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The Effect of Nozzle Temperature, Layer Height, and Infill Pattern on Dimensional Accuracy and Flexural Strength of 3D Printed Cu-PLA Filaments

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ABSTRACT

This study aims to find the optimal parameters to produce good dimensional accuracy and maximum bending strength in the FDM 3D printing using a Cu-PLA filament. The parameters used in this research are nozzle temperature, layer height, and infill pattern with 2 levels for each parameter. The experimental design used the Taguchi L4 method (2^3). The specimens were printed according to the ASTM D790 standard using the REXYZ A1 3D printer machine. From the results of the calculation of the average S/N ratio, the best dimensional accuracy when using variations of nozzle temperature 220 ºC, layer height 0.3 mm, and infill pattern lines. While the maximum bending strength when using a nozzle temperature variation of 240 ºC, layer height of 0.4 mm, and the octet infill pattern. Each factor contributes to dimension accuracy in per cent as accuracy is 9.16 %, nozzle temperature, 4.01 % layer height, and 19.56 % infill pattern. In other words, all factors did not have a significant contribution to the accuracy. Meanwhile, the contribution of each parameter to the bending strength is nozzle temperature 57.66 %, layer height 15.22 %, and infill pattern 0.44 %.

1. INTRODUCTION

Fused Deposition Modeling (FDM) is a solid-based rapid prototyping method developed in the 1980s and commercialized by Stratasys Inc. [1]. The working principle of FDM is the process of heating solid-shaped thermoplastics into semi-solids using a heated nozzle, the material is pushed into the nozzle using a stepper motor, then the semi-solid material is removed through the nozzle layer by layer on the work table [2]. This technology is also known as additive manufacturing, or more well known as 3D printing. 3D printing is a breakthrough in the world of technology. The emergence of 3D printing technology also affects several industrial fields, especially from an economic perspective, the sense that making a prototype does not need to be expensive or has a complicated production process. The application of rapid prototyping on mechanical components with techniques and small production quantities can produce prototypes quickly

[3].

3D printing results are influenced by several factors, including coating thickness, nozzle temperature, fill density, bed temperature, nozzle movement speed, infill pattern, and printing orientation using materials made of Polylactic Acid (PLA), and Acrylonitrile Butadiene Styrene (ABS) [4]. In its development, raw materials are available in the form of filaments with a mixture of metals and Polylactic Acid (PLA). One example of a filament made from plastic and metal is the copper-PLA filament. Research on the use of Copper-PLA filaments was carried out [5] by printing bending test specimens and varying the infill pattern on the specimen and showing the greatest value of bending strength in the concentric infill pattern. They used two types of filament composition: 80% Cu - 20% PLA and 20% Cu - 80% PLA. Another study conducted by [6] using Copper-PLA filament consisting of 45% Cu and 55% PLA, showed the best parameter settings nozzle temperature 230ºC, layer height 0.35 mm, print speed 90 mm/s, and bed temperature 60ºC.

Utilize the Cu content filament for functional products, it needs further research on the mechanical properties of the printed products. In contrast, there were few published papers on the use of copper-PLA filaments. This paper aims to continue the research of [6] in finding the optimum both flexural strength and dimensional accuracy.

2. RESEARCH METHODS

2.1 Tools and Materials

The 3D printer used in this research is a portable Cartesian Rexyz A1 3D printer. It is a small type 3D printer with a working dimension of 180 x 180 x 180 mm. It can be used for plastic-based filaments such as PLA, PETG, and TPU. The extruder used is a single Bowden one with a direct drive extruder. It operated using an SD card & USB interface [7]. The filament used in this research is a copper-PLA filament. It has the main specifications as follows: diameter of 1.75 mm, printing temperature at 200-220 ^{o}C, bed temperature of 60 ^{o}C, and the density of 2.46 g/cm^3[8]. Base temperature: no heat/（60-80）°C [8]. The bending test used UTM HT-2402 bending test machine of 50 kN [9]. The bending test used is the three-point bending test, 1 $\frac{kgf/mm^2}{min}$ loading rate. To measure the product dimensions, it used a 0.05 mm accuracy digital calliper. and UTM testing machine HT-2402 are shown in Figures 1 a, b, c, and d, respectively. The appearance of the Rexyz A1 3D printer, the copper-PLA filament, the digital calliper, and the bending machine is presented in Figure 1(a) to 1(d), respectively.

