SINERGI Vol. 26, No. 1, February 2022: 99-106
http://publikasi.mercubuana.ac.id/index.php/sinergi
http://doi.org/10.22441/sinergi.2022.1.013

Analysis of the effect 3D printing parameters on tensile strength using Copper-PLA filament

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Abstract
This research aims to find the optimal combination of parameters to obtain the maximum tensile strength of 3D printing products made of eCopper, which consists of 45% Cu and 55% PLA. The parameters used were nozzle temperature, layer height, print speed and bed temperature with three levels each. The Taguchi L9 (3^4) experiment was used for design and analysis. The product was printed in the form of a tensile test specimen according to the ASTM D638 Type I standard using a Cartesian FDM 3D printer. The average response S/N ratio calculation found that the highest tensile strength would be obtained when applying combination parameters of nozzle temperature 230 °C, layer height 0.35 mm, print speed 90 mm/s and bed temperature 60 °C. While each parameter contributes to the tensile strength by the order are nozzle temperature, layer height, print speed, and bed temperature 59.44%, 20.53%, 18.06% and 1.97%, respectively.

Keywords:
3D printing;
Copper-PLA filament;
Taguchi method;
Tensile strength;

Article History:
Received: August 24, 2021
Revised: October 20, 2021
Accepted: October 29, 2021
Published: February 10, 2022

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INTRODUCTION

Additive manufacturing is a formal name of 3D printing, a previously used technology for rapid prototyping [1]. Additive manufacturing also facilitates the evaluation and testing of designs before producing the finished product [2]. In addition, this technique is a breakthrough in the world of technology, namely the ability to make a prototype at a low cost and a simple process [3]. The application of 3D printing products has also been widely used in the automotive and medical industries [4]. The existence of 3D printing technology in manufacturing has brought major changes to the world.

The rapid prototyping technology was first invented by Chuck Hall using a stereolithographic (SLA) 3D printer. He used UV light to form plastic into layers. Scott Crump introduced another technique of 3D printing called fused deposition modelling (FDM) in 1988 by melting and pouring the plastic into a thin layer. Further, he applied the CNC to automate the process. With this technology, his machine melted and layered the plastic filament on a flat surface. There are some other techniques of additive manufacturing, such as selective laser sintering (SLS), laminated object manufacturing (LOM), and solid ground curing (SGC) [1]. However, fused Deposition Modeling (FDM) is the most widely used technique in additive manufacturing because of its effectiveness and simplicity [5]. The working principle of 3D printing is to accumulate layers of heated material and then press it through a nozzle using computer control [6].

Several FDM 3D printing process characteristics have references, including dimensional accuracy, surface roughness, and mechanical properties [7]. Furthermore, the materials used in 3D printing are generally made of plastic. Still, materials with a mixture of plastic and metal have become available in its development, such as eSteel, eBronze, eBrass, and eCopper.

Published papers on using copper-PLA 3D printing were barely found. Research on the use of plastic and metal mixed filaments, more precisely between copper and PLA, was carried out by [7] by printing flexural test specimens varying the filling pattern on the specimen and producing the greatest flexural strength value in the concentric shaped pattern [8].

In order to prepare this filament to be able to functional purpose, research on mechanical properties of the FDM 3D printed using copper-PLA should be carried out. Therefore, research on this material is relatively wide open. Therefore, this paper aims to obtain printed products with maximum tensile strength with filament material consisting of 45% Cu and 55% PLA, known as the eCopper brand.

METHOD

Tools and Materials

The equipment used in this research is a Cartesian REXYZ A1 3D printer. There is no particular reason for utilizing this Cartesian-type printer; it is merely based on the availability of the machine in the laboratory. The schematic of the working principle of this single-column printer is presented in Figure 1. The fed filament used was eCopper filament. The photo of this rolled filament and its specification is depicted in Figure 2. A tensile test was carried out using the Zwick/Roell Z020 tensile testing machine with a capacity load of 20 KN. The test is the height of 1050 mm, and width of 440 mm, as shown in Figure 3.

