OPTIMIZING PROCESS PARAMETERS FOR FILAMENT 3D PRINTING USING THERMOPLASTIC POLYURETHANE (TPU) WITH RESPONSE SURFACE METHODOLOGY (RSM)

Umi Khulsum Salbiah
Mechanical Engineering Study Program
Sekolah Tinggi Teknologi Wastukancana Purwakarta, Purwakarta, Indonesia
Email: Umikhulsum.shalbiah@gmail.com

Apang Djafar Shieddique
Mechanical Engineering Study Program
Sekolah Tinggi Teknologi Wastukancana Purwakarta, Purwakarta, Indonesia
Email: apang@wastukancana.ac.id

Rohman Rohman
Mechanical Engineering Study Program
Sekolah Tinggi Teknologi Wastukancana Purwakarta, Purwakarta, Indonesia
Email: rohman@wastukancana.ac.id

ABSTRAK

3D Printing menggunakan proses fabrikasi *Fused Deposition Modelling* (FDM), yaitu teknologi *Additive Manufacturing* (AM) yang membangun objek secara lapis demi lapis (Pristiansyah dkk, 2019). Penggunaan teknologi 3D Printing telah meningkat pesat dalam beberapa tahun terakhir, berkontribusi signifikan terhadap kualitas dan efisiensi biaya pembuatan prototipe. Filamen TPU (*Thermoplastic Polyurethane*) sering digunakan karena menghasilkan produk yang lebih berat, keras, dan tahan lama. Optimasi proses cetak 3D printing penting untuk mencapai hasil yang optimal, salah satunya dengan metode *Response Surface Methodology* (RSM). Dalam penelitian ini, RSM digunakan dengan 2 faktor untuk mencari respon terbaik dalam kekuatan tarik dan kekerasan material TPU. Hasil eksperimen menunjukkan bahwa parameter optimal untuk kekuatan tarik adalah suhu sekitar 190ºC dan kecepatan cetak 45mm/m, menghasilkan kekuatan tarik sebesar 2,34 kgf/mm2. Sedangkan untuk kekerasan maksimal, parameter optimal adalah suhu 214,15ºC dan kecepatan cetak 45mm/m, dengan nilai kekerasan 72,67 HRR. Dengan demikian, metode RSM dapat menjadi pendekatan yang efektif dalam meningkatkan hasil cetakan 3D Printing pada material TPU.

Kata kunci : *3D printing, filament TPU, response surface methodology (RSM)*

ABSTRACT

3D Printing utilizes the fabrication process of Fused Deposition Modeling (FDM), which is an Additive Manufacturing (AM) technology that builds objects layer by layer (Pristiansyah et al., 2019). The use of 3D Printing technology has rapidly increased in recent years, significantly contributing to the quality and cost efficiency of prototype production. TPU (Thermoplastic Polyurethane) filament is often used because it produces heavier, harder, and more durable products. Optimizing the 3D printing process is crucial to achieving optimal results, one of which is through the Response Surface Methodology (RSM) method. In this study, RSM was used with 2 factors to find the best response in tensile strength and material hardness of TPU. The experimental results showed that the optimal parameters for tensile strength are a temperature of around 190°C and a print speed of 45mm/m, resulting in a tensile strength of 2.34 kgf/mm². Meanwhile, for maximum hardness, the optimal parameters are a temperature of 214.15°C and a print speed of 45mm/m, with a hardness value of 72.67 HRR. Thus, the RSM method can be an effective approach in improving the 3D Printing results on TPU material.