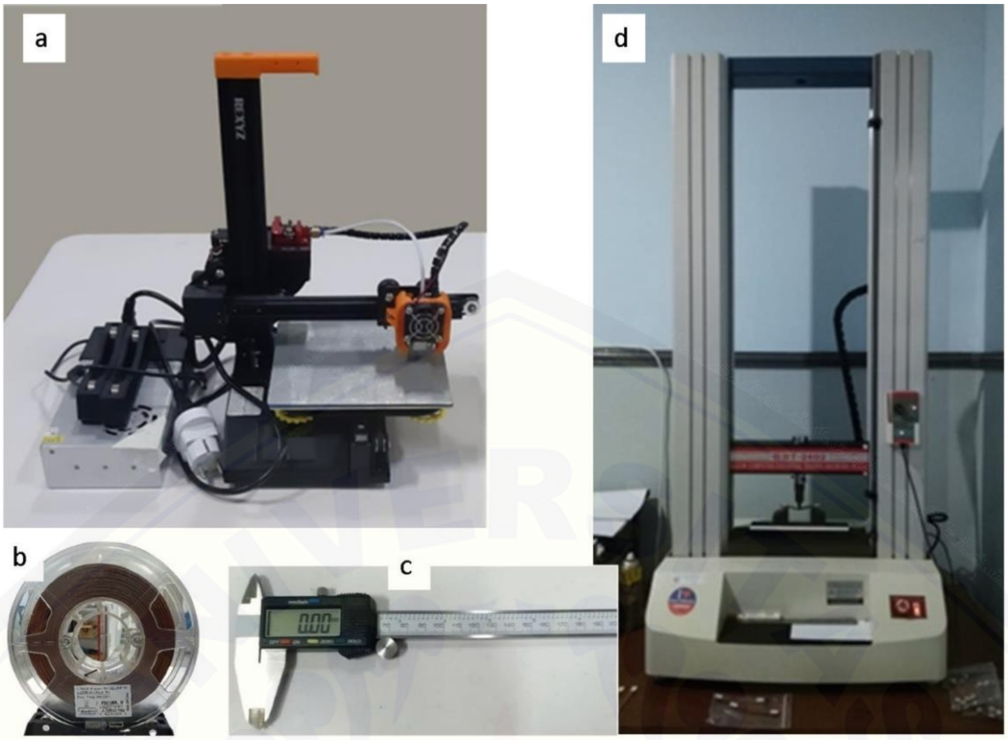

Figure 1. The equipment used for experimentation: (a) REXYZ A1 3D printer machine, (b) the copper-PLA filament, (c) a digital micrometre of 0.01 mm accuracy, and (d) UTM HT-2402 testing machine

2.2 Research Variables

The independent variables used in this study have 2 levels which are presented in Table 1. The control variables used were fan speed 100 (%), infill density 100 (%), print speed 80 (mm/s), and bed temperature 60 (^{o}C). The parameters and levels chosen were based on the preliminary experiments and considering the machine, and filament specifications.

Table 1. Variable in research

Control Factor	Parameter	Level 1	Level 2
A	Layer height (mm)	0.3	0.4
B	Nozzle temperature (^{o}C)	220	240
C	Infill pattern	Lines	Octet

2.3 Experimental Design

The Taguchi design orthogonal array matrix L4 (2^3) was employed for designing the experiments. The combination of parameters and levels according to Taguchi is presented in Table 2 columns 1-4. Dimensional measurement data and bending test results are presented in Table 2 columns 6 & 9, respectively. Then the data was processed using Minitab 20 software (free trial version). In the Taguchi method, the analysis of the S/N ratio is very important to determine the strength of the variable (signal, S) used to affect the results compared to the variable left out (noise, N).

2.4 Research Procedure

The first procedure in this research was to design the ASTM D790 bending test object using Solidworks software, then the file was saved in *STL format. The parameter setting process is carried out using the Ultimaker Cura slicer software, then saved in *G-code format. The dimensions of the specimen and the parameter setting process can be seen in Figure 2(a). The specimens were printed using a 3D printer, then followed by measuring for dimensional accuracy and bending strength. The measuring dimensional accuracy in three directions X, Y, and Z are presented in Figure 2(b). Measurement was repeated in each direction (axis) by shifting 5 mm from the previous measuring measurement. The bending test process, a sample of the specimen after the bending test, and all specimens are presented in Figure 3 (a-c), respectively. The bending test used is the three-point bending test, 1 $\frac{kgf/mm^2}{min}$ loading rate.