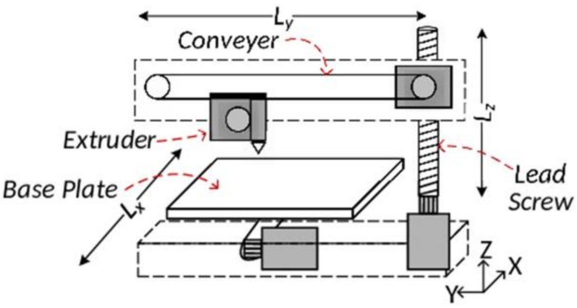

Figure 1. Working schematic of a Cartesian single column 3D printer [9]

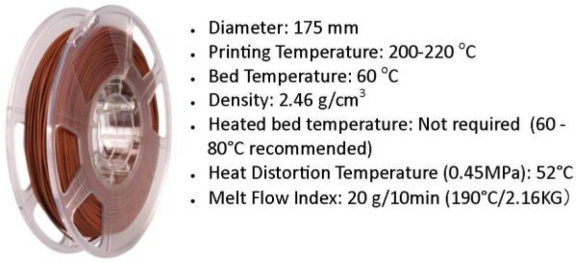

Figure 2. eCopper filament and its physical properties

Figure 3. Zwick/Roell Z020 tensile testing machine

Research Variable

Several process parameters significantly influence printing efficiency and characteristic of the printed parts, such as air gap, build orientation, extrusion temperature, infill pattern & density, thickness layer, number of shells, raster width & orientation, and heat treatment of post printing [10]. Most of the previous researchers used parameters of variables of layer thickness (or layer height), print speed, build orientation, and raster angle [11]. However, according to the authors' experiences, the nozzle temperature and bed temperature inevitably develop well printed parts. Therefore, the four chosen parameters in this research are layer thickness, print speed, nozzle temperature, and bed temperature. Each of these has three levels, as presented in Table 1. Those levels were selected based on preliminary trials before designing the experiments. The controlled variables were fan speed of 100 (%), infill 100 % and room temperature of 28-30°C. The measured output was tensile strength.

Table 1. Variables and levels used in the experiments

Control factor	Parameter	Level 1	Level 2	Level 3
A	Nozzle temperature (ºC)	220	230	240
B	Layer height (mm)	0.3	0.35	0.4
C	Print speed (mm/s)	80	90	100
D	Bed temperature (ºC)	50	60	70

Design of Experiment

The experimental data were obtained based on the Taguchi method experimental design using the L9 (3^4) orthogonal array presented in Table 2, columns 1-6. The tensile strength of each experiment was presented in column 7 and the average in the next column. Then data processing was carried out using Minitab 20 software (free trial version). In the Taguchi method, an analysis signal to noise ratio (S/N ratio) is essential to know how robust the chosen variables (signal) are affecting the result in comparison to the abandoned ones (noise). Therefore, the higher the value of the S/N ratio, the better is the result, regardless of the quality criteria chosen.

Research Procedure

The first procedure of this research is to draw a model in the form of the ASTM D638 Type I tensile test specimen using CAD software and then save the image file in *.stl format, then to set the parameters using the Ultimaker Cura slicer software. Simulation and adjustment were carried out on nozzle temperature, bed temperature, layer height and print speed on this software. The dimension of the specimen and setting parameters process can be seen in Figure 4 and Figure 5, respectively. Other preparations were made carefully before printing, such as setting the distance between the nozzle and the bed using a feeling gauge; trial to melt and load the filament manually and automatically through the program.

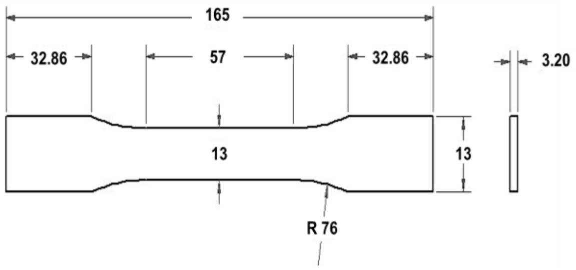

Figure 4. ASTM D638 type 1 tensile test specimen CAD design [12]

