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Mechanical properties of FDM 3D printed component using self-made PLA-titanium filament: hardness perspective

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Abstract

3D printing, also known as additive layer manufacturing, is a technique that creates three-dimensional objects or any shape from a digital model. It works by building objects layer-by-layer, similar to how a laser printer operates. Fused Deposition Modeling (FDM) is a widely used technique in 3D printing because it is easy to use, cost-effective in production, and environmentally friendly. This study focuses on a self-made filament made of a PLA-titanium mixture. PLA is a biodegradable thermoplastic polymer sourced from plants, whereas titanium is a strong, lightweight, and corrosion-resistant metal. To measure the hardness of different materials, there are several methods available. In this study, the Shore D hardness test, specifically designed for polymer materials, was used. Data were collected using the Taguchi method, specifically L4 (23), and the data were analysed using Analysis of Variance (ANOVA). The variations in print parameters examined in this study include nozzle temperature (230°C and 240°C), layer height (0.2 mm and 0.3 mm), and print speed (30 mm/s and 40 mm/s). The aim of this study was to determine whether there were any changes in the hardness of the specimens. The ANOVA results revealed that the most influential parameter was print speed, with a contribution value of 56.01%. The results demonstrated that the printing parameters affected the hardness of the printed specimens. The highest hardness level of 56.3 Shore D was obtained with a nozzle temperature of 240°C, a layer height of 0.3 mm, and a print speed of 30 mm/s. The application of this study was demonstrated through the creation of dentures made from PLA-titanium.

Keywords:
3D printing, hardness test, shore D, PLA, titanium.

1 Introduction

3D Printing is an additive manufacturing method that uniquely, innovatively, and creatively creates products using digital models. This technique allows product manufacturing without the need for expensive traditional cutting or casting machines. Also known as additive layer manufacturing, 3D printing creates objects in three dimensions or in any shape of the digital model. It operates similarly to a laser printer, building objects by printing multiple layers on top of each other [1, 2].

There are several techniques in 3D printing, one of which is Fused Deposition Modelling (FDM). FDM is widely used because of its easy operation, lower cost in the production process, and environmentally friendly nature [3].

The materials used in 3D printing are Acrylonitrile Butadiene Styrene (ABS), Polylactic Acid or Polylactide (PLA), PETG, and wood. The selection of filaments is essential in obtaining mechanical, thermal and chemical properties [4]

Previously, several studies on 3D printing using titanium were conducted. One such study was carried out by Grygier (2022) to investigate the deposition of biocompatible polymers on titanium alloys using 3D printing (FDM). The research demonstrated the feasibility of depositing PLA and PA (Polyamide) directly onto Ti6Al4V titanium alloy using FDM 3D printing. However, the study could have provided more satisfactory results in terms of the strength of the bonds achieved and the repeatability of the process [5]. Research conducted by Lin (2018) aimed to determine the biocompatibility of 3D-printed titanium alloy plates. The study found that these plates exhibited good biocompatibility, potentially offering innovative solutions for the clinical treatment of acetabulum fractures [6].

In this study, a filament was fabricated with a mixture of PLA and titanium. PLA is a biodegradable thermoplastic polymer derived from plant sources, such as plants that contain starch and sugar. Titanium is a metal that has strong, lightweight, and corrosion-resistant properties [7, 8].

Hardness testing is a faster and cheaper method for determining the mechanical properties of a material. There are several types of hardness tests, namely, ball indentation test (Brinell), pyramid indentation (Vickers), cone and ball indentation tests (Rockwell), microhardness tests,and knoop hardness [9]. Shore hardness testing uses two types of durometers: type A and type D. Type A durometers are used for softer materials such as rubber, while type D durometers are for harder materials such as acrylic, glass and fibre. The International Standard ISO 868 and draft ISO/CD 18898 describe verification methods for checking the Shore hardness testertypes A and D. Hardness tests for polymer materials use Shore D hardness testing, specifically for polymer materials [10][11].

The quality of a 3D printing product is determined by the process parameters. Some parameters commonly used in 3D printing are the layer height, bed temperature, printing speed, infill density, raster angle, extruder temperature, and infill pattern. The purpose of testing the effect of several parameters on the 3D printing process using PLA-titanium filaments was to determine whether there was a change in the hardness value of the specimen. This research was applied to dentures made from PLA-titanium. The hardness value on the tooth surface of composite resin is 81.022 SHD (Shore Hardness D) [12].