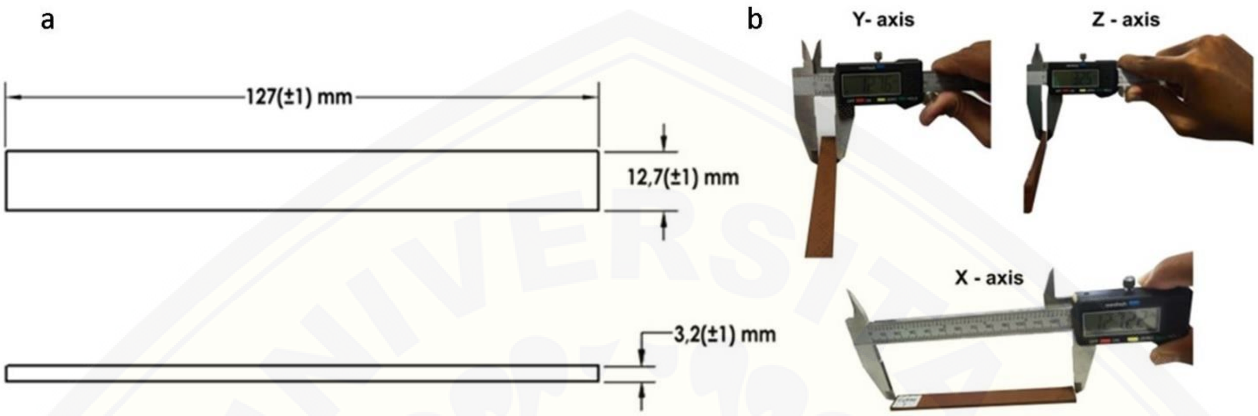

Figure 2. Specimen and its measurement: (a) dimension, (b) measurement in X, Y, and Z direction

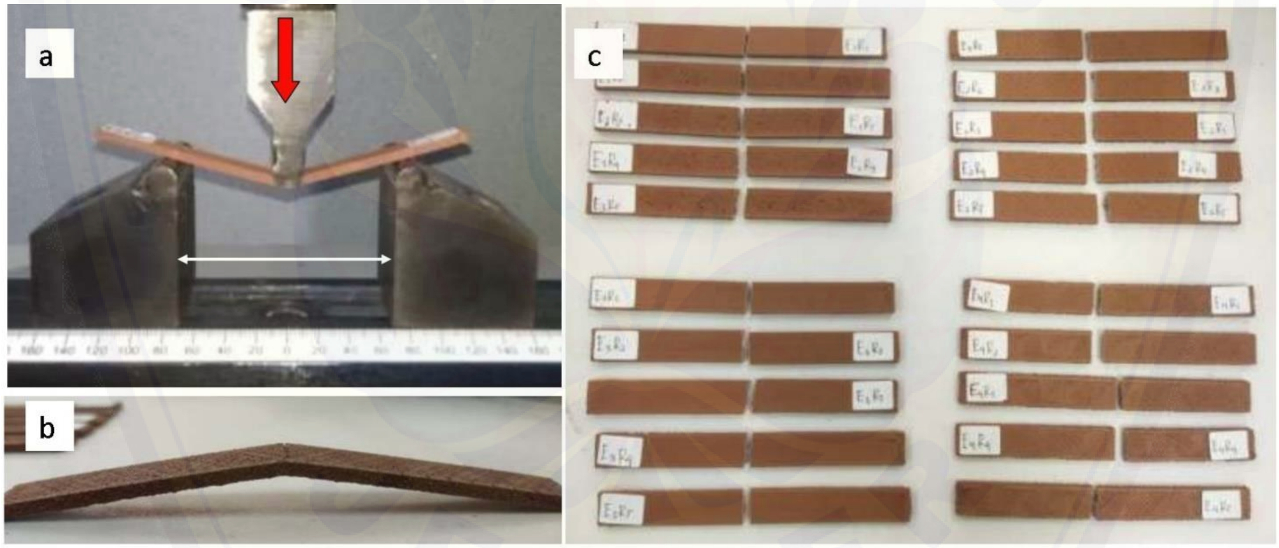

Figure 3. Bending test: (a) photo of bending test on progress, (b) a specimen after bending test, (c) all of the specimens after bending tests

3. RESULTS AND DISCUSSIONS

The dimensional accuracy data and bending test results based on the L4 orthogonal array matrix (23) and the calculation of the S/N ratio are shown in the following Table 2 columns 8 & 11. The dimensional accuracy is calculated as the deviation of the real dimension to the programmed one. The data deviation data in Table 2 column 6 are the average measurement on three axis X, Y, and Z. The programmed dimension is according to the aforementioned ASTM standard for the bending test as described in Figure 2(a).

