Improving The Strength of The PLA 3D Printing Using Response Surface Methodology

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Abstract
Added manufacturing is a breakthrough in the world of manufacturing, one of which is 3d printing technology. This technology makes it easy for us to make customized goods that are cheap, fast, and efficient (do not produce scrap/chips). However, the reliability of 3D printed products is still often in doubt, the weakness of 3D printed products is their strength. In this paper, we experimented with variables infill density, extruder temperature and infill pattern that affect strength in the 3D printing process. The higher the infill value makes the product stronger, but it requires more material and processing time, besides that the mass of the product will be heavier. While the pattern is related to the internal structure of the product with a certain shape. Test the strength of the PLA 3D printing products with a combination of these three variables using impact charpy, and analysis using the Response surface methodology (RSM) including optimization procedures to obtain the most optimum parameter depending on the product required. The maximum impact reach 164.18 KJ/m-sq, when infill density is 100%, extruder temperature is 220 C-deg and using Cubic infill pattern. This information will be very helpful for developing products with 3D Printer-based processes with PLA materials.

Keywords*: 3D-Printing, Respon Surface Methodology, Impact Charpy, Polylactic acid (PLA), Fused deposition modeling (FDM)*

Abstrak
[Meningkatkan Kekuatan Hasil Cetakan Printer 3 Dimensi untuk Material PLA dengan Metodologi Respon Surface] *Added manufacturing merupakan sebuah terobosan baru dalam dunia manufaktur, salah satunya adalah Teknologi 3d printing. Teknologi ini membuat kita menjadi mudah membuat suatu barang dengan tingkat keunikan tinggi yang murah, cepat, dan efisien (tidak menghasilkan scrab/ chip). Akan tetapi keandalan dari produk hasil 3D printing masih sering diragukan, hal yang menjadi kelemahan dari produk hasil 3D printing adalah kekuatannya. Pada makalah ini kami melakukan eksperimen dengan memperhatikan 3 variabel penting yang mempengaruhi kekuatan dalam proses 3D Printing yaitu infill density, extruder temperature dan infill pattern. Semakin tinggi nilai infill density produk akan semakin kuat, namun memerlukan material dan waktu proses yang lebih, selain itu produk akan semakin berat. Sedangkan pattern berkaitan dengan struktur internal produk dengan bentuk tertentu. Hasil produk 3D Printing dengan kombinasi dari ketiga variabel tersebut akan diuji kekuatan dengan impact charpy, dan analisa menggunakan Response surface methodology (RSM), termasuk optimization procedures untuk mendapatkan parameter yang paling optimum. Maksimum nilai impact yang dicapai adalah 164.18 KJ/m-sq, ketika infill density 100%, extruder temperature 220 C-deg dan menggunakan Cubic infill pattern. Informasi ini akan sangat membantu untuk mengembangkan produk dengan proses berbasis 3D Printer dengan material PLA.*

Kata Kunci*: 3D-Printing, Respon Surface Methodology, Impact Charpy, Polylactic acid (PLA), Fused deposition modeling (FDM)*

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1. Introduction

Additive manufacturing is a moving forward in manufacturing technology that changes the way of conventional manufacturing processes such as cutting and forging (Groover, 2020; Chua et al., 1998). 3D printing is a technology that can describe additive manufacturing very well (Lee et al., 2017; Teixeira et al., 2022). 3D printing can be used to print a product with various materials such as polymers, nanocomposites, and metals (Siddiqui et al., 2023; Choudary et al., 2023; Martinelli et al., 2023). However, the use of polymer materials is still the dominance of the 3D printing process. The type of polymer that is often used is Polylactic acid (PLA). PLA has several properties, it is easy to melt at low temperatures, has a small temperature expansion and is included in bioplastics material (Tian et al., 2016; Chen et al., 2017).

Table 1. Summary of Research on Mechanical Properties of 3D Printing Part from PLA Material.