2 Research Method

The PLA-titanium filament used as a material in the specimen manufacturing was made using PLA seed material and titanium powder. The filament was successfully fabricated through the extrusion process. The single-screw extrusion machine was electrically powered by a motor. PLA seed and titanium powder were fed to the extruder via hooper. The extruded filament was collected using a spooler. The next step was to print the specimen using a 3D printing machine. Hardness test specimens were printed according to the ASTM D2240 standard, which is recommended for hardness testing using Shore D test equipment [13]. Twelve specimens were printed using the Ender V3 3D printing machine, and then a hardness test was performed using a Shore D testing machine.

Factorial design using the Taguchi orthogonal arrays L_4 $(2)^3$ method was employed with three variables: nozzle temperature, layer height, and printing speed. Each of these has two levels [14]. Then, the hardness test strength data were processed with Analysis of Variance (ANOVA) and S/N Ratio. The factors and their levels are listed in Table 1.

Table 1. Factor and level variable

Factor	Level 1	Level 2
Nozzle temperature (°C)	230	240
Layer height (mm)	0.2	0.3
Print speed (mm/s)	30	40

3 Results and Discussion

The filament printing results use a composition of 60% Polylactic Acid (PLA) seeds and 40% titanium powder. The temperature setting in both heater bands is 200°C using a thermocouple. The filament as shown in Fig. 1.

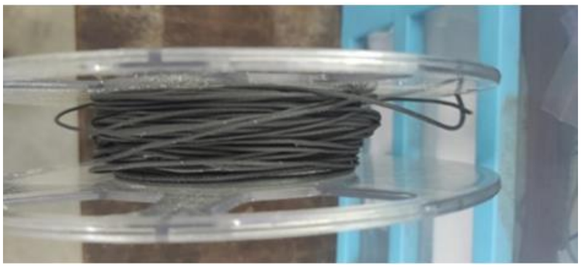


Fig. 1. Filament PLA-titanium.

The printing results using ASTM D2240 have as many as 12 specimens. The specimen measures 6.4 mm thick, 20 mm long and wide. The results of printing untested specimens as shown in Fig. 2.

Fig. 2. Hardness test specimens.

Hardness testing was performed at five different points on each specimen, resulting in five hardness values for each specimen. The hardness value of the Shore D scale was calculated by averaging the hardness values. The hardness data are presented in Table 2 (columns 2-7).

Table 2. Hardness test result data

Parameter control			Hardness test (Shore D) Replication			S/N Ratio
Nozzle temperature (°C)	Layer height (mm)	Print speed (mm/s)	1	2	3	
2	3	4	5	6	7	8
230	0.2	30	54.2	54.1	55	34.72
230	0.3	40	35	30.4	44	30.94
240	0.2	40	49.8	46.4	47.3	33.58
240	0.3	30	52.1	56.3	50.7	34.47

The minor hardness test was 30.4 Shore D in experiment 2, with a nozzle temperature of 230°C, a layer height of 0.3 mm, and a print speed of 40 mm/s. The most considerable hardness test value was 56.3 HD in experiment 4 with a nozzle temperature of 240°C, layer height of 0.3 mm, and print speed of 30 mm/s.

This study used ANOVA calculations. ANOVA is a calculation analysis method used to estimate the magnitude of the contribution of each factor to all response measurements. The analysis model in this study uses a two-way variant consisting of calculating degrees of freedom, the sum of squares, the average number of squares and the F ratio [15]. ANOVA in this study was calculated based on means data. The following ANOVA calculation results as shown in Table 3.

Table 3. ANOVA Table

Control factor	DoF (Degree of freedom)	SS (Sum of square)	MS (Mean squares)	F (Factor)
Nozzle temperature	1	74.5	74.5	4.99
Layer height	1	122.24	122.24	8.19
Printing speed	1	402.52	402.52	26.97
Error	8	119.39	14.92	
Total	11	718.65	65.33	

In this study, using the S/N ratio large is better because the more significant the hardness value obtained, the better the quality of the product. The S/N ratio is the ratio between signal (controlled factor) and noise (uncontrollable factor) [15]. The calculation of the S/N ratio of significance is better for each hardness-testing experiment, as shown in Table 2 (column 8). The formula for the signal to noise ratio as shown in Eq. 1.

$$\text{S/N Ratio Large is Better} = -10\log\left(\frac{1}{n}\sum_{i=1}^{r}\frac{1}{Yi^2}\right) \qquad (1)$$

The average plot of the S/N Ratio at each level of variation in the parameters used in this study, namely nozzle temperature, layer height, and print speed, is shown in Fig. 3 for the S/N ratio chart. In the graph, the S/N ratio indicates the optimal level results for each variation of the parameters used. The print speed has the highest graph compared to layer height and nozzle temperature.