At a glance from Table 2 column 7, the deviation resulting from the infill pattern of the octet is higher (0.39 & 0.41) than that of the line ones (0.25 & 0.36). The octet pattern resulted in a coarser surface as evident in

Figure 4, both from the upper and side surfaces.

Table 2. Dimensional accuracy and bending test results

Combination	Control Parameters			Replication	Dimensional Measurement			Bending Test		
	Nozzle Temperature (^oC)	Layer Height (mm)	Infill Pattern		Deviation (mm)	Average	S/N Ratio (dB)	Flexural strength (MPa)	Average	S/N Ratio (dB)
1	2	3	4	5	6	7	8	9	10	11
1	220	0.3	Lines	I	0.18	0.25	10.684	22.57	**14.11**	22.086
				II	0.15			11.67		
				III	0.16			11.64		
				IV	0.21			11.14		
				V	0.51			13.51		
2	220	0.4	Octet	I	0.37	0.39	8.193	16.87	16.89	24.611
				II	0.41			17.39		
				III	0.44			16.81		
				IV	0.35			16.96		
				V	0.37			19.41		
3	240	0.3	Octet	I	0.29	0.41	7.616	24.48	**23.97**	27.612
				II	0.38			24.39		
				III	0.44			22.94		
				IV	0.44			24.38		
				V	0.50			23.68		
4	240	0.4	Lines	I	0.30	0.36	8.213	18.17	20.06	26.015
				II	0.40			20.30		
				III	0.33			21.24		
				IV	0.42			19.94		
				V	0.34			20.09		

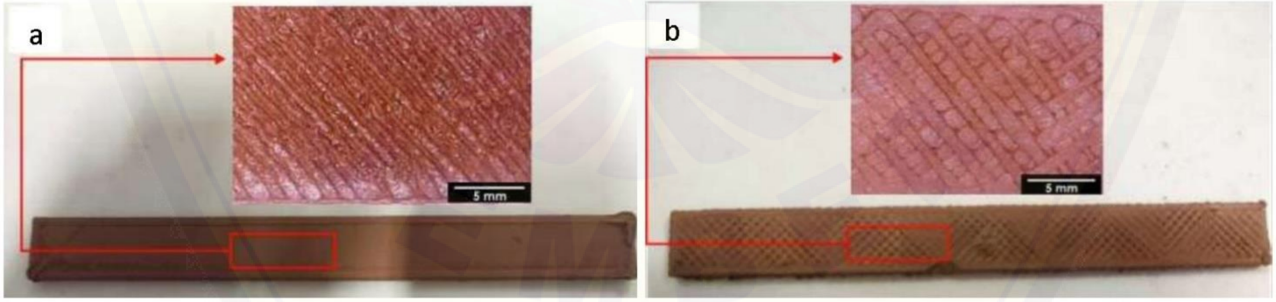

Figure 4. Surface photos of specimens made by different infill patterns: (a) line, (b) octet

From Table 2 of column 10, it is obvious that the maximum average of flexural strength is 23.97 MPa, while the minimum one was 14.11 MPa. This value showed that the specimens were brittle in comparison to the pure 3D printed PLA is 43.6 MPa [10]. The brittle specimens of copper-PLA mean they did not have sufficient elasticity to bear the load. The relative perpendicular of the fracture to the longitudinal plane is also proof that the specimen was brittle (Figure 5). The result confirmed the previous experiments using the tensile test that the Cu-PLA printed products were easily broken [6]. Some previous research experienced similar outcomes, that adding different metal content on PLA filaments - such as Copper [11], composite matrix [12], bronze [13] - would reduce the flexural strength of the printed specimens.