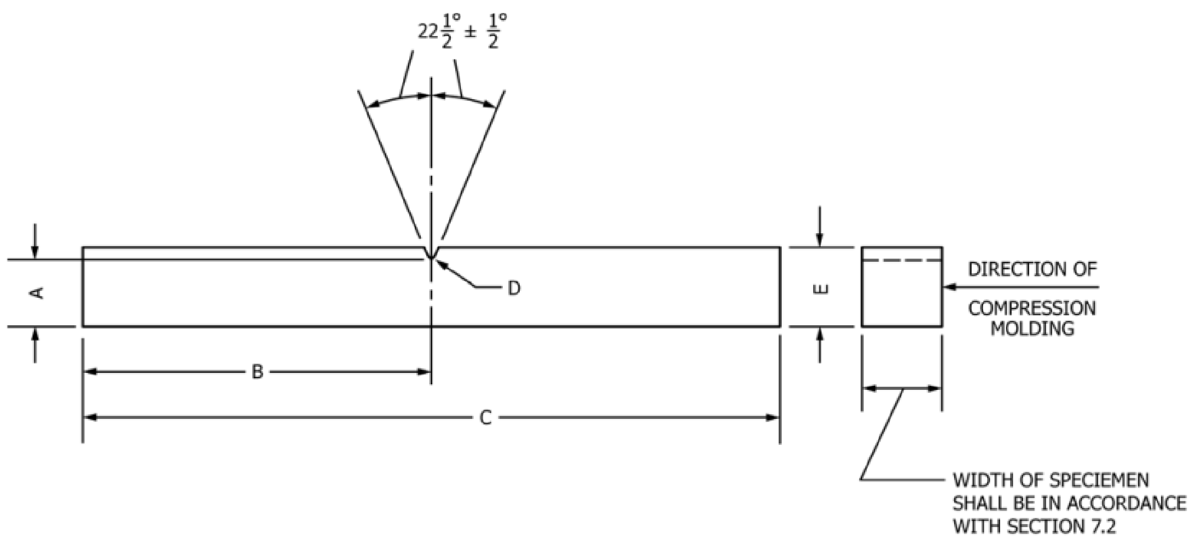
No	Author	Research	Mechanical test	Sample size
1	Yadav et al., 2023	infill density, lay bed position	Tensile	not diclared
2	Yilan et al. 2023	Infill density, Infill pattern, printing speed, used anova	Tensile	@1 total 18
3	Tura et al. 2022	infill density, print speed, shell count	Tensile	not diclared
4	Bhandarkar et al., 2022	Infill pattern, infill density, extruder temperature, taguchi	Tensile, roughness	@1
5	Mani et al., 2022	layer thickness, infill density, extruder temperature, taguchi	Tensile, roughness	@1
6	Mishra et al., 2021	carbon fiber PLA, Infill pattern, infill density, printing speed, used anova	Tensile dan flexural	54 speciment
7	Travieso-Rodriguez et al., 2021	ABS, PLA, PLA Wood,	Tensile dan flexural	27 speciment
8	Khawly et al., 2021	infill density	Impact testing	@1
9	Pandzic et al., 2020	infill density, compare ultimaker 3d print model	Tensile	@1
10	Hasan et al., 2020	storage 6 month and heat treatment at 57.5C	Tensile	96 speciment
11	Triyono et al., 2020	nozzle hole diameter 0.3; 0.4; 0.5; 0.6	Porosity and tensile	@1 total 4
12	Farayibi and Omiyale, 2020	infill density, extruder temperature, taguchi	Tensile, Impact, hardness	@1

Even though the use of PLA material for the 3D printing process is very popular, there are still few research that discuss the use of appropriate parameters for printing with PLA. The search results of research on mechanical properties for PLA material in the 3D printing process in the Scopus database can be seen in Table 1.

In Table 1 it can be seen that all studies only use a very small number of samples, even though the plastic material produced by a 3D printer allows for variances between samples with the same parameters. In addition, in general statistics it is almost impossible to make conclusions from a single sample. This paper will focus on finding the optimum parameters to get the maximum value of mechanical properties. This paper will use 3 variables that have a major significant effect on the strength value of 3d printing products, namely: Infill density, extruder temperature and the pattern used. The mechanical properties to be used are impact charpy following the ASTM-D6110 standard.

