Title:
Investigation of tensile attributes of 3D printed parts using the Taguchi method

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Introduction:

3D printing or additive manufacturing (AM) technologies provide flexible and efficient solutions in processing complex geometric structures of product. AM deposits the material layer upon layer to form the geometric shape of a product [5]. Extensive research activities have been conducted to enhance the quality of printed products, particularly their mechanical characteristics and precision in dimensions [6]. Although different solutions have been proposed to select printing parameters to improve the process efficiency and product quality [4], there is a lack of research on product tensile properties affected by printing parameters.

This research investigates effects of 3D printing parameters on tensile attributes of the product. The tensile characteristics of polylactic acid (PLA) specimens are studied using the Taguchi design of experiments approach. The Taguchi L18 Orthogonal array is formed based on 2 and 3 mixed levels of factors. Processing factor effects on response variables of the ultimate tensile strength and tensile modulus are studied to find the optimal set of printing parameters.

Main idea:
Taguchi design of experiment (DOE) is employed to assess the combination of parameters of the fused deposition modeling (FDM) method including the infill pattern, infill density, layer height, printing speed, printing temperature and wall thickness. The research is conducted through the material and parameter selection, experimental design, sample design and 3D printing, tensile testing and experimental result analyzing through the Taguchi S/N ratio analysis as shown in Fig.1.

Experimental Design
Taguchi Orthogonal Array (OA) design is a variant of the standard fractional factorial design approach for a set of combinations of various factors in different levels. All levels of each factor are equally considered by using balanced Taguchi orthogonal arrays.

The mixed-elements (levels) array of orthogonal arrays is one of most widely used array types in Taguchi method. A mixed-element orthogonal array is a matrix with $m + n$ columns and N rows, where initial m columns contain s items and subsequent n columns contain t elements. This matrix is denoted by symbol $OA_N(S^m \times t^n)$. A typical method for creating a mixed-element array is $OA_N(2^1 \times s^m)$, where s is a prime integer (like 3 or 5) or a power of a prime number and $N = 2s^2$. $OA_N(2^1 \times s^m)$ represents a $N/(2^1 \times s^m) = (1/s)^{m-2}$ fractional factorial plan. Therefore, $OA_{18}(2^1 x 3^5)$ can be considered as a part of a complete $(2^1 x 3^5)$ factorial design, that is $(1/3)^{5-2} = (1/3)^3$ [2].

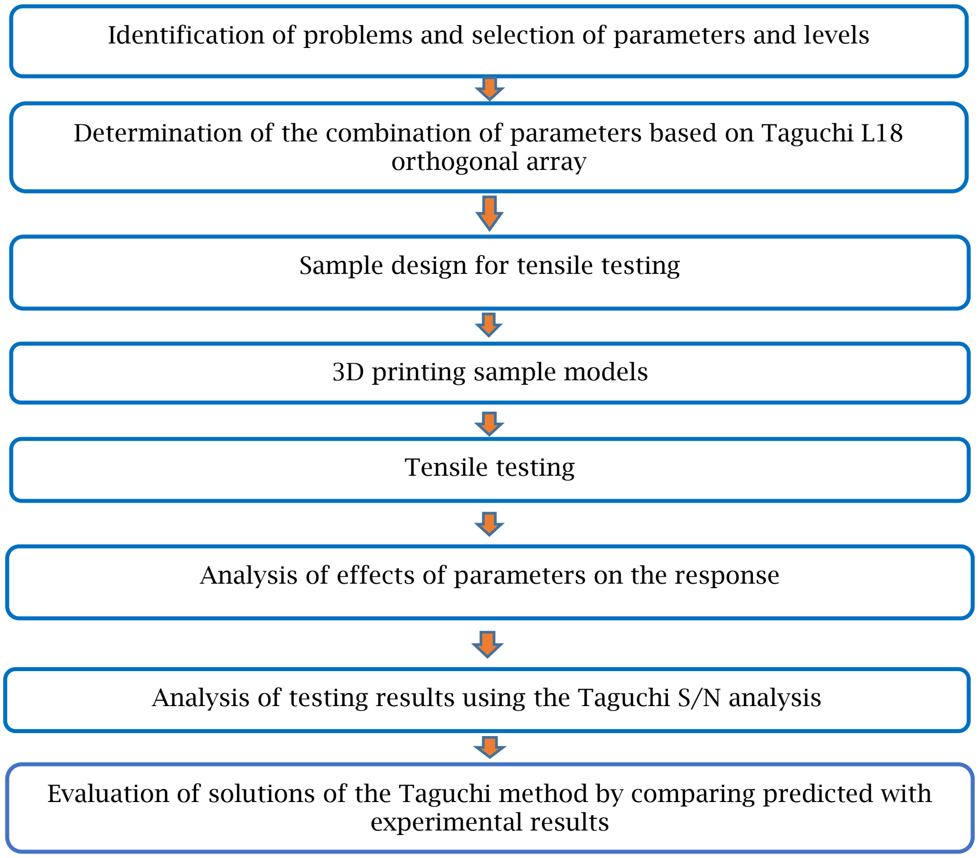

Fig. 1: Flowchart of the method.