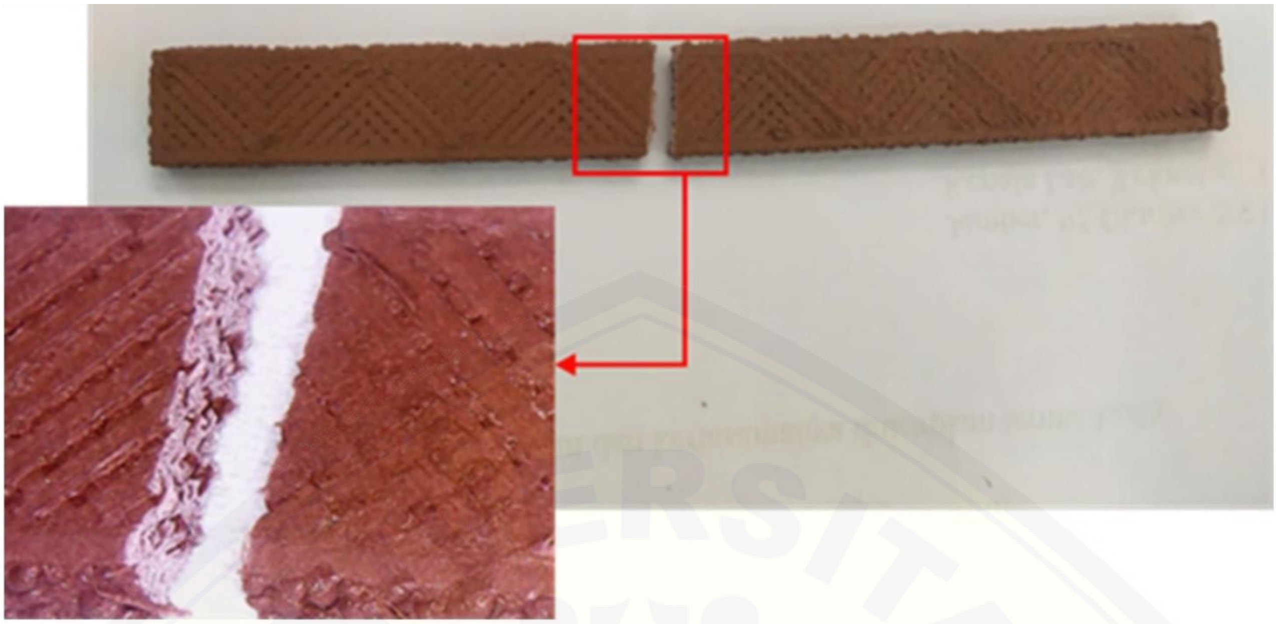

Figure 5. Bending test specimen fracture photo

A. Calculation of S/N Ratio

This calculation is used to evaluate the optimal level for each parameter. Related to the S/N ratio, there are three quality criteria in the Taguchi method, either smaller is better, larger is better, or nominal is better. In evaluating the accuracy, the first criterion was chosen, while in the analysis of bending strength the second criterion was applied. The formula (1) for dimensional accuracy using smaller is better.

$$S/N\ Ratio = -10\log\left[\frac{1}{n}\sum_{i=1}^{n} y_i^2\right] \ldots\ldots\ldots\ldots\ldots\ldots\ldots (1)$$

The formula (2) for bending strength using larger is better.

$$S/N\ Ratio = -10\log\left[\frac{1}{n}\sum_{i=1}^{n} \frac{1}{y^2}\right] \ldots\ldots\ldots\ldots\ldots\ldots\ldots (2)$$

The Minitab 20 software was used to carry out the S/N ratio calculations. Calculations of the S/N ratio of dimensional accuracy and bending strength were presented in Table 3. Therefore, the optimum S/N ratio values in each test are different. For the measurement of dimensional accuracy, the lower S/N ratio value is at level 2 of each parameter, while for bending the highest S/N ratio value is at level 2 of each parameter. The S/N ratio can be displayed in the graphs shown in Figure 6. It can be concluded from the difference in the value of the S/N ratio from each test that the variables that affect each test are different. In measuring the dimension of the variable the most influential is the infill pattern because the infill pattern has a small deviation value from the other variables. While in the bending test the variable that has the highest influence is the nozzle temperature because the nozzle temperature has a large bending value from the other variables.

Table 3. Calculation of the S/N ratio of the dimensional accuracy and bending strength

Control Factor	Dimensional Accuracy			Bending Strength		
	Average S/N ratio		Difference	Average S/N ratio		Difference
	Level 1	Level 2		Level 1	Level 2	
Nozzle Temperature	9.44	8.24	1.20	23.35	26.81	3.47
Layer height	9.15	8.52	0.63	24.85	25.31	0.46
Infill Pattern	9.77	7.91	1.86	24.05	26.11	2.06

