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Improving the tensile properties of 3D printed PLA by optimizing the processing parameter

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Abstract

Low-cost desktop 3D printing is now dominated by free and open source self-replicating rapid prototype. However, optimum printing process parameters have not been provided by the manufacturer, since there are several process parameters that need to be optimized to obtain acceptable dimension error and strength properties. This paper aims to present the optimum process parameters for the 3D printing process of Polylactic Acid (PLA) part using Taguchi Method. A specimen standard of ASTM D638 Type IV made of biodegradable polymer, PLA, has been used as a tensile strength test to represent printed part quality. Four printing process parameters: temperatures, extrusion width, infill density and infill pattern have been optimized using Taguchi Methods. Test was carried out to find the highest tensile strength based on the optimum parameter setting and validated them with experiment. The result shows that the tensile strength response was predominantly influenced by infill density followed by nozzle temperature, infill pattern and extrusion width. The optimum level setting was obtained at 75% of infill density (C3), 215oC of nozzle temperature (A3), honeycomb infill (D1) and 0.3 mm of extrusion width (B1).At optimized parameters the tensile strength PLA parts significantly was found of 30.52 MPa at a confidence interval of 95%.

***Keywords**: 3D printing; accuracy; PLA; taguchi; tensile strength*

1. INTRODUCTION

The manufacturing industry with additive manufacturing (AM) or 3D printing technology is widely used in products with complex shapes that cannot be easily fabricated by conventional fabrication technologies such as airplanes, bioengineering, medical devices, medical implants and automotive products. The types of AM available on the market include fused deposition modeling (FDM), direct metal deposition (DMD), selective laser sintering (SLS), inkjet modeling (IJM) and stereo-lithography (SLA) (1).

Today AM application process has reached a simpler and easier to use stage with a more compact machine (kit). The widely used AM kit technique is rapid prototyping based on FDM which has accounted for nearly half of the number of machines on the market (2). FDM is a machine controlled by computer language to drive extruder nozzles extruding a filamentary polymer material (3). Several choices of polymer filament materials include acrylonitrile butadiene styrene (ABS), polycarbonate (PC), polystyrene, nylon, polylactic acid (PLA), and polyurethane. PLA is one of the most common materials used in 3D printing products with its superiority as a biodegradable material. The FDM manufacturing process can be applied in many applications, but optimized process parameters play important role to guarantee quality of products, reduction time and cost (2).

The challenge of 3D printing technology is the possibility of making a prototype to redesign a product quickly, strongly and cheaply (4). There is a lot of research has been carried out regarding the performance of FDM technology by manipulating the process parameters to evaluate the impact on the mechanical properties. The parameters involve in the studies include nozzle temperature, layer thickness, percentage infill, raster orientation and extrusion width (5, 6, 7, 8). The Taguchi's design matrix, signal to noise ratio (S/N) and analysis of variance (ANOVA) were commonly utilized as one method to optimize parameters on 3D printing products. However, at present, there is not so much study on the performance for low-cost 3D printer regarding the mechanical properties. Recently, research on evaluation on the mechanical properties using MakerBot Replicator 2 Desktop 3D printer has been done by manipulating layer thickness, percent infill and print orientation (9). Tymark et al. (10) conducted a study on the tensile strength and elastic modulus of printed products using normal environmental conditions for general users of open-source 3D printers. From these results indicate that the parts that are removed or subtracted during the printing process by RepRap 3D printers have cheaper production process costs. Vicente et al. (11) conducted a study on the influence of infill parameters on tensile strength in 3D printing products. The results showed that at the same density, the honeycomb pattern (honeycomb) had better tensile strength, although the difference between the pattern parameters was less than 5%. This difference can be due to the variation in the number of extruded plastics for each pattern. In such cases it may explain the cause of the difference in the modulus of elasticity. Sukindar et al (12) conducted a study using open source 3D printers developed by Repetier-Host software with PLA materials and three-level variations for three parameters including layer thickness, shell thickness, and print speed. Results from ANOVA showed that shell thickness gave significant result in influencing tensile strength test result. This proves that by increasing the thickness of the shell from 0.4 mm to 1.2 mm will increase the tensile strength of the specimen.

This research focuses on the influence of parameter process on mechanical properties of the PLA products being fabricated by using Prusa I3 3D printer using Repetier-Host software. This study manipulates four parameters including temperature nozzle, extrusion width, infill density and infill pattern. All of these parameters are evaluated statistically so that the effect of each process parameter and optimum level combination can be understood, then evaluate the combination of optimum level parameter using a confirmation experiment.