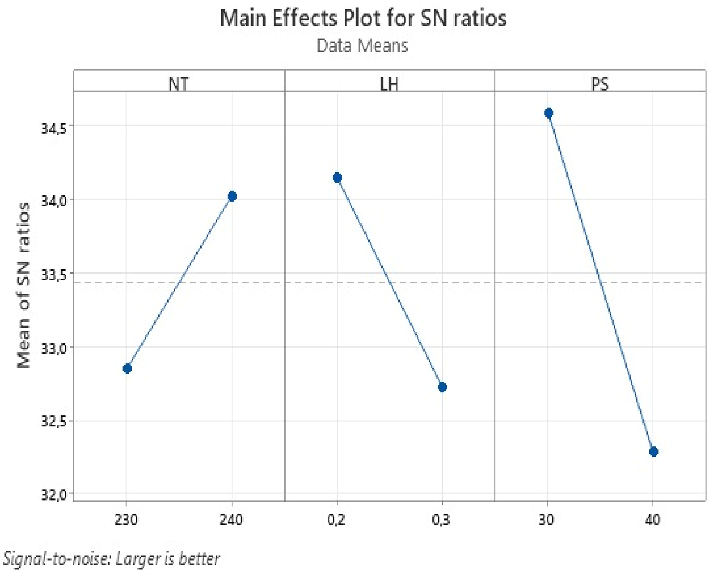
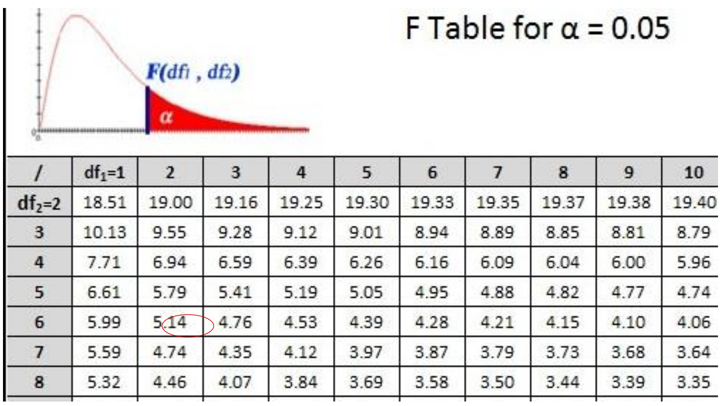


Fig. 3. Chart S/N Ratio.

This study used the F distribution 0.05 and produced an F-Table value of 4.07 with an α of 0.05 with 95% confidence. 4.07 is obtained from the formula involving 3 parameters, and 2^3 equals 8. The F-Table as shown in Fig. 4.



/	df_1=1	2	3	4	5	6	7	8	9	10
df_2=2	18.51	19.00	19.16	19.25	19.30	19.33	19.35	19.37	19.38	19.40
3	10.13	9.55	9.28	9.12	9.01	8.94	8.89	8.85	8.81	8.79
4	7.71	6.94	6.59	6.39	6.26	6.16	6.09	6.04	6.00	5.96
5	6.61	5.79	5.41	5.19	5.05	4.95	4.88	4.82	4.77	4.74
6	5.99	5.14	4.76	4.53	4.39	4.28	4.21	4.15	4.10	4.06
7	5.59	4.74	4.35	4.12	3.97	3.87	3.79	3.73	3.68	3.64
8	5.32	4.46	4.07	3.84	3.69	3.58	3.50	3.44	3.39	3.35

Fig. 4. F distribution table.

This study used an F distribution of 0.05 and produced an F-Table value of 4.07 with an α of 0.05 and a confidence of 95%. After looking at the F-Table to see its significance, print speed, nozzle temperature, and layer height factor significantly affect the hardness value of the specimen in this test. The value of F-Ratio is greater than F-Table. The results of the F test as shown in Table 4.

Table 4. F test

Parameter	F-Ratio	P
Nozzle temperature	4.99	Significant
Layer height	8.19	Significant
Print speed	26.97	Significant

In research, per cent contribution is used to assess how much influence each factor has on the response studied. After calculating the error in this study, it has a value of 16.61%. The result of this value allows for variables that influence response but are not included in the orthogonal matrix [14]. The results of the per cent contribution value obtained to the hardness value of the specimen test as shown in Table 5.