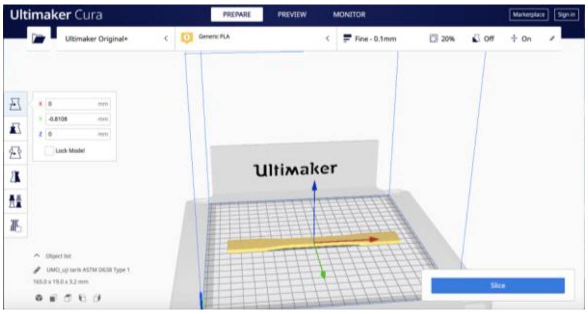

Figure 5. Parameter setting using Ultimaker Cura software

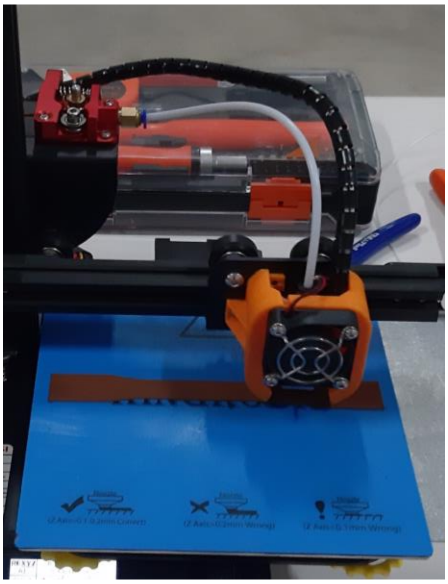

Figure 6. Specimen printing process

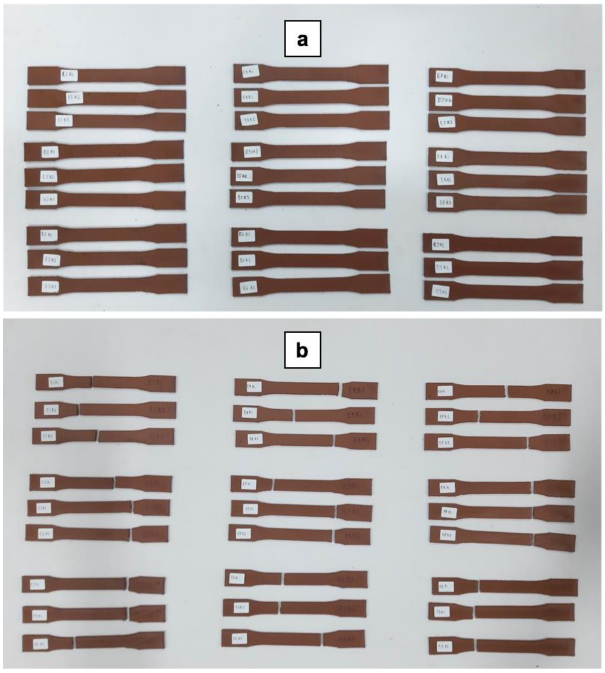

Figure 7. (a) 3D printing result (b) specimens after testing

Table 2. Tensile strength test results data with a combination of parameters according to the L9 (3^4) orthogonal matrix

Combination	Control Parameters				Replication	Tensile strength value (MPa)	Average	S/N Ratio (dB)
	Nozzle Temperature (ºC)	Layer height (mm)	Print speed (mm/s)	Bed Temperature (ºC)				
1	2	3	4	5	6	7	8	9
1	220	0.3	80	50	I II III	16.4 20.8 17.6	18.26	25.1062
2	220	0.35	90	60	I II III	19.5 19.1 20.3	19.66	25.8516
3	220	0.4	100	70	I II III	17.8 19.1 18.8	18.56	25,3627
4	230	0.3	90	70	I II III	19.8 20.1 19.7	19.86	25.9616
5	230	0.35	100	50	I II III	20.9 20.6 20	20.5	26.2307
6	230	0.4	80	60	I II III	19.3 19.6 19.3	19.40	25.7553
7	240	0.3	100	60	I II III	18.9 18.6 18.7	18.73	25.4517
8	240	0.35	80	70	I II III	19.2 17.7 19.2	18.70	25,4175
9	240	0.4	90	50	I II III	18.8 18.6 18.8	18.73	25,4520

Following the slicing using the Ultimaker Cura software, the specimens were printed using a 3D printer, and then all specimens were tested for tensile strength. Figure 6 shows the printing process, and Figure 7 is a 3D printing product and specimens after testing.