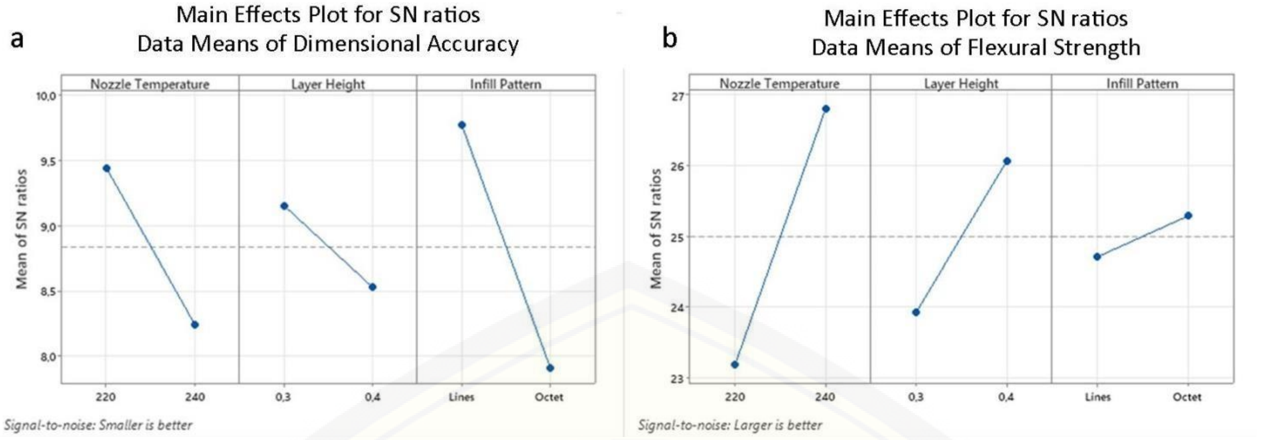

Figure 6. Plot the mean S/N ratio of (a) dimensional accuracy, (b) flexural strength

B. Analysis of Variance (ANOVA)

ANOVA is a calculation method that allows quantitatively estimating the contribution of each factor to all response measures. The analytical model used is a two-way analysis of variance. The two-way analysis of the variance table consists of the calculation of the degrees of freedom, the sum of the squares, the mean of the sum of the square, and the F-ratio. The formula for the degree of freedom is

$DoF\ total\ =\ (n\ -\ j)$……………………..(3)

The formula for the sum of the squares is:

$SS_T = \sum y_1{}^2 - y^2$ ………………..………....(4)

The formula for the mean of the sum of the square is:

$MS_{factor} = \frac{SS_{factor}}{df_{factor}}$ ……………..…………....(5)

The formula for the F-ratio is:

$F_{ratio} = \frac{MS_{factor}}{MS_e}$ …………………….………(6)

The ANOVA in this study was calculated based on mean data representing dimensional accuracy and flexural strength values. Table 4 shows the results of ANOVA calculations using Microsoft Excel software.

The following calculation presents an example of the calculation of significant and not significant variables. Calculation of insignificant variables using nozzle temperature and significant variables using infill pattern.

a. Variable of nozzle temperature

1. Total degrees of freedom

$$DoF\ total\ =\ (n\ -\ j)$$
$$DoF\ total\ =\ (20\ -\ 4)$$
$$DoF\ total\ =\ 16$$

1. Degree of freedom of each factor (factor A: nozzle temperature)

$$DoF_A \quad = (n - 1)$$
$$DoF_A \quad = (2 - 1)$$
$$DoF_A \quad = 1$$

2. Sum of squares

$$SS_T = \sum y_1{}^2 - y^2$$

$SS_T\ =\ (0.18+0.15+0.16+0.21+\ldots+0.42+0.34)^2$
$-\ ((0.18 + 0.15 + 0.16 + 0.21 + \ldots + 0.42 + 0.34)^2)/20$
$SS_T\ =\ 0.231$

4. The sum of the squares of each factor (factor A: nozzle temperature)

$$SS_A = \left[\sum_{i=1}^{KA}\left(\frac{A_i^2}{n_{Ai}}\right)\right] - \frac{T^2}{N}$$
$$SS_A = \left[\frac{3.190^2}{10} + \frac{3.840^2}{10}\right] - \frac{7.030^2}{20}$$
$$SS_A = 2.492 - 2.471$$
$$SS_A = 0.021$$