2. METHODS

A new open-source 3D Printer, Pursa-I3**,** consisting of four stepper motors with three axes, a single nozzle with diameter of 0.4 mm and a pair of the lead screw for all the three axes movement has been used as shown in Figure 1. The maximum building parts for this machine is 200 mm (length) x 200 mm (width) x 180 mm (height).

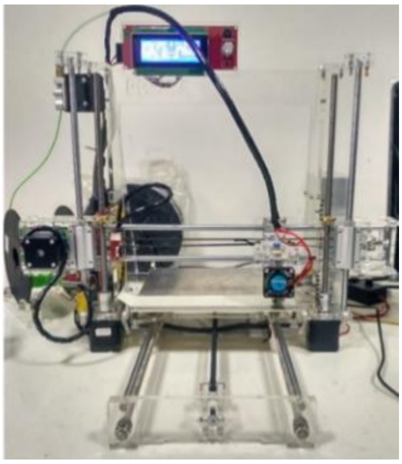


Figure 1. Pursa-I3 being used in the research

The tensile test specimen was drawn by using CAD software in accordance to ASTM D-638 type I (Standard Test Method for Tensile Properties of Plastics (13) as shown in Figure 2 (a) with 4 mm thickness. Afterwards, the drawing was saved in the .OBJ format. The CAD file need to be processed by software called slicers, which are used to convert the model into a series of layers and generate G-code files containing commands that are tailored to the type of 3D printer used. In addition, the slicing process will produce important information such as printing time, filaments required, total number of lines and layers.

The tensile test sample was printed with 1.75 mm diameter of Poly lactic acid (PLA) filament in green colour. All the parameters have been controlled using Repetier-Host Software (Hot-World GmbH & Co. KG, Germany). Design of experiment (DOE) has been performed using Minitab 16.0 (Minitab, USA) software. Taguchi's method has been performed in 3^4 and a total of nine samples have been printed and the parameters involve shown in Table 1. The parameters involve in this study are nozzle temperature (°C), extrusion width (mm), fill density (%) and fill pattern as well which considered as variable parameters. The value of each level of process parameters used in this study is derived from PLA data sheet material, pre-experiments and from previous research literature studies. The process and level parameters are shown in Table 1.

Table 1. Processing parameters and their level

Parameters	**Level**		
	1	**2**	**3**
Nozzle temperature: A (°C)	205	210	215
Extrusion width: B (mm)	0.3	0.35	0.4
Infill density: C (%)	25	50	75
Infill pattern:D	Honeycomb (1)	Grid (2)	Triangles (3)

In addition to the process parameters studied, the other parameter values is determined by the default settings of the Slic3r program and based on the pre-experimental results. The process parameters set by default are shown in Table 2.

Table 2. Default processing parameters

Parameters	**Unit**	**Values**
Layer height	Mm	0.2
Perimeters	-	3
Solid Layer (top & botom)	-	3
Top/botom fill pattern	-	Rectiliniear
Raster angle	deg	45
Print angle	deg	0
Feed rate	mm/m	100
Flow rate	%	125

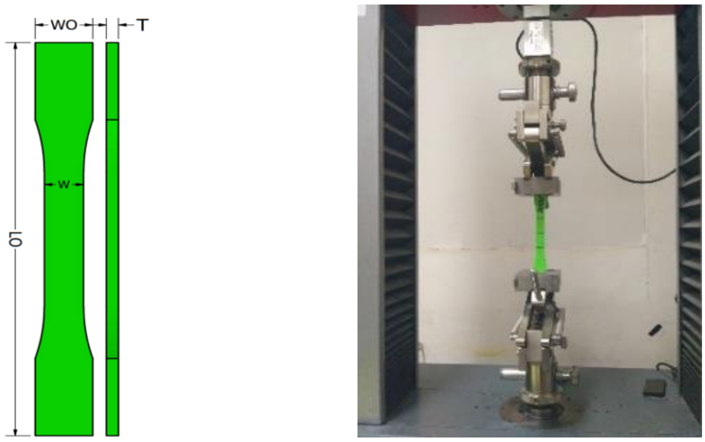
The measured dimensions are length overalls (LO), width overalls (WO), width of narrow (W), and thickness (T) as shown in Figure 2.a. The Universal Testing Machine (UTM) type Zwick roell Z020 was used for tensile testing with loading speed of 1 mm / min. The tensile testing process is shown in Figure 2.b.