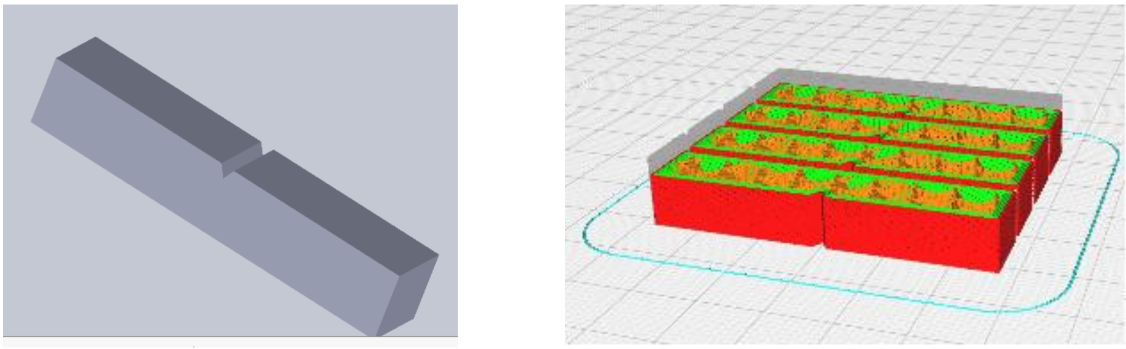
2. Method

This paper uses response surface methodology to determine the factors that significantly effect to mechanical properties of 3D printed products (Suryadarma et al., 2022). This methodology is also used to determine the optimum parameters recommended for printing using PLA material. Specimens were made following ASTM D6110 standards as in Figure 1. Specimens were drawn using SolidWorks software and saved as .stl files. Then slicing using Ultimaker Cura software to produce G-Code which is then run on a 3D printing machine with the type of Fused deposition modeling (FDM) as in Figure 2.



	mm	in.
A	10.16 ± 0.05	0.400 ± 0.002
B	63.5 max	2.50 max
	61.0 min	2.40 min
C	127.0 max	5.00 max
	124.5 min	4.90 min
D	0.25R ± 0.05	0.010R ± 0.002
E	12.70 ± 0.15	0.500 ± 0.006

Figure 1. Dimensions of Simple Beam, Charpy Type, Impact Test Specimen (ASTM D6110)



(a) **(b)**

Figure 2. The process of making specimens with CAD - CAM (a) CAD process with SolidWorks; (b) CAM process with Ultimaker Cura

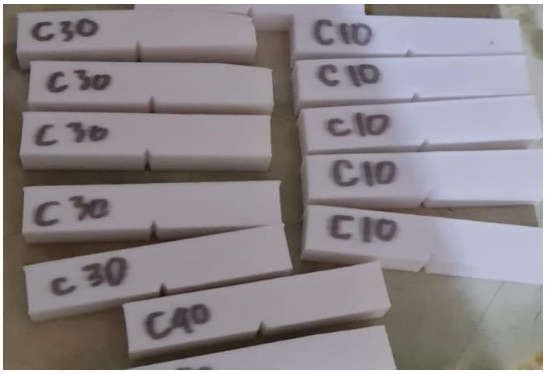


Figure 3. PLA specimens with several parameters ready to be tested

The test used a Charpy impact testing machine on 80 parameter combinations as in Figure 4 with 4 samples for each combination. The total specimens to be tested are 320 pcs. The mechanism for testing the impact charpy machine is by impact the hummer to the test specimen, then calculating the amount of energy absorbed by the specimen. The amount of energy absorbed then divided by the cross-sectional area of the impact area to obtain the impact value. This test used a machine with a hummer pendulum weight of 6kg and a hummer pendulum arm length of 0.5 meters.

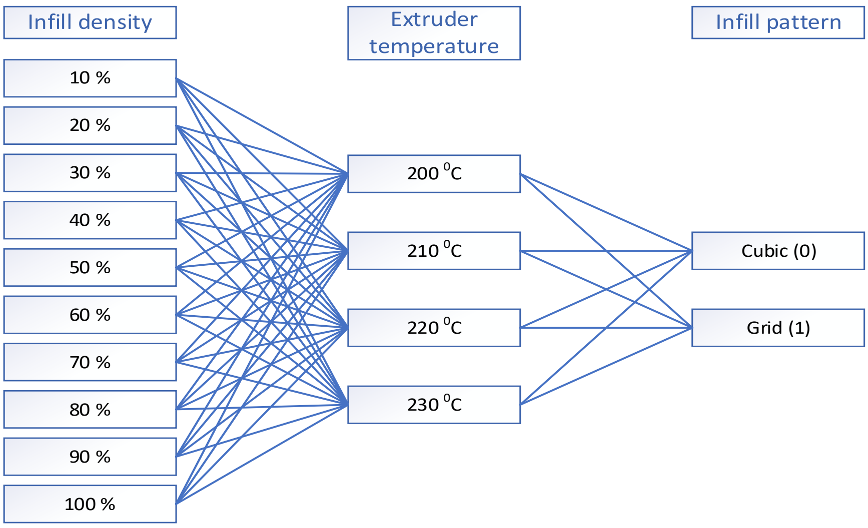


Figure 4. Parameter combination for the test specimens.