3. Sum of squares due to error

$$SS_e = SS_T - SS_A - SS_B - SS_C$$
$$SS_e = 0.231 - 0.021 - 0.009 - 0.045$$
$$SS_e = 0.155$$

6. Average of the squares of each factor (factor A: nozzle temperature)

$$MS_A = \frac{SS_A}{df_A}$$
$$MS_A = \frac{0.021}{1}$$
$$MS_A = 0.021$$

7. Mean squared error

$$MS_E = \frac{SS_E}{df_E}$$
$$MS_E = \frac{0.155}{16}$$
$$MS_E = 0.0097$$

8. F-ratio (factor A: nozzle temperature)

$$F_{ratio} = \frac{MS_A}{MS_e}$$
$$F_{ratio} = \frac{0.021}{0.0097}$$
$$F_{ratio} = 2.179$$

b. Variable of infill pattern

1. Total degrees of freedom

$$DoF\ total = (n - j)$$
$$DoF\ total = (20 - 4)$$
$$DoF\ total = 16$$

2. Degree of freedom of each factor (factor A: nozzle temperature)

$$DoF_A = (n - 1)$$
$$DoF_A = (2 - 1)$$
$$DoF_A = 1$$

3. Sum of squares

$$SS_T = \sum {y_1}^2 - y^2$$

$$SS_T = (0.18+0.15+0.16+0.21+\ldots+0.42+0.34)^2$$
$$- ((0.18 + 0.15 + 0.16 + 0.21 + \ldots + 0.42 + 0.34)^2)/20$$

$$SS_T = 0.231$$

4. The sum of the squares of each factor (factor C: infill pattern)

$$SS_C = \left[\sum_{i=1}^{KC}\left(\frac{C_i^2}{n_{Ci}}\right)\right] - \frac{T^2}{N}$$

$$SS_C = \left[\frac{3.040^2}{10} + \frac{3.990^2}{10}\right] - \frac{7.030^2}{20}$$

$$SS_C = 2.516 - 2.471$$

$$SS_C = 0.045$$

5. Sum of squares due to error

$$SS_e = SS_T - SS_A - SS_B - SS_C$$

$$SS_e = 0.231 - 0.021 - 0.009 - 0.045$$

$$SS_e = 0.155$$

6. Average of the squares of each factor (factor C: infill pattern)

$$MS_C = \frac{SS_C}{df_C}$$

$$MS_C = \frac{0.045}{1}$$

$$MS_C = 0.045$$

7. Mean squared error

$$MS_E = \frac{SS_E}{df_E}$$

$$MS_E = \frac{0.155}{16}$$

$$MS_E = 0.0097$$

8. F-ratio (factor C: infill pattern)

$$F_{ratio} = \frac{MS_C}{MS_e}$$

$$F_{ratio} = \frac{0.045}{0.0097}$$

$$F_{ratio} = 4.653$$

Table 4. ANOVA calculation results

Control Factor	DoF	Dimensional accuracy SS	MS	F	Per cent Contribution (ρ)	P	Flexural Strength SS	MS	F	Per cent Contribution (ρ)	P
1	2	3	4	5	7	8	9	10	11	12	13
Nozzle Temperature	1	0.021	0.021	2.179	9.16 %	Not Significant	212.502	212.502	34.573	57.66 %	*Significant*
Layer height	1	0.0093	0.009	0.953	4.01 %	Not Significant	56.101	56.101	9.127	15.22 %	*Significant*

Infill Pattern	1	0.0451	0.045	4.653	19.56 %	Significant	1.614	1.614	0.263	0.44 %	*Not Significant*
Error	16	0.1551	0.0097		67.27 %		98.344	6.146		26.68 %	
Total	19	0.231			100 %		368.560			100 %	

C. Percent Contribution

The percentage contribution shows the contribution of each factor to the total variation, that is how much each factor influences the response under study. The contribution of the percentage calculation results is obtained from the sum of the squares of each factor (SS) divided by the number of squares then multiplied by 100 (%). Table 4 columns 7 & 11 above are respectively the results of the percentage contribution of dimensional accuracy and bending strength.

The percentage contribution to the error value in bending strength is 26.68%. According to [14], if the error that occurs is less than 15%, there is no neglected factor affecting the measured output. Vice versa, if the error is more than 15%, it means some dominant factors affect the output but are neglected in the design of experiments [15]. If the error is more than 50%, the results will not be reliable [16].

The percentage contribution to the error value on dimensional accuracy is 67.27%. This happens due to the influence of parameters not examined in this study, including fan speed, infill density, print speed, and bed temperature. According to [17] fan speed, infill density, print speed, and bed temperature influenced the tensile strength of the 3D printed specimens.

3.1 Parameters Effect Discussion

1. Nozzle Temperature against flexural strength

Nozzle temperature is a factor that affects the bending properties of 3D printing metal products. Nozzle temperature also affects the attachment of each layer to 3D printing products. In this study, the contribution of nozzle temperature to the flexural strength of 3D printing metal products is the highest contribution from other factors, which is 57.23%.