Table 3. Factorial Design L9 (34) and the results

Runs	Parameters level				Mass (gr)	Time(mnt)	Dimension (mm)				Tensile (MPa)
	A (oC)	B (mm)	C (%)	D	m	t	Lo	Wo	w	T	TS
1	205	0.3	25	1	6.75	79.7	165.41	19.13	13.04	3.96	19.91
2	205	0.35	50	2	8.10	77.30	165.17	19.00	13.12	3.86	20.55
3	205	0.4	75	3	9.18	79.90	165.31	19.06	13.14	3.98	21.76
4	210	0.3	50	3	8.78	91.85	165.19	19.14	13.03	3.95	22.61
5	210	0.35	75	1	10.56	91.82	165.25	19.06	13.06	3.89	33.86
6	210	0.4	25	2	6.71	58.10	165.30	19.04	13.03	4.05	18.17

Table 3. Factorial Design L9 (34) and the results (continued)

Runs	Parameters level				Mass (gr)	Time(mnt)	Dimension (mm)				Tensile (MPa)
	A (oC)	B (mm)	C (%)	D	m	t	Lo	Wo	w	T	TS
7	215	0.3	75	2	11.08	104.75	165.13	19.06	13.03	3.82	30.56
8	215	0.35	25	3	7.00	66.67	165.09	18.83	12.99	3.87	21.26
9	215	0.4	50	1	8.54	71.70	164.82	18.85	12.96	3.92	25.14



(a) (b)

Figure 2. (a) Dimension measurement, (b) Tensile testing

Based on Taguchi's Orthogonal Array (OA) design, L9 (3^4) mixed array have been selected and presented in Table 3.

The optimum parameter process was determined using S/N ratio and Anova analysis. Once the optimum parameter was obtained, it's average of tensile strength (μ_{pred}) is predicted using the equation (1) with confidence interval (CI) being calculated using equation (2), and the confirmation experiment also conducted in order to evaluate the result.

$$\mu_{pred} = \bar{y} + (\bar{A}_3 - \bar{y}) + (\bar{B}_2 - \bar{y}) + (\bar{C}_3 - \bar{y}) \quad (1)$$

$$CI = \pm\sqrt{F_{\alpha,df1,df2} \times Mse \times \left(\frac{1}{n_{eff}}\right)} \quad (2)$$

$$\mu_{pred} - CI \leq \mu_{predi} \geq \mu_{pred} + CI \quad (3)$$

3. Result and Discussion

In this study, we obtained 27 ASTM D638 type I specimens from 9 experiments with 3 replicates for each run printed using 3D printers (Figure 3.a). Furthermore, data collection of product dimensions and tensile testing were conducted (Table 3). It can be seen that the dimensions of the specimen being fabricated are compliance with the standard. Whilst the printing result is shown in Figure 3.a., the fractured specimen being tensile tested is presented in Figure 3.b.

Figure 3. (a) Printed specimens (b) Tested specimens

Load-displacement graphs from the tensile test behavior are showed by Figure 4. The graphs demonstrate the typical graph for plastic material showing two main regions; elastic and plastic region. However, there is small plastic region due to its bond strength of each layer. From the test obtained the largest and the smallest F_{max} value were found in 5th run -R3 of 187.99 kgf and 6th run -R2 of 86.80 kgf respectively (Figure 4a and b). The tensile strength of the specimen was found lower than that of its properties (14) since the strength is mostly determined by its bonding strength between the extrudent.

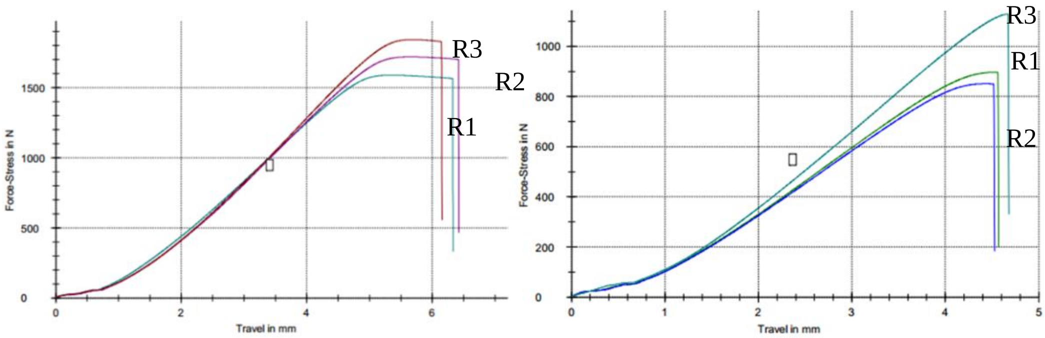


Figure 4. The relation of Load displacement-force of : (a) 5th runs , (b) 6th runs.