Tab. 1 lists factors and levels of experimental design in this research. There are two levels (1, 2) for the wall thickness and three levels (1, 2, 3) for others five factors, where levels 1, 2 and 3 represent low, medium and high levels of related factors. Therefore, L18 orthogonal array $OA_N\,(S^m\ x\ t^n)$ is formed based on factors and levels. The orthogonal design is written as $OA_{18}\,(2^1\ x\ 3^5)$, where t=2, n=1, s=3 and m=5. Number of columns for matrix = $m + n$ = 5+1 =6. The number of rows for matrix $N = 2s^2$ =18.

Factor	**Level 1**	**Level 2**	**Level 3**
Wall thickness (mm)	0.8	1.0	
Layer height (mm)	0.1	0.2	0.3
Infill density (%)	25	50	75
Infill pattern	Cubic	Triangular	Cross
Print speed (mm/s)	50	75	100
Printing temperature (℃)	200	210	220

Tab. 1: Experimental parameters and levels.

Taguchi Method

An orthogonal array is used based on the Taguchi method to develop the experiment design. Experiment factors and associated levels are first chosen to form an orthogonal array. The approach uses two factors for considerations: control factors and noise factors. The Taguchi loss function is employed to assess performance features. It provides a measure of robustness by limiting effects of noise components for control factors to reduce variability in the process [3]. The signal to noise ratio decides the impact of the response to the target value in various noise environments.

Case Study
According to ASTM D638 type 1 standard dimensions, a tensile specimen is designed as shown in Fig 2. The specimen is utilized to search relationships of FDM control factors for the printing part quality.

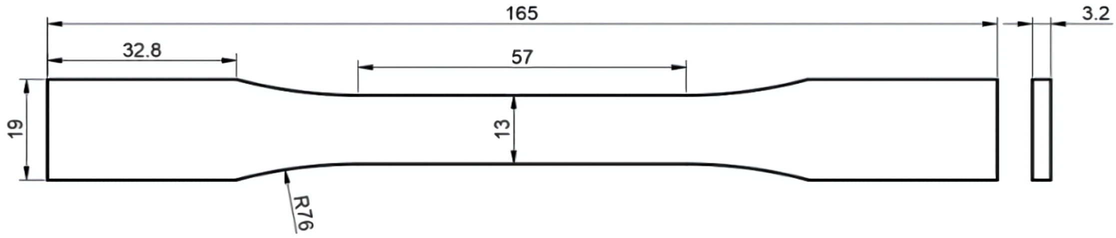

Fig. 2: Tensile specimen (Dimensions are in mm).

Data are statistically analyzed based on the S/N ratio response to increase the tensile strength of 3D printed parts. The bigger, the better mode is used for S/N ratio of the printed parts as shown in Tab. 2, where n represents the number of experiments performed, and Y refers the measured value.

S/N ratio	Experimental objective	Equation for S/N ratio
The bigger, the better	Maximization the response	$S/N = -10 * \log(\Sigma(1/Y^2)/n)$

Tab. 2: Signal to noise (S/N) ratio [1].

Impacts of processing factors on the response variables are assessed using the Taguchi L18 orthogonal array. For each combination of control parameters and levels, experiments are conducted. Tab. 3. Lists the L18 orthogonal array design along with the experimental result from tensile test data.

Sample	Wall thickness (mm)	Layer height (mm)	Infill density (%)	Infill pattern	Print speed (mm/s)	Printing temp (°C)	Ultimate tensile strength (UTS) MPa	Tensile modulus (MPa)
1	0.8	0.1	25	Cubic	50	200	16.50	501.53
2	0.8	0.1	50	Triangular	75	210	18.50	615.63
3	0.8	0.1	75	Cross	100	220	15.90	555.83
4	0.8	0.2	25	Cubic	75	210	22.15	670.56
5	0.8	0.2	50	Triangular	100	220	24.43	719.33
6	0.8	0.2	75	Cross	50	200	18.90	628.62
7	0.8	0.3	25	Triangular	50	220	27.40	512.74
8	0.8	0.3	50	Cross	75	2007	25.52	782.53
9	0.8	0.3	75	Cubic	100	210	30.20	829.93
10	1	0.1	25	Cross	100	210	14.90	438.39
11	1	0.1	50	Cubic	50	220	21.60	633.09

12	1	0.1	75	Triangular	75	200	20.55	661.57
13	1	0.2	25	Triangular	100	200	21.13	585.52
14	1	0.2	50	Cross	50	210	19.70	612.63
15	1	0.2	75	Cubic	75	220	31.12	830.65
16	1	0.3	25	Cross	75	220	29.60	787.32
17	1	0.3	50	Cubic	100	200	25.40	710.39
18	1	0.3	75	Triangular	50	210	32.90	920.67

Tab. 3: L18 orthogonal array and tensile experimental data.

Experiment

Each FDM-3D printed PLA specimen is examined using a quasi-static tensile testing device with 1 mm/min loading rate at the room temperature for its mechanical characteristics including the ultimate tensile strength and tensile modulus. Experimental results like as UTS (ultimate tensile strength) and tensile modulus of the mechanical properties are listed in Tab. 3.