RESULT AND DISCUSSION

The data of the tensile strength test results according to the 3^4 orthogonal array and the results of the calculation of the S/N ratio can be seen in the following Table 2. The tensile strength value ranges from 16.4 MPa to a maximum of 20.9 MPa, at an average of 19.27 MPa. This result is comparable to pure PLA with the same process [13]. While [14] could improve the tensile strength of 3D printed PLA by optimizing the process parameters. Adding copper to the PLA in the filament has reduced the tensile strength by about 30% [15].

From observation of the fracture shape of the test specimen, it can be seen that the fracture is without ductile deformation around the crack tip or no necking at the broken specimen. Therefore, we may conclude that the tensile test specimen made of eCopper is brittle [16]. It may be because they do not have enough elasticity to withstand a load. This result is in line with the fractographic observation of [15], with a different composition of the filament, it consists of 10.35% Cu, and the rest is PLA. Figure 8 is a photo of a specimen fracture tested for tensile strength.

Average Response S/N Ratio

This calculation is the result of the average response of the S/N ratio and is also used to evaluate each optimum level for each parameter. The results of calculating the average response of the S/N ratio based on the results of the Minitab 20 software can be seen in Table 3. It is obvious that the highest S/N value is all at level 2 of each parameter.

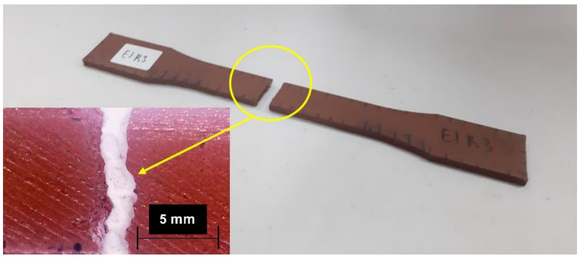

Figure 8. The fracture shape of the tensile test specimen

Table 3. The average response of S/N ratio values for each control factor

Control factor	Average S/N ratio			Difference
	Level 1	Level 2	Level 3	
Nozzle temperature	25.44	**25.98**	25.44	0.54
Layer height	24.52	**25.83**	25.52	0.33
Print speed	25.43	**25.76**	25.68	0.33
Bed temperature	23.43	**25.69**	25.58	0.11
Total average		25.62		

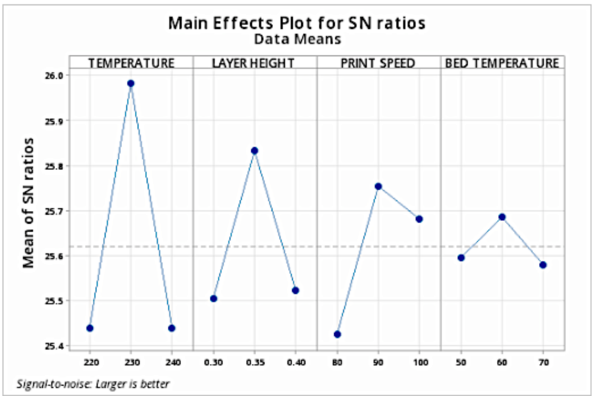

Figure 9. The plot of the mean S/N ratio

The S/N ratio can also be presented in the form of a graphic, as shown in Figure 9. The differences in S/N ratio value between the maximum and minimum represent how the variable affects the tensile strength. It is evidence that nozzle temperature is the most affecting variable to the strength, while bed temperature is the least once.

Analysis of Variance (ANOVA)

ANOVA is an analytical technique used to quantitatively estimate the effect of each factor on all response measures. The analysis model uses a two-way analysis of variance consisting of calculating the degrees of freedom, the sum of squares, the average number of squares and the F-ratio [9]. ANOVA in this research is calculated based on the data of the S/N ratio which represents the value of the tensile strength**.** The following Table 4 presents the results of ANOVA calculations based on the Minitab 20 software.

It is clear from Table 4 that the residual is zero, or it has no residual error. A special result like this may occur when using Taguchi design 3^4. For example, Maazinejad et al. [17] experienced zero error when conducting Taguchi design experiments.

