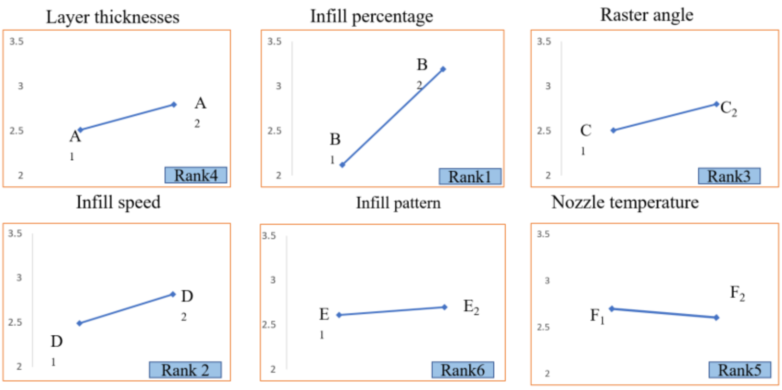


Fig. 7 The mean effects graphs on elastic modulus

5.2.2 Influence on mass

Table 9 shows the Response table of processing parameters on mass for mean effects. As expected, the highest level of influence on mass is *B*, infill percentage, and its %Delta (57.66%) is much higher than others. The trend of all effects of parameters on mass also can be obtained from the Fig. 8.

Table 9 Response table of processing parameters on mass

	A	*B*	*C*	*D*	*E*	*F*
Level1	1.53	1.448	1.55	1.553	1.55	1.573
Level2	1.603	1.685	1.583	1.58	1.583	1.565
|Delta|	0.073	0.237	0.033	0.027	0.033	0.008
%Delta	17.76	57.66	8.03	6.57	8.03	1.95
Rank	2	1	3	5	3	6

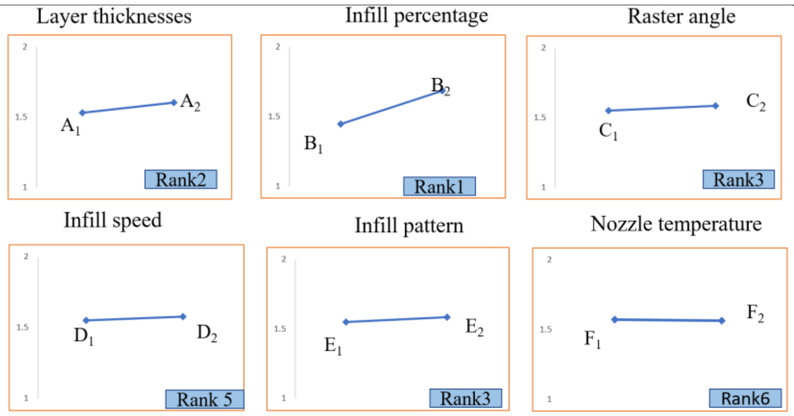


Fig. 8 The mean effects graphs on mass

5.2.3 Influence on Strength-to weight ratio

Table10 shows the Response table of processing parameters on strength-to weight ratio for mean effects. The highest level of influence on the strength-to weight ratio is *E*, infill pattern. The rank 2 is infill percentage, which determines mass directly.

Table 10 Response table of processing parameters on Strength-to weight ratio

	A	*B*	*C*	*D*	*E*	*F*
Level1	19.69	18.94	19.22	19.67	18.83	19.59
Level2	19.19	19.93	19.65	19.21	20.05	19.29
|Delta|	0.5	0.99	0.43	0.46	1.22	0.3
%Delta	12.82	25.38	11.03	11.79	31.28	7.69
Rank	3	2	5	4	1	6

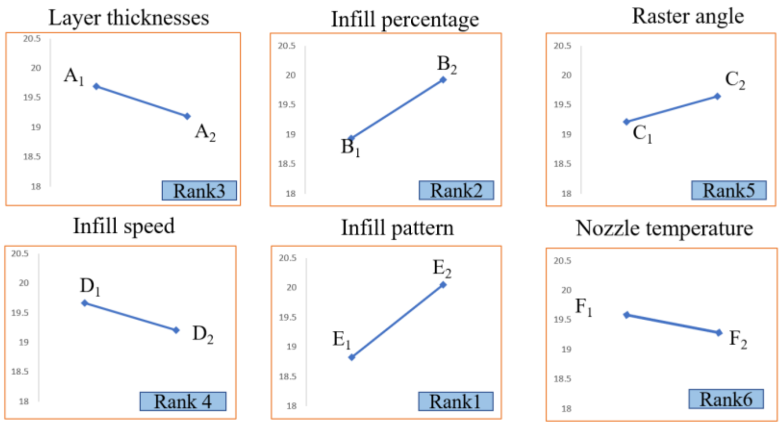


Fig. 10 The mean effects graphs on Strength-to weight ratio

6 Conclusion

To judge the influence of various parameters in FDM, six main parameters were studied by application of Taguchi method, and four results were compared. The main conclusions are as follows.

1. Infill percentage is the most important parameter among all studied parameters. It is related to higher *UTS*, elastic modulus, mass and strength-to weight ratio. The rankings are 1, 1, 3, 1 and 2 separately. It is also the determining factor for the mass.
2. Infill pattern is also an important parameter for FDM process. It can influence the results except the elastic modulus significantly.
3. Layer thickness (ranking 4, 4, 4, 2 and 3) and raster angle (ranking 5, 3, 2, 3 and 5) are both important parameters. From the analysis of the FDM process, the layer thickness can be quantitatively analyzed, but the control of the raster angle is not easy to realize, because when selecting different infill patterns, printing angle and direction may change.
4. Infill speed has not obvious impact on the result, except the elastic modulus (Rank 2) and its %Delta is close to layer thickness and raster angle.
5. For this study, nozzle temperature has the minimal impact on material properties (Raining: 4, 5, 5, 6, 6), so it may be treated as a constant value in following studies.

Infill percentage, infill pattern and layer thickness will be selected in the future study, and more levels will be considered to obtain more accurate results. Infill pattern analysis can given more attention because it not only determines the printing path, but also have a great influence on the internal structure of the printing parts. It also shows that Taguchi method application can be used in experiments with multi factors and multi levels and obtain satisfactory results.

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