Analysis of mechanical characteristics of specimens

Main effects plots of the ultimate tensile strength (UTS) and tensile modulus for specimens are shown in Figs. 3(a) and 3(b) to determine the optimal set of parameters for the greatest tensile strength. The graph shows that if we increase the wall thickness, layer height, infill density and printing temperature, and reduce printing speed using a cubic infill pattern, the UTS can be improved.

It can be concluded that the combination of parameters with layer height (B) of 0.3 mm, infill pattern (D) of triangular, printing temperature (F) at 220℃, printing speed (E) at 75 mm/s, infill density (C) of 50% and wall thickness (A) at 1 mm, or B3D1F3E2C3A2, gives the maximum tensile strength.

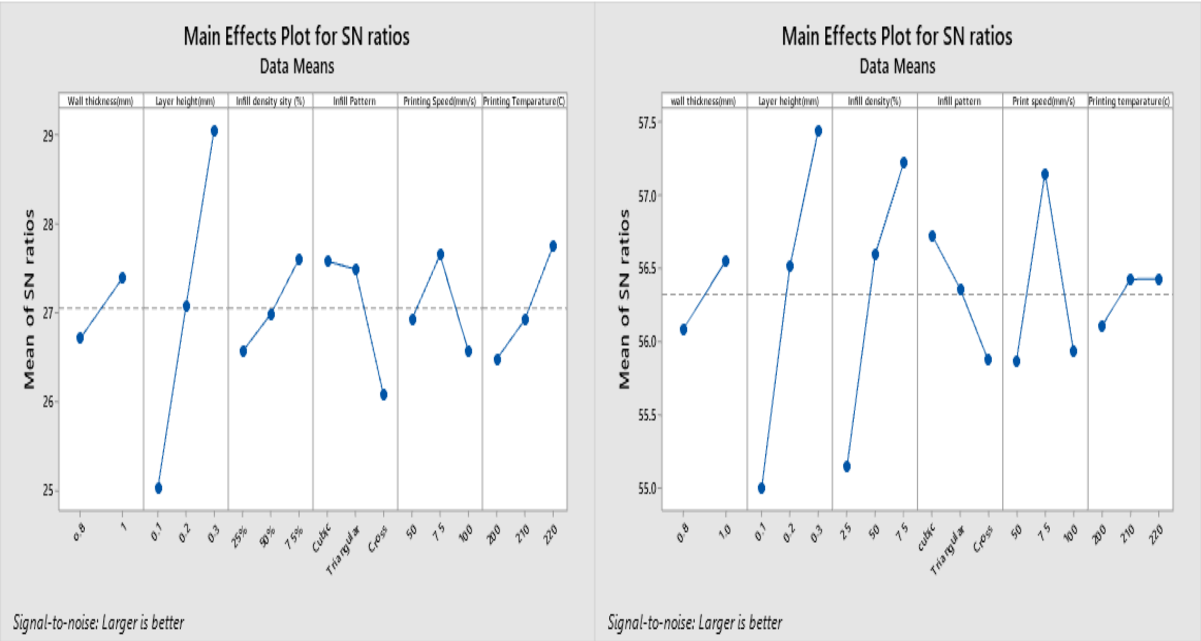

Fig. 3: S/N ratio effect plots for (a) ultimate tensile strength (UTS) (b) tensile modulus.

Similarly, based on the S/N ratio in Fig. 3(b), it can be concluded that the combination of B3C3E2D1A2F2, i.e., layer height (B) at 0.3, infill density(C) of 75%, printing speed (E) of 75mm/s, infill pattern (D) for cubic, wall thickness (A) of 1 mm and printing temperature (F) of 210℃, gives the optimal tensile modulus for the PLA material.

Comparison of experimental data and expected results

The proposed method is evaluated by comparing the DOE method and lab testing solution for the prediction accuracy of the mechanical characteristics of sample parts as shown in Tab. 4. The most disparity between the experimental and Taguchi method solutions is 9.24%. Therefore, it is concluded that the Taguchi approach can accurately predict the mechanical characteristics for 3D printed parts.

Mechanical characteristics	**Experimental result**	**Predicted result**	**Difference (%)**
Ultimate tensile strength	32.90	35.94	9.24
Tensile modulus	920.67	996.07	8.12

Tab. 4: Comparison of the experiment and Taguchi method results.

Conclusions:

The Taguchi DOE approach is used in this research to determine the ideal FDM process parameters and simultaneously examine the impact of various processing variables on the tensile characteristics of parts produced by 3D printing. This research uses the FDM technology to build 18 samples by different parameter combinations of the wall thickness, layer height, infill density, infill pattern, printing speed and printing temperature in the 3D printing process. The greater, the better criterion is used to examine S/N ratio diagrams of mechanical qualities of tested samples. Based on the Taguchi S/N ratio analysis, the ideal condition for the maximum ultimate tensile strength of the printed parts is identified. Although the modulus of elasticity shows slight variations in the parameter optimization, the evaluation of the Taguchi design shows its capability in predicting mechanical characteristics of 3D printed products. Our following work will examine compression attributes of 3D printed parts.

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