Table 4. ANOVA calculation result

Control factor	DF	SS	MS	F
Nozzle temperature	2	0.58807	0.294036	*
Layer height	2	0.20331	0.101555	*
Print speed	2	0.17863	0.089313	*
Bed temperature	2	0.01949	0.009744	*
Error	0	*	*	*
Total	8	0.98930		

Table 5. Percentage of contribution

Parameter	Percentage of contribution (ρ)
Nozzle temperature	59.44%
Layer height	20.53%
Print speed	18.06%
Bed temperature	1.97%
Error	0%
Total	100 %

Percentage of Contribution

The contribution percentage shows how much influence the control parameter has on the response under research. The contribution percentage calculation result is obtained from the sum of the squares of each factor (SS) divided by the total number of squares then multiplied by 100 (%). Table 5 is the result of the contribution percentage.

Discussion of Parameter Effect

Nozzle temperature

The nozzle temperature parameter in the 3D printing process greatly affects the material's tensile strength and mechanical properties. In addition, the temperature at the nozzle plays an important role in the adhesion between layers when printing the tensile test specimen. In this research, the effect of the nozzle temperature parameter has the highest percentage contribution of 59.44%, as shown in Table 5. The most optimum nozzle temperature parameter in this research was at level 2 with a value of 230 ^{o}C. This is evidenced by several micro-photographs of specimen fractures using a digital microscope which can be seen in the following Figure 10, Figure 11, and Figure 12.

a). Nozzle temperature 220 ^{o}C

It can be seen in Figure 10, at a temperature of 220 ^{o}C, the layers are attached to the right and left sides of the test object, while in the middle of the specimen there are some empty spaces between layers.

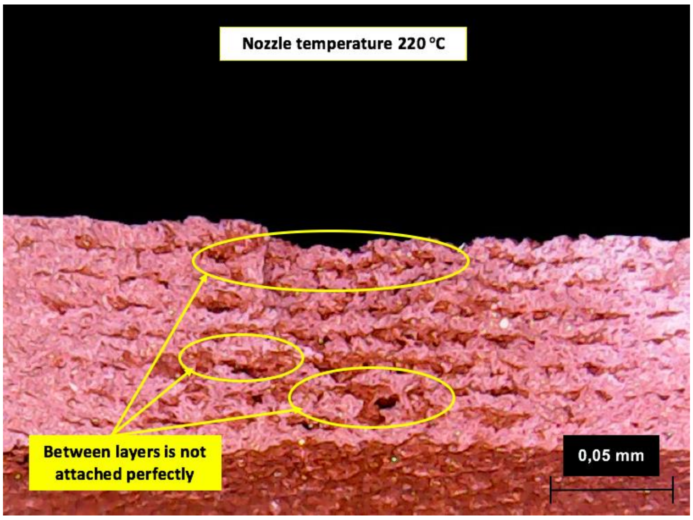

Figure 10. Specimen fracture with the nozzle temperature parameter setting 220 °C

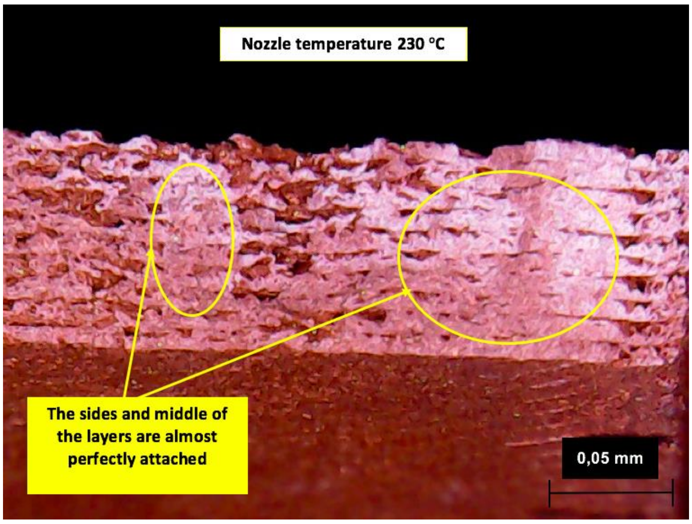

Figure 11. Specimen fracture with the nozzle temperature parameter setting 230 °C