The most optimal nozzle temperature to produce the best flexural strength in this study was at nozzle temperature level 2, which was 0.4 mm. This can be proven by micro-images of the specimen fracture after bending testing. Micro-photos of specimen fractures taken using a digital microscope is shown in the following Figures 7 (a) & (b).

a. Nozzle Temperature 220 ^{o}C

It can be seen in Figure 7(a) that using a temperature of 220 ^{o}C, the bonds between the layers are attached well. However, in the middle of the specimen, there is a layer, which is still not perfectly attached.

It can be seen in Figure 7(b) that using a temperature of 240 ^{o}C the bonding of each layer is very good. The layers of each layer are barely visible, which indicates that the layers adhere perfectly. This is by the results of [18], which stated that the higher the nozzle temperature used, the more attached the bond between layers. It made the bending strength higher.

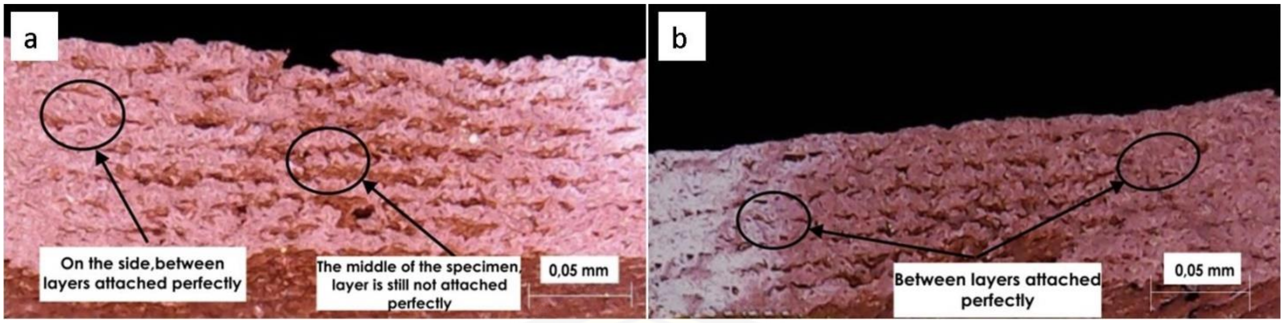

Figure 7. Micro photo of specimen fracture at different nozzle temperatures: (a) at 220 °C, and (b) at 240 °C

2. Layer height to bending strength

Layer height is a factor that affects the bending properties of 3D printing metal products. In this study, layer height has a contribution value of 16.13%. The optimal layer height to produce bending strength in this research is layer height level 2, which is 0.4 mm. The results are the following were found by [10], wherein this study uses filaments from PolyLactic Acid (PLA). They found that the higher the layer height used, the higher the bending strength value produced.

3. Infill pattern

a. Infill pattern effect on bending strength

Infill pattern is a factor that affects the bending properties of 3D printing metal products. In this study, the contribution of the infill pattern to the bending strength of 3D printing metal products is the lowest contribution from other factors, which is 0.14%. The optimal infill pattern to produce bending strength in this study is the level 2 infill pattern, namely octet. Previous research by [19] stated that the closer the spacing of the filling patterns, the higher the flexural strength produced.

b. Infill pattern on dimensional accuracy

Infill pattern is one of the parameters in the metal 3D printing process that is useful for adjusting the filling pattern of each layer when printing. The percentage contribution of the infill pattern parameter is 19.56%. The infill pattern parameter has an optimal level at level 1, namely lines. [20] stated that the more sparse the distance between filling patterns, the lower the number of deviations.

4. CONCLUSIONS

Studies to determine the optimal factors that influence both dimensional accuracies, as well as flexural strengths, have been carried out using Taguchi L4 (2^3) followed by S/N ratio and ANOVA analysis. Then the optimal parameters for flexural strength of 43.6 MPa were obtained when using combining parameters of nozzle temperature 240 °C, layer height 0.4 mm, and octet infill pattern. The factors that contributed to the flexural sequentially were nozzle temperature, layer height, and infill pattern contributing at the percentage of 57.66 %, 15.22 %, and 0.44 %, respectively.

Meanwhile, the optimal parameters for dimensional accuracy with the deviation of 0.25 mm were achieved when using combination factors of nozzle temperature 220 °C, layer height 0.3 mm, and lines infill pattern. The most contributing factors to the flexural properties of the test specimens were the infill pattern of 19.56 %, the nozzle temperature parameter having a contribution of 9.16 %, and the layer height having a contribution of 4.01%.

5. ACKNOWLEDGMENT

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