Table 5. Percent contribution

Control factor	Percent contribution
Nozzle temperature	10.37%
Layer height	17.01%
Print speed	56.01%
Error	16.61%
Total	100%

High print speeds cause specimen test results not to cool optimally between layers, resulting in less dense mould structures and being prone to cracks or structural failure. Conversely, a slower print speed can result in prints with a denser and more robust structure.

In this study, print speed has the percentage of parameters with the most significant influence, which is 56.01%. The optimal level that produces the hardness value at print speed is level 1, which is 30 mm/s. The S/N value for the print speed ratio at level 1 is 34.60. Based on Pratama and Adib's (2022) research, the results of parameter variations, the lower the print speed, it can produce prints with a denser and stronger structure [16]. High print speed can result in suboptimal specimen test results as it may not allow for adequate cooling between layers, leading to less dense and crack prone print structures. Conversely, lower print speeds tend to produce prints with denser and stronger structures, as evident in the highlighted areas in the red marked image.

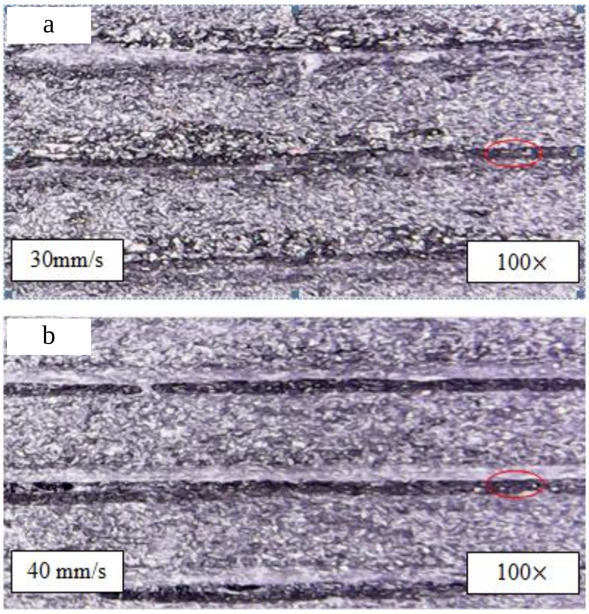


Fig. 5. Microprint speed test (a) is better than (b).

Layer height affects the thickness of each layer of 3D Printing. Increasing the thickness enhances the material's resistance to deformation, thereby influencing the hardness value obtained in the test results. A more significant number of layers on the print results strengthens the connection between layers, which can increase the strength of the print.

As seen in Fig. 6, the contribution of layer height has a parameter percentage of 17.01%. The optimal level that produces hardness values at layer height is level 1, 0.2 mm, with a S/N value 34.15.

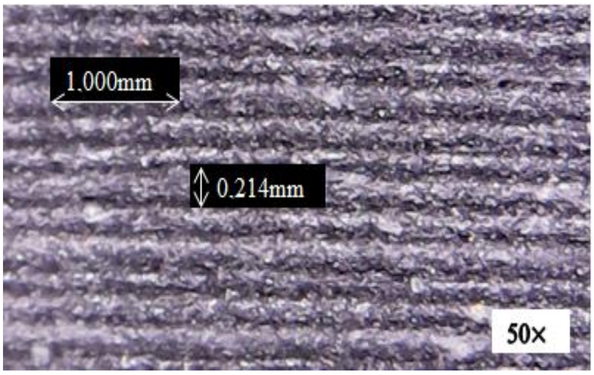


Fig. 6. Micro layer height test 0.2 mm.

Based on Sandi's (2022) research on layer height, the lower the variable, the higher the hardness value and the higher the layer height, the smaller the hardness value due to the higher layer density [17].

The nozzle temperature had the least influence on the hardness values of the 3D printing results in this study. Nozzle temperature affects the hardness value because the strength and weakness of the layer-by-layer bond in resisting pressure affect the value of the hardness test results. High nozzle temperature affects the mechanical properties of the mould. When the filament was heated to high temperatures, the strength of the mould increased as the plasticity of the material decreased and the stiffness properties increased.

In the study of the hardness value made from PLA-titanium, the contribution of nozzle temperature accounts for 10.37% of the parameters. The optimal level that produced the hardness value at the nozzle temperature was level 2 at 240°C. The S/N value of the nozzle temperature level 2 ratio is 34.03. Based on Arifin's (2021) research on nozzle temperature, the higher the results of 3D printing with the nozzle temperature, the greater the load that can be withstood [14].