Keywords: *3D printing, filament TPU, response surface methodology (RSM)*

1. INTRODUCTION

Plastic waste is one of the sources of problems for all living things, especially humans and their environment. So there is a need for awareness of this adverse impact. Measures such as the use of environmentally friendly alternatives, plastic reduction education, and government policies to limit the production and distribution of single-use plastics are increasingly being promoted [1]. In the current industrial era, technological developments are progressing very rapidly, one of which is 3D printing technology or also known as additive manufacturing. One well-known 3D printing technology is Fused Deposition Modeling (FDM). The working principle of FDM is by extruding thermoplastic through a hot nozzle at a melting temperature, then the product is made layer by layer [2]. Rapid prototyping such as 3D printing is one of the most efficient tools in product development. The Fused Deposition Modeling (FDM) method, in which products are produced through this process, has the potential to compete with conventional manufacturing methods such as injection moulding [3]. Until now, the FDM method has been widely used in the 3D printing process due to its ease of use, lower cost, environmental friendliness, and greater simplicity in product development, prototyping, and manufacturing [4]. The research conducted by Zaldi Sriwansyah Suzen, titled "Optimization of 3D Printing Product Parameters on Tensile Strength Using TPU (Thermoplastic Polyurethane) Filament", is based on the results of tensile tests. The calculation of the S/N ratio is shown in Table 5 and Figure 6, indicating that the highest tensile strength was achieved in Experiment 7 with a value of 12.97 MPa, while the lowest result was found in Experiment 2 with a value of 11.87 MPa. Based on Table 5, the highest-ranked parameter was the Z-orientation [4]. The research conducted by Silsa Zakaria, Rizky Stighfarrinata, and Amalia Ma'rifatul Maghfiroh, titled *"Optimization of 3D Printing Process Parameters on the Tensile Strength of PETG Filament Using the Taguchi Method"*, revealed that based on the tensile test data of the specimens, the highest average tensile strength was 49.14 MPa, while the lowest average tensile strength was 45.55 MPa [5]. Meanwhile, the research by Sandi Riskiawan, Hastuti Delima, Helmina Andami, Mardiyati, and Steven found that the optimum printing temperature, printing speed, retraction distance, and retraction speed for printing TPU filament were 230°C, 40 mm/s, 1 mm, and 40 mm/s, respectively. Specimens printed in the 0° orientation showed higher tensile strength compared to those printed in the 90° orientation [6]. This research will optimize the parameters of Thermoplastic Polyurethane (TPU) 3D Printing filament using the Response Surface Methodology (RSM) method, with the hope of increasing understanding of TPU use in 3D Printing and contributing to the reduction of plastic waste through recycling.

2. METHOD

The specimen printing process in this study was carried out using a 3D printer, with the research flow diagram shown in Figure 1 [7].

2.1 *Flowchart*

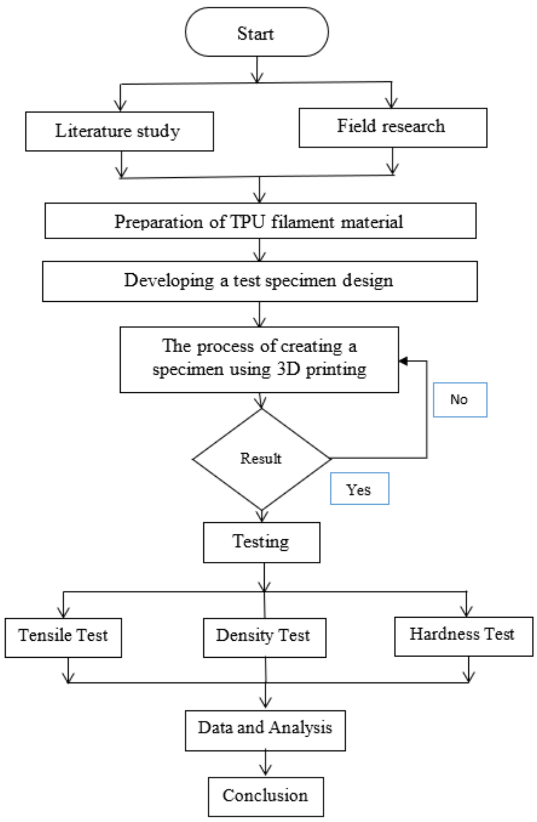

Figure 1. Flowchart

2..2 *Preparation of Thermoplastic Polyurethane (TPU) Material*

This research will use TPU (Thermoplastic Polyurethane) material. TPU is a type of thermoplastic polymer that possesses elastic properties and relatively good mechanical strength [8]. In this study, 95A TPU filament material was used as the raw material for 3D printing, in a transparent black color and branded as FLSUN Filament [9]. TPU can be seen in Figure 2.