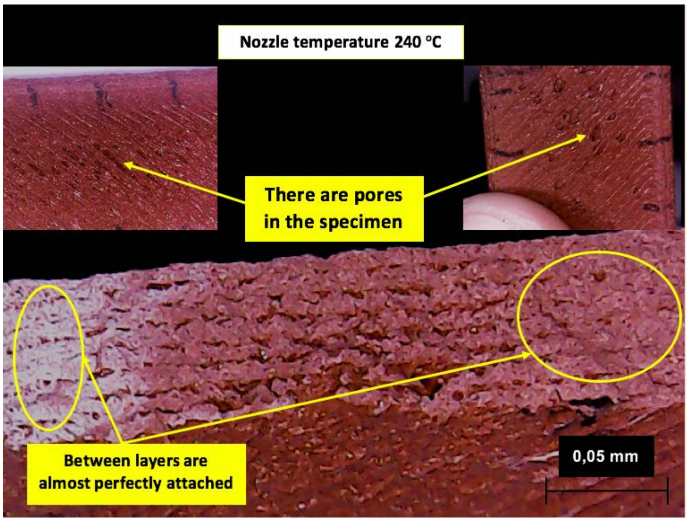

Figure 12. Specimen fracture with the nozzle temperature parameter setting 240 °C

b). Nozzle temperature 230ºC

It is evident from Figure 11 that at the temperature of 230 ºC, the layers on the side and centre of the test object is more closely attached compared to that at 220 ºC. Therefore, it seems that the temperature of 230 ºC is the optimum level of the nozzle temperature. The results are in accordance with [18], which stated that the better the attached layer, the higher the tensile strength value.

c). Nozzle temperature 240 ºC

During the specimen printing process, the filling was defective at the nozzle temperature of 240 ºC or the 3rd level nozzle temperature. The imperfect filling formed pores. It may be because of a higher nozzle temperature. The extruded molten filament is too soft; therefore, it flows freely. Instead of filling the lack region, it went to other sides. This is evident from the photo results using a digital microscope which is indicated by a yellow arrow and is shown in Figure 12.

Layer height

The layer height parameter in the process and results of 3D printing is also a factor that cannot be ignored on the tensile strength of 3D printing specimens. In this research, the percentage contribution was 20.53%, and the optimum level for this parameter was obtained at level 2 with a value of 0.35 mm. This is probably due to the low layer height at level 1, which is 0.3 mm, making the layer arrangement too thin. Research conducted by [19] on the parameter of layer height 3D printing made of Polylactic Acid (PLA) stated that the higher the layer height, the stronger the tensile strength. In contrast, a layer height of 0.4 mm has exceeded the maximum limit, reducing the product's tensile strength.

Print speed

The print speed parameter or the speed of the nozzle movement affects the tensile strength of the 3D printing process. This parameter has a contribution percentage of 18.06%, with the optimum level obtained at level 2 or 90 mm/s. A slower speed of 80 mm/s makes the layer arrangement less neat because the nozzle movement is too slow. While at a print speed of 100 mm/s resulted in a thinner layer due to the nozzle movement being too fast.

Bed temperature

In this research, the bed temperature parameter is not very influential to the tensile strength of the printed products at a rate of less than 2%. At this low level of contribution, it may be abandoned. In the future, bed temperature may not be used as the setting parameter.

CONCLUSION

Determination of optimal parameters in this research using the Taguchi method with the help of Minitab software, namely by taking the optimal level of each factor or parameter, then the optimal parameter is obtained, namely nozzle temperature 230 ºC (level 2), layer height 0.35 mm (level 2), print speed 90 mm/s (level 2) and bed temperature 60 ºC (level 2).

Based on the calculation of the percent contribution in this research, it was found that the nozzle temperature parameter had the most significant influence among other parameters, namely 59.44%, the layer height parameter was 20.53%. On the other hand, the print speed parameter had a contribution percentage of 18.06%, while the bed parameter temperature does not significantly affect the percentage contribution of 1.97%.

ACKNOWLEDGMENT

This research was supported by the Research and Community Development Bureau of Universitas Jember through Post-Doctorate research grant scheme No. 3473/UN25.3.1/LT/2020. We also thank Mas Oki Pranajaya, the technician of Mechanical Design Laboratory.

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