In Fig. 7, it can be seen that the microstructure of the PLA-titanium mixed 3D printing filament with nozzle temperatures of 230°C and 240°C is not too noticeable. Titanium powder does not melt completely, which means the extrusion process does not have much effect on titanium powder. This is because the temperature of the 3D printing machine used is far from the melting temperature of titanium (1668°C); therefore, at temperatures of 230°C and 240°C, titanium only appears to be warmed.

The results of this study show that the highest hardness value was 56.3 Shore D. This result has a hardness value that is sufficient for application to product objects. The PLA-titanium material used in this study is safe to use on the human body. One example of a suitable product object related to this research is dentures. Polylactic Acid (PLA) is a biocompatible, biodegradable, non-toxic, and non-carcinogenic polymer for the human body, derived from renewable resources. Therefore, they are highly suitable for medical and food packaging applications. Titanium is biocompatible. It is completely non-toxic to humans and animals, partly due to the fact that titanium is corrosion-resistant. As a result, it can be safely implanted into the body without causing adverse reactions. Fig. 8 is results of product printing using a 3D printing machine.

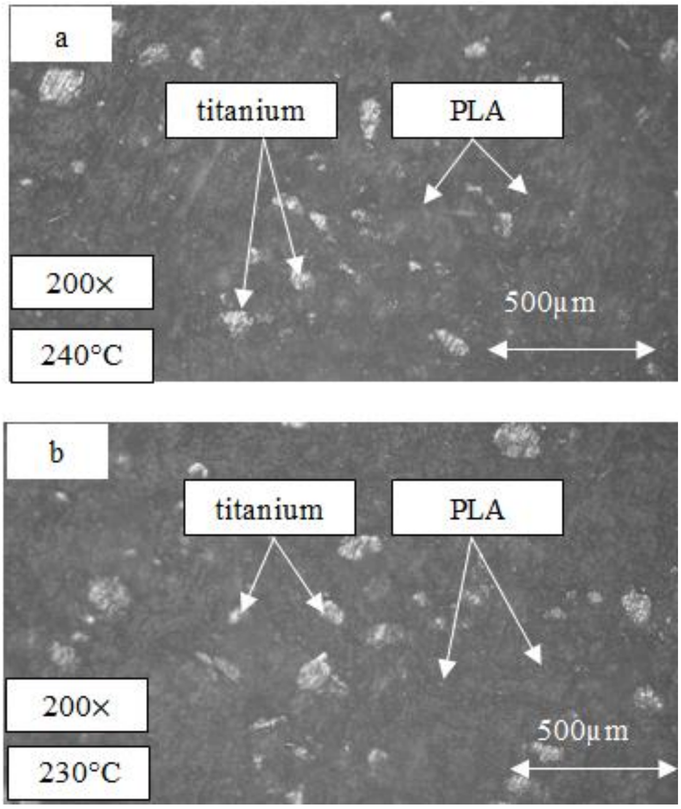


Fig. 7. Microprint speed tests (a) and (b) are not too noticeable.


Fig. 8. Dentures.

4 Conclusion

The influence of parameters can affect the level of hardness; the higher the print temperature, the higher the value of the hardness test results, while a suitable print speed parameter can reduce the possibility of deviations and defects in the print. In addition, the optimal layer height parameter can affect the quality of the mould surface and the level of strength in the print fill.

Based on this study, the variation in parameter values that produce the most optimal hardness value strength is nozzle temperature of 240°C, layer height of 0.2 mm, and print speed of 30 mm/s. Combining optimal print parameters can produce strong hardness values**.**

References

[1] Rasyid, S., RusdiNur, M. M., &Basongan, Y. (2022). Simulation and Experimental Evaluation of Tensile Properties and Macrostructure Changed of 3D printer PLA Filament.Polimesin, 20(2), 121–127.

[2] Putra, K. S., & Sari, U. R. (2018). Pemanfaatan Teknologi 3D Printing Dalam Proses Desain Produk Gaya Hidup. Seminar Nasional Sistem Informasi Dan Teknologi Informasi 2018, 1–6

[3] Aminur, M., Mat, S., Sam, M. S., Ramli, F. R., Alkahari, M. Ri., & Kudus, S. I. A. (2020). Design and development of 3D printer filament extruder. Proceedings of Mechanical Engineering Research, December, 293–294.