The initial angle of the hummer pendulum is 135 degrees. The parts of the impact machine can be seen in Figure 5. Because at the beginning before the impact (when the initial angle is 135 degrees) and the final position after the impact (when it reaches the maximum deviation read on the needle) the pendulum speed is zero, the kinetic energy value is equal to zero . So the energy absorbed by the specimen is the difference between the potential energy before and after the collision as in Equation (1).

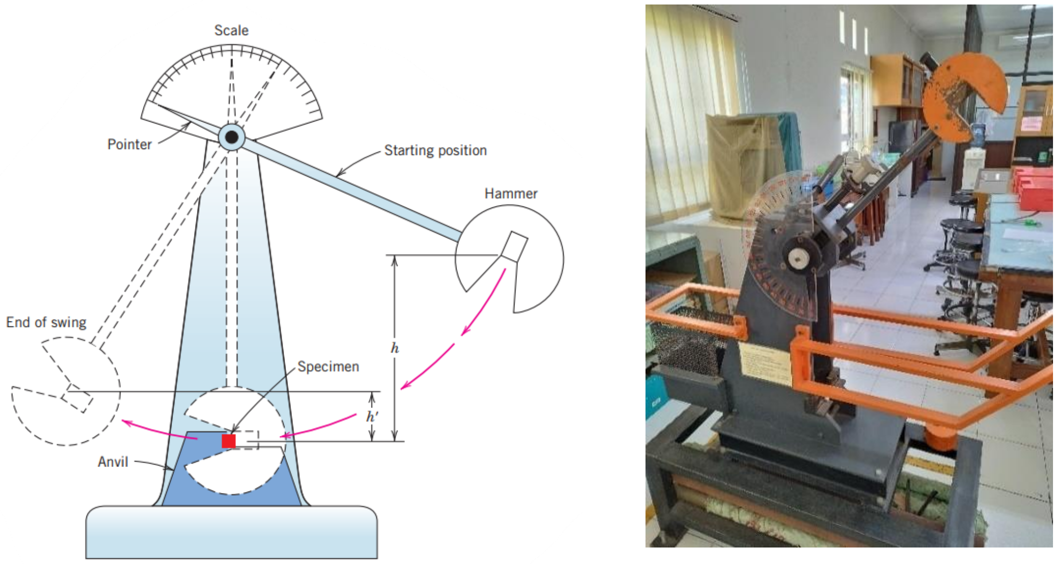
$$E_i = Ep_1 - Ep_2 \tag{1}$$

with,

E_i = Absorbed energy (Joule)

Ep_1 = Potential energy at the position before the collision (Joule)

Ep_2 = Potential energy at the maximum deviation position after the collision (Joule)



(a) **(b)**

Figure 5. Impact charpy machine (a) Illustration (Callister dan Rethwisch, 2020) ; (b) Machines for testing in the Laboratory.

Based on Equation (1) and Figure 4a. then the equation for the amount of energy absorbed can be calculated based on the initial and final pendulum deviation angles as in Equation (2).

$$E_i = m.g.l(\cos\beta - \cos\alpha) \tag{2}$$

with,

E_i = Absorbed energy (Joule)

m = Pendulum hummer mass (kg)

l = Pendulum hummer length (meter)

α = Pendulum hummer starting position (degree, value is 135^0)

β = Pendulum hummer at the maximum deviation position after the collision (degree)

So that the impact value can be calculated as equation (3).

$$K = \frac{1000.E_i}{A.W} \quad (3)$$

with,

K = Impact value (KJ/m²)
E_i = Absorbed energy (Joule)
A = Specimen thickness (mm), see Figure 1 dimension A
W = Width of specimen (mm), see Figure 1

3. Results and Discussion

The results of the experiments as part 2 can be seen in Table 2.

Table 2. Summary of Research on Mechanical Properties of 3D Printing Part from PLA Material.