Figure 2. Termoplastic polyurethane (TPU) material

2.3 *Specimen Manufacturing Process*

2.3.1 *Designing Specimens with AutoCAD*

For the next process, material samples will be printed according to the number to be analyzed and sized based on the ASTM D638 TYPE IV standard [10] as in Figures 3 and 4.

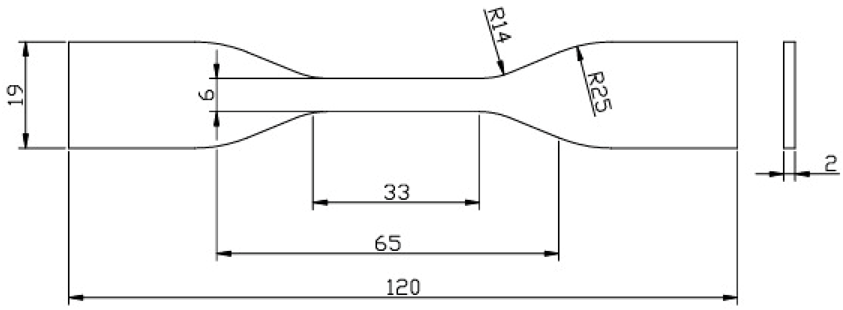

Figure 3. Design of tensile test specimen

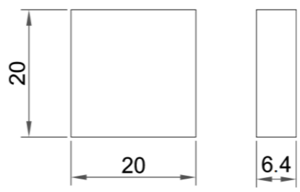

Figure 4. Design of hardness test specimen

2.3.2 *The Printing Process*

The choice of the ASTM D638 TYPE I standard is due to its relevance in assessing properties plastic tensile is very possible, while the Anet ET4 3D printing machine, in Figure 5 that was chosen because it has the advantages of precision and reliability [11].

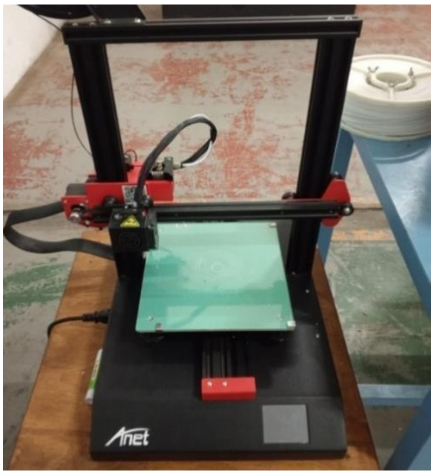

Figure 5. 3D printing machine

The procedure for printing specimens with a 3D printing machine starts with preparing the TPU filament to be used and loading it onto the machine. Next, connect the power cable to turn on the machine and connect the machine to the laptop using a USB cable. Then, run the UltiMakerCURA software on the laptop and perform the slicing process on the ASTM D638-IV specimen design image to start the printing process. Figure 6 visualizes this process.

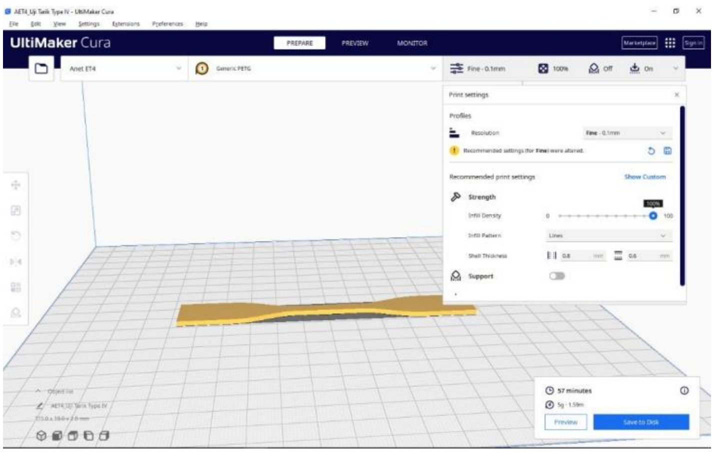

Figure 6. Slicing process in UltiMakerCURA

2.4 *Testing Process*

2.4.1 *Tensile Test*

Tensile testing is carried out by continuously applying a tensile force to the specimen as in Figure 7, causing the material (its elongation) to increase steadily and consistently until it breaks, with the aim of determining the tensile strength value [12].