Three replications of R1, R2, and R3 from each experiment were used to calculate the signal to noise ratio (S/N Ratio). Table 4 depicts the mean S/N ratio for each level of the 3D printing process parameters.

Table 4. Response Table for Signal to Noise Ration

Level	Nozzle temperature	Extrusion width	Infill Density	Infill Pattern
1	26.12	27.79	25.79	28.11
2	27.52	27.75	27.06	26.92
3	28.03	26.43	28.82	26.64
Delta	1.91	1.32	3.03	1.47
Rank	2	4	1	3

The larger S/N Ratio related to the better quality characteristics. From S/N Ratio analysis, tensile strength response is predominantly influenced by infill density, nozzle temperature, infill pattern, and extrusion width subsequently. The infill density at level 3 shows the highest S/N Ratio value (28.82) for tensile strength responses followed by nozzle temperature at level 3 (28.03), infill pattern at level 1 (28.11) and extrusion width at level 1 (27.79). Based on S/N ratio values the optimum level setting was obtained at 75% of infill density (C3), 215°C of nozzle temperature (A3), honeycomb infill (D1) and 0.3 mm of extrusion width (B1).

The analysis of variance aims to determine the significance of process parameters on tensile strength of the specimens being fabricated. It provides a strong representation to depict the level of significance of the factor evaluated and how far the process parameter influences the response. The results from ANOVA are presented in Table 5.

Table 5 Analysis of Variance

Source	Sq	Df	Mq	F-*ratio*	P	ρ%
Nozzle Temperature	125.66	2	62.83	8.69	0.002	14.17
Extrusion width	61.18	2	30.59	4.23	0.031	5.95
Infill Density	373.78	2	186.89	25.86	0.000	45.78
Infill Pattern	94.15	2	47.08	6.51	0.007	10.15
e	130.07	18	7.23	1.00	-	23.94
St	784.85	26	30.19	-	-	100.00
Mean	15238.22	2	-	-	-	-
ST	16023.07	27	-	-	-	-

Statically, F test is applied to understand which design parameters has a significant influence on the quality characteristic. Generally, a significant effect on the quality characteristic of the change the design parameter is taken into account when the value of F>4. In this research, infill density is a highly significant factor and plays a major role in affecting the tensile strength of the 3D printing product.

Based on the results of S/N Ratio and ANOVA analysis, they show the same result for the rank order of the most influential process parameters. The infill density parameter shows a major role in influencing the tensile strength. The increase of infill density increases the density of the material in which more filament to bear the load due to higher mass filament extruded. Yet it affects the period of 3D printing process to produce a stronger product. The nozzle temperature also has a significant influence on bound strength because it regulates the initial temperature of the material to be deposited. So it has a direct effect on the temperature of the extrusion interface that regulates the movement of molecules in polymers (15). Bound strength can directly affect the strength of the layer-by-layer product. In the printing process, there is an adhesion process which melted extrudent will attach to the solid extrudent that has been extruded earlier. The bond formation in the FDM process is influenced by the thermal energy of the semi-liquid material. The quality of the bonds formed between each filament extrusion depends on the growth of the neck formed between the adjacent filament extrusion and the molecular randomness between the extrusion surfaces (3). The increase of extrusion temperatures is strengthen the bonds between extrudent and minimize the occurrence of gaps between layers. Thus, for PLA materials, a nozzle temperature of 215 ° C can be used as optimum process parameters because it can produce adhesion to adjacent extrusion to be better resulting in a stronger product. The cause of the small contribution value of nozzle temperature (ρ: 14.17%) compared with the contribution of infill density (ρ: 48,78%) due to infill density is very influential on mass of product.

Larger extrusion width has more mass being extruded resulting in longer time for cooling process. Generally, a larger extrusion tends to produce larger contact areas between layers leading to an increase of bond strength (15). But in this study shows different results. Table 3 shows that the 7th experiment (extrusion width of 0.3 mm and tensile strength 30.57 MPa) is stronger than the 3th (extrusion width of 0.4 mm and tensile strength 21.76 MPa). It could be suggested that in the slicing process using the Slic3r software, the arrangement of extrusion width of 0.3 mm produces a denser surface and smaller gaps than 0.4 mm as illustrated by Figure 5 of the slicing result.