No	Infill density (%), X1	Extruder Temp (⁰C), X2	Infill Pattern (0=Cubic; 1=Grid), X3	Impact Sample 1 (KJ/m²)	Impact Sample 2 (KJ/m²)	Impact Sample 3 (KJ/m²)	Impact Sample 4 (KJ/m²)	Impact Mean (KJ/m²), Y	Impact Std. Dev. (KJ/m²)
1	100	200	0	149.40	153.71	149.58	153.38	151.52	2.35
2	90	200	0	157.14	114.04	125.25	149.52	136.49	20.22
3	80	200	0	87.33	94.67	86.87	72.13	85.25	9.45
4	70	200	0	75.85	37.09	50.84	64.87	57.17	16.85
5	60	200	0	47.20	54.30	27.23	47.20	43.98	11.66
6	50	200	0	37.16	33.70	50.56	8.65	32.52	17.50
8	30	200	0	37.09	54.10	20.83	30.49	35.63	14.01
9	20	200	0	36.93	43.89	37.04	8.69	31.64	15.64
10	10	200	0	8.68	11.64	8.67	17.73	11.68	4.27
11	100	200	1	141.48	125.38	136.95	149.25	138.27	9.98
12	90	200	1	79.32	94.26	79.56	106.31	89.86	13.00
13	80	200	1	68.40	57.85	64.81	72.30	65.84	6.15
14	70	200	1	57.64	30.44	64.85	37.00	47.48	16.38
15	60	200	1	27.26	17.80	33.71	11.60	22.60	9.82
…	…	…	…	…	…	…	…	…	…
66	50	230	0	27.23	27.17	24.02	24.01	25.61	1.84
67	40	230	0	20.91	20.86	24.08	20.84	21.67	1.60
68	30	230	0	17.77	20.85	20.83	14.68	18.53	2.95
69	20	230	0	14.63	17.73	11.64	17.73	15.43	2.92
70	10	230	0	8.69	5.74	27.28	5.72	11.86	10.38
71	100	230	1	161.34	133.35	148.96	117.57	140.31	19.00
72	90	230	1	109.69	113.54	79.67	87.16	97.52	16.64
73	80	230	1	68.52	79.48	61.25	83.24	73.12	10.08
74	70	230	1	43.70	72.30	50.52	40.37	51.72	14.35
75	60	230	1	30.40	37.00	33.77	33.72	33.72	2.70
76	50	230	1	24.02	17.74	23.95	20.93	21.66	2.98
77	40	230	1	17.73	23.95	14.66	17.79	18.53	3.90
78	30	230	1	14.71	20.78	17.76	5.74	14.75	6.50
79	20	230	1	14.66	14.67	11.63	14.64	13.90	1.51
80	10	230	1	8.65	8.68	5.72	8.68	7.93	1.47

Table 2 shows the relationship between infill density (X1), extruder temperature (X2), infill pattern (X3) and impact value (Y). X1, X2, X3 are independent variables that have been determined at the beginning, while Y is a dependent variable that is effect by the independent variable. The equation between the independent and dependent variables for the value X3 = 0 can be seen in Equation 3. The equation between the independent and dependent variables for the value X3 = 1 can be seen in Equation 4.

$$Y = -1627 - 1.957X1 + 15.79X2 + 0.02415X1^2 - 0.03738X2^2 + 0.00355X1X2 \quad (3)$$

$$Y = -1680 - 2.140X1 + 16.02X2 + 0.02415X1^2 - 0.03738X2^2 + 0.00355X1X2 \quad (4)$$

Equation 3 and Equation 4 have an R-sq value of 97.03% so statistically it can be said that the Y value can be predicted well by the independent variables X1,X2,X3. Table 3 shows that the model's significance value is small (0.000), which means that the overall model is fit. Figure 6 shows at alpha = 0.05 X1 is the independent variable that has the greatest significant effect on this model. Meanwhile, X2 has the least significant effect on the model.