[4] Triono, A., Darsin, M., Wcs, I. M. I., Asrofi, M., Prakoso, S. H., & Fajrul, R. (2023). Flexural Strength Optimization as Effect of Infill Pattern Variation in FDM 3D Printing of Multi-layers ABS-PLA Flexural Strength Optimization as Effect of Infill Pattern Variation in FDM 3D Printing of Multi-layers ABS-PLA (Issue April). Atlantis Press International BV. https://doi.org/10.2991/978-94-6463-134-0

[5] Grygier, D., Kujawa, M., & Kowalewski, P. (2022). Deposition of Biocompatible Polymers by 3D Printing (FDM) on Titanium Alloy. Polymers, 14(2). https://doi.org/10.3390/polym14020235

[6] Lin, X., Xiao, X., Wang, Y., Gu, C., Wang, C., Chen, J., Liu, H., Luo, J., Li, T., Wang, D., & Fan, S. (2018). Biocompatibility of Bespoke 3D-Printed Titanium Alloy Plates for Treating Acetabular Fractures. BioMed Research International, 2018. https://doi.org/10.1155/2018/2053486

[7] Lim, L. T., Auras, R., & Rubino, M. (2008). Processing technologies for poly(lactic acid). Progress in Polymer Science (Oxford), 33(8), 820–852. https://doi.org/10.1016/j.progpolymsci.2008.05.004

[8] Sofyan, B. T. (2021). Pengantar Material Teknik (2nd ed.). UNHAN RI PRESS.

[9] Kumayasari, M. F., & Sultoni, A. I. (2017). Studi Uji Kekerasan Rockwell Superficial vs Micro Vickers. Jurnal Teknologi Proses Dan Inovasi Industri, 2(2). https://doi.org/10.36048/jtpii.v2i2.789

[10] Mohamed, M. I., & Aggag, G. A. (2003). Uncertainty evaluation of shore hardness testers. Measurement: Journal of the International Measurement Confederation, 33(3), 251–257. https://doi.org/10.1016/S0263-2241(02)00087-8

[11] Sandi, A., Mahardika, M., Cahyono, S. I., Salim, U. A., Pratama, J., & Arifvianto, B. (2022). Pengaruh variasi parameter cetak dan post process terhadap tingkat kekerasan spesimen hasil cetak tiga dimensi berbasis stereolithography (SLA). Conference SENATIK STT Adisutjipto Yogyakarta, 7, 33–46. https://doi.org/10.28989/senatik.v7i0.454

.[12] Ristian Putri, Y. I., Firdausy, M. D., & Woroprobosari, N. R. (2018). Tingkat Kekerasan Permukaan Resin Komposit Akibat Masa Kedaluwarsa Material. ODONTO : Dental Journal, 5(1), 45. https://doi.org/10.30659/odj.5.1.45-48

.[13] Sumathy Raj, S., Anton Michailovich, K., Subramanian, K., Sathiamoorthyi, S., & Thanneerpanthalpalayam Kandasamy, K. (2018). Philosophy of Selecting ASTM Standards for Mechanical Characterization of Polymers and Polymer Composites. Mater. Plast, 58(3), 247–256.

[14] Zamheri, Arifin, A. (2021). Pengaruh Parameter Pada Proses 3d Printing Menggunakan Fillament Eal-Fill Terhadap Akurasi Dimensi Dan Kekerasan Dengan Pendekatan Metode Taguchi. 7(2), 30–34

[15] Soejanto. (2009). Desain eksperimen dengan metode Taguchi (1st ed.). Graha Ilmu.

[16] Pratama, J., & Adib, A. Z. (2022). Pengaruh Parameter Cetak pada Nilai Kekerasan serta Akurasi Dimensi Material Thermoplastic Elastomer (TPE) Hasil 3D Printing. 25(1), 35–44

[17] Sandi, A., Mahardika, M., Cahyono, S. I., Salim, U. A., Pratama, J., & Arifvianto, B. (2022). Pengaruh variasi parameter cetak dan post process terhadap tingkat kekerasan spesimen hasil cetak tiga dimensi berbasis stereolithography (SLA). Conference SENATIK STT Adisutjipto Yogyakarta, 7, 33–46. https://doi.org/10.28989/senatik.v7i0.454

[18] Taqdissillah, D., Mutaqqin, A. Z., Darsin, M., Dwilaksana, D., &Ilminnafik, N. (2022). The Effect of Nozzle Temperature, Infill Geometry, Layer Height and Fan Speed on Roughness Surface in PETG Filament. Journal Mechanical Engineering Science and Technology (JMEST) Vol. 6, No. 2, November 2022, pp. 74-84.