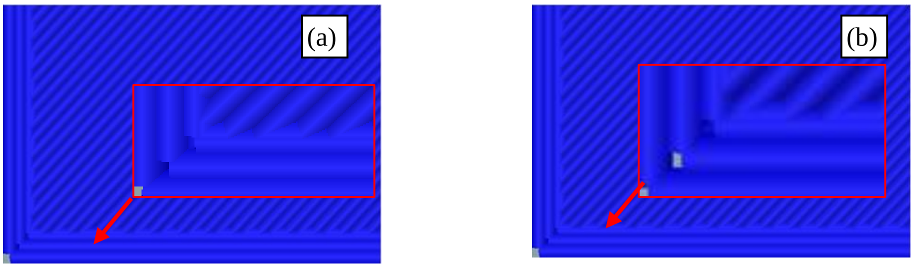


Figure 5. Gap result from slicing process with extrusion width of (a) 0.3 mm, (b) 0.4 mm

A honeycomb infill pattern has more bonding structure and has a slightly larger density product mass than the others. During the fabrication process, the honeycomb structure expressed of hexagons is carried by forming each hexagon one by one on each layer. On the other hand, to produce the grid (triangle) and triangle (triangle) structures, at least two processes are required on each layer to form the structures. It will generate a cooled extrudent at a side before it is binding to the other side that leads to a decrease in bonding strength. Therefore, the bonds between the structures being formed of the honeycomb infill pattern are stronger than the others.

The experimental confirmation of tensile strength based on optimum process parameters i.e.: 75% of infill density (C3), 215°C of nozzle temperature (A3), honeycomb infill (D1) and 0.3 mm of extrusion width (B1) with replication 3 times were carried out. The tensile strength was obtained of 30.52 ±0.46MPa. This result indicates that the tensile strength meets the 95% confidence level where the result is within the confidence interval (30.32 MPa ≤ 34.63 MPa ≤ 38.95MPa).

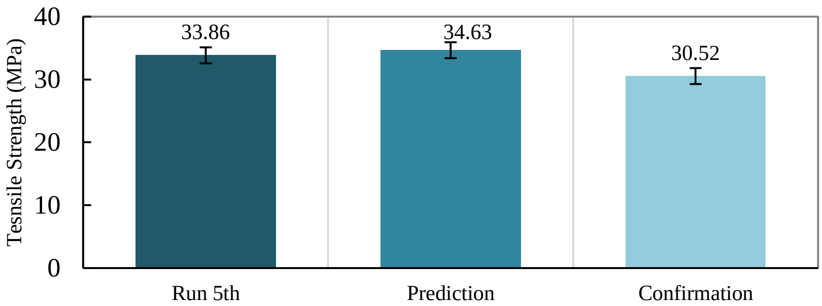


Figure 6. The comparison of the tensile strength

Figure 6 shows the tensile strength of the 5th experiment approaching the average predictive value, while the tensile strength of the confirmation experiment is lower than those of the 5th and the prediction. Yet, its deviation standard is smaller than the previous nine experiments as depicted in Figure 7 demonstrating more homogeneous product.

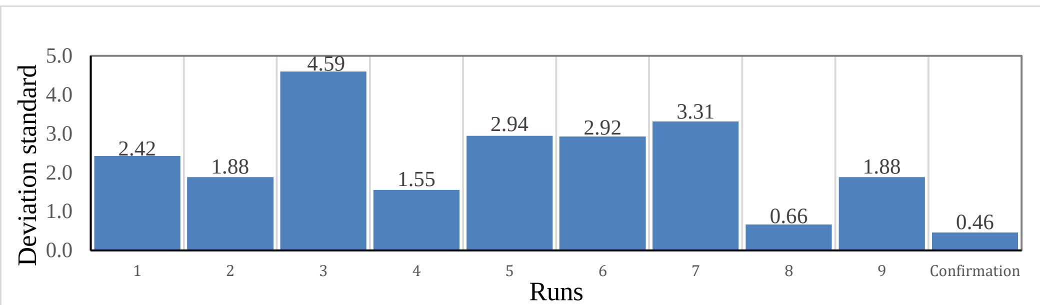


Figure 7. The values of the deviation standard

Based on the standard deviation value, it indicates that the confirmation experiment has a higher consistency level than the others. In this case the optimization of the parameters generated by using Taguchi method that able to improve the quality especially on homogeneity of tensile strength.

4. Conclusion

It can be concluded that the tensile strength response is predominantly influenced by infill density followed by nozzle temperature, infill pattern and extrusion width. The optimum levels are attained at 75% of infill density (C3), 215ºC of nozzle temperature (A3), honeycomb infill (D1) and 0.3 mm of extrusion width (B1). At optimized parameters the tensile strength PLA parts was found of 30.52 MPa at a confidence interval of 95%.

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