Table 3. Analysis of Variance

Source	DF	Adj SS	Adj MS	F-Value	P-Value
Model	8	154656	19332	289.90	0.000
Linear	3	128117	42706	640.40	0.000
X1	1	124049	124049	1860.19	0.000
X2	1	8	8	0.11	0.736
X3	1	4060	4060	60.89	0.000
Square	2	25763	12881	193.16	0.000
X1*X1	1	24645	24645	369.56	0.000
X2*X2	1	1118	1118	16.76	0.000
2-Way Interaction	3	776	259	3.88	0.013
X1*X2	1	104	104	1.56	0.216
X1*X3	1	547	547	8.20	0.005
X2*X3	1	126	126	1.89	0.174
Error	71	4735	67		
Total	79	159391			

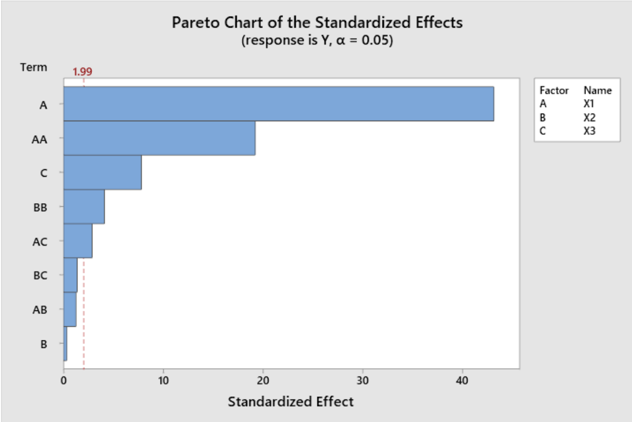


Figure 6. Pareto Chart of the Standardized Effects (response is Y, α = 0.05)

3.1. Parameter Optimization

This paper uses the Response Surface Methodology to obtain the optimimum parameters. Figure 7 illustrates the relationship between each variable and the value of the strength of the impact. It can be seen that the infill density (X1) has a significant exponential relationship to the impact strength. The Impact value will increase in proportion to the increase in the infill density variable (X1). Meanwhile, extruder temperature and infill pattern have little effect on impact strength. Figure 8a illustrates the relationship between the Infill density variable and the extruder temperature when using the cubic infill pattern. Dark green areas depict areas that have high impact strength. Figure 8b illustrates the relationship between the Infill density variable and the extruder temperature when using the infill pattern grid. Dark green areas depict areas that have high impact strength. This Contour Plot can be used as a reference to determine printing parameters according to the mechanical strength requirements of the product being made. In Figure 9 the surface plot between the infill pattern cubic and the infill pattern grid has a similar shape, this shows that there is no significant difference between using the infill pattern grid and cubic. Based on Figure 9,

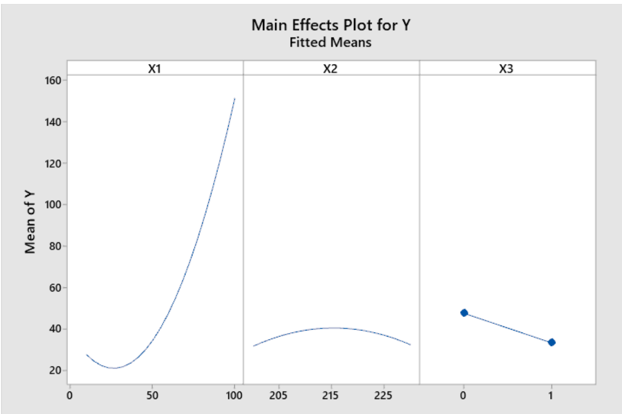
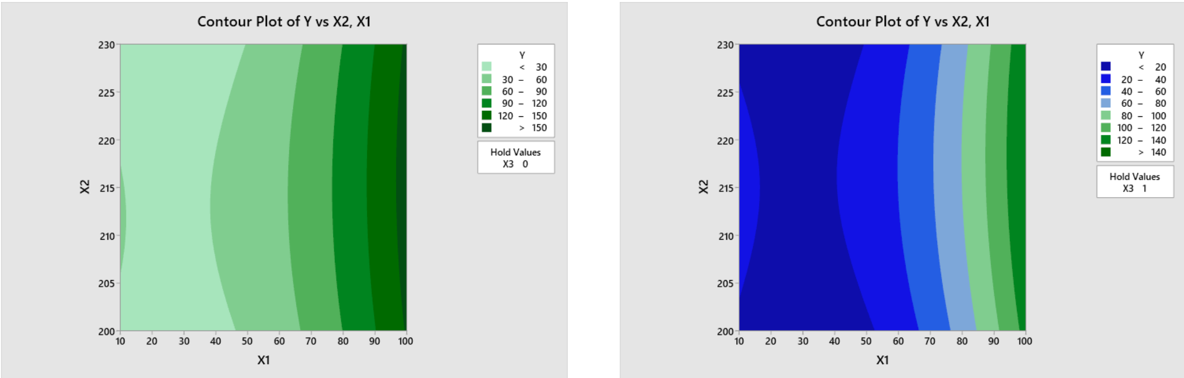


Figure 7. The relationship between each variable and impact strength.



(a) **(b)**

Figure 8. Contour Plot (a) X1,X2,X3=0 vs Y ; (b) X1,X2,X3=1 vs Y

(a) **(b)**

Figure 9. Surface Plot (a) X1,X2,X3=0 vs Y ; (b) X1,X2,X3=1 vs Y

Based on Figure 10, the maximum impact value is obtained when the infill density is 100%, the extruder temperature is 216.0606 ⁰C and a cubic infill pattern is used.

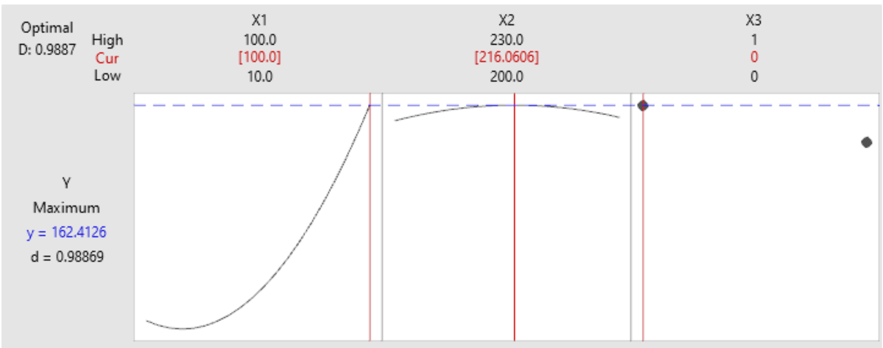


Figure 10 . Parameter Maximization

4. Conclusion

Based on the results of experiments and statistical analysis, the recommended setting to obtain the maximum impact value is setting infill density 100%, extruder temperature 216 ⁰C and infill pattern cubic. However, if you want to reduce product weight and PLA material costs, the recommended setting for infill density is 50-70%. Further research is expected to be carried out by adding other parameters of 3D printing process, for example printing speed, layer height, wall thickness, top/bottom thickness and other infill pattern.

References

Bluman, A. G. (2017). Elementary Statistics: A Step by Step Approach for MATH 10. McGraw Hill Education.

Bhandarkar, V. V., Patil, I. G., Shahare, H. Y., & Tandon, P. (2022, October). Understanding the Influence of Process Parameters for Minimizing Defects in 3D Printed Parts Through Remote Monitoring. In ASME International Mechanical Engineering Congress and Exposition (Vol. 86632, p. V02AT02A012). American Society of Mechanical Engineers.

Callister Jr, W. D., & Rethwisch, D. G. (2020). Callister's materials science and engineering. John Wiley & Sons.

Chen, Q., Mangadlao, J. D., Wallat, J., De Leon, A., Pokorski, J. K., & Advincula, R. C. (2017). 3D printing biocompatible polyurethane/poly (lactic acid)/graphene oxide nanocomposites: anisotropic properties. ACS applied materials & interfaces, 9(4), 4015-4023.

Choudary, R., Saini, N., Chopra, D. S., Singh, D., & Singh, N. (2023). A comprehensive review of 3D bioprinting biomaterials: Properties, strategies and wound healing application. Journal of Materials Research, 1-37.

Chua, C. K., Chou, S. M., & Wong, T. S. (1998). A study of the state-of-the-art rapid prototyping technologies. The International Journal of Advanced Manufacturing Technology, 14, 146-152.

Farayibi, P. K., & Omiyale, B. O. (2020). Mechanical behaviour of polylactic acid parts fabricated via material extrusion process: A taguchi-grey relational analysis approach. International Journal of Engineering Research in Africa, 46, 32-44.

Groover, M. P. (2020). Fundamentals of modern manufacturing: materials, processes, and systems. John Wiley & Sons.

Hasan, M. S., Ivanov, T., Vorkapić, M., Simonović, A., Daou, D., Kovacević, A., & Milovanović, A. (2020). Impact of aging effect and heat treatment on the tensile properties of PLA (poly lactic acid) printed parts. Materiale Plastice, 57(3), 147-159.

Khawly, G. N., Fabbri, N. R., McClung, A. J., & Ocampo, J. D. (2021). Impact Testing of a Commercial Poly-Lactic Acid. In Mechanics of Biological Systems and Materials & Micro-and Nanomechanics & Research Applications: Proceedings of the 2020 Annual Conference on Experimental and Applied Mechanics (pp. 5-8). Springer International Publishing.

Lee, J. Y., An, J., & Chua, C. K. (2017). Fundamentals and applications of 3D printing for novel materials. Applied materials today, 7, 120-133.

Mani, M., Karthikeyan, A. G., Kalaiselvan, K., Muthusamy, P., & Muruganandhan, P. (2022). Optimization of FDM 3-D printer process parameters for surface roughness and mechanical properties using PLA material. Materials Today: Proceedings, 66, 1926-1931.

Martinelli, A., Nitti, A., Po, R., & Pasini, D. (2023). 3D Printing of Layered Structures of Metal-Ionic Polymers: Recent Progress, Challenges and Opportunities. Materials, 16(15), 5327.

Mishra, A., Srivastava, V., & Gupta, N. K. (2021). Additive manufacturing for fused deposition modeling of carbon fiber–polylactic acid composites: the effects of process parameters on tensile and flexural properties. Functional Composites and Structures, 3(4), 045007.

Pandzic, A., Hodzic, D., Hajro, I., & Tasic, P. (2020, January). Strength Properties of PLA Material Obtained by Different Models of FDM 3D Printer. In Proceedings of the 31st DAAAM International Symposium on Intelligent Manufacturing and Automation, Mostar, ISSN (pp. 1726-9679).

Siddiqui, S., Surananai, S., Sainath, K., Khan, M. Z., Kuppusamy, R. R. P., & Suneetha, Y. K. (2023). Emerging Trends in the Development and Application of 3D Printed Nanocomposite Polymers for Sustainable Environmental Solutions. European Polymer Journal, 112298.

Suryadarma, E. H. E., Ai, T. J., Bawono, B., & Siswantoro, A. T. (2022). Improving bimetal bond quality between cast steel and aluminum alloys using response surface methodology. International Journal of Metalcasting, 1-10.

Teixeira, J., Schaefer, C. O., Rangel, B., Maia, L., & Alves, J. L. (2022). A road map to find in 3D printing a new design plasticity for construction–The state of art. Frontiers of Architectural Research.

Tian, X., Liu, T., Yang, C., Wang, Q., & Li, D. (2016). Interface and performance of 3D printed continuous carbon fiber reinforced PLA composites. Composites Part A: Applied Science and Manufacturing, 88, 198-205.

Travieso-Rodriguez, J. A., Jerez-Mesa, R., Llumà, J., Gomez-Gras, G., & Casadesus, O. (2021). Comparative study of the flexural properties of ABS, PLA and a PLA–wood composite manufactured through fused filament fabrication. Rapid Prototyping Journal, 27(1), 81-92.

Triyono, J., Sukanto, H., Saputra, R. M., & Smaradhana, D. F. (2020). The effect of nozzle hole diameter of 3D printing on porosity and tensile strength parts using polylactic acid material. Open Engineering, 10(1), 762-768.

Tura, A. D., Lemu, H. G., Melaku, L. E., & Mamo, H. B. (2022, October). Impact of FDM 3D Printing Parameters on Compressive Strength and Printing Weight of PLA Components. In International Workshop of Advanced Manufacturing and Automation (pp. 495-504). Singapore: Springer Nature Singapore.

Yadav, P., Sahai, A., & Sharma, R. S. (2023). Experimental studies on the mechanical behaviour of three-dimensional PLA printed parts by fused filament fabrication. Journal of The Institution of Engineers (India): Series D, 104(1), 233-245.

Yilan, F., ŞAHİN, İ. B., Fatih, K. O. Ç., & URTEKİN, L. (2023). The Effects of Different Process Parameters of PLA+ on Tensile Strengths in 3D Printer Produced by Fused Deposition Modeling. El-Cezeri, 10(1), 160-174.