Printed ISSN: 1411-4348
Online ISSN: 2541-4577

Figure 7. Tensile testing machine

In conducting tensile strength testing, the first step is to measure the length, width, thickness, and cross-sectional area of the specimen. Next, the Universal Testing Machine (UTM) and computer are turned on to prepare the machine's operation. Here is a U.T.M Testing Program in Figure 8 as follows:

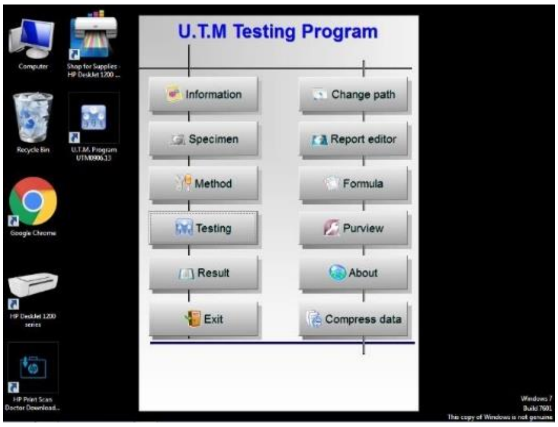

Figure 8. Universal testing machine program

The specimens are then placed in the grips of the testing machine according to the specified marks, using the UP button to raise or the DOWN button to lower the grips. After that, the Universal Testing Machine program is activated. Next, material data is entered into the Method Window, including Type, Gauge, Grip Length, and testing method, which in this case uses the plastic method at a pull rate of 20 mm/minute. The testing display is created by opening information such as the test number, test date, and material name. The test is conducted by pressing the RUN button on the toolbox, and the test results are printed by pressing the PRINT button. Finally, the material is released from the grips on the testing machine, and the length of the material is measured in the area previously marked.

2.4.2 *Rockwell Hardness Test*

Rockwell Hardness Testing is among the most commonly used techniques in mechanical engineering to determine the relative hardness of a material [13].

Figure 9. Rockwell hardness test

Rockwell hardness testing, as in Figure 9, according to the ASTM D 785 standard, is conducted using the R scale, a steel ball indenter, and a 60 kgf force. The Rockwell hardness testing method begins by placing the material on the test table or base. Next, the steel ball indenter is pressed against the material to be tested, and the lever is pulled to apply the major load. After that, wait for about 15-20 seconds. After a certain period of time, the major load is removed, but the minor load is retained for Rockwell hardness measurement.

2.5 *Density Test*

The measurement of mass per unit volume of an object. The higher the density of an object, the greater its mass for each unit of volume [14].

Figure 10. Density test

The steps for density testing begin with measuring the specimen to obtain its length, width, and thickness in order to determine the specimen's volume. Once the volume of the specimen is known, it is weighed to determine its mass. Subsequently, density is calculated using the formula for density, formulated as in Equation 1, and the density test as in Figure 10:

$$\rho = m/v \tag{1}$$

where

ρ = Density
m = Mass
v = volume [15]

2.6 *Design of Experiment Using RSM Method*

In research involving a second-order response surface, an appropriate experimental design is to use central composite design (CCD) or Box-Behnken design. This design requires a larger number of experimental units than the 2-level factorial design used for first-order response surfaces. For example, the use of response surface methodology (RSM) in Minitab software using central composite design can be seen in Table 1.

Table 1. Design of experiment (DOE) using RSM method

StdOrder	RunOrder	PtType	Blocks	Temperature (C)	Print Speed (mm/menit)
1	1	1	1	180	40
2	2	1	1	200	40
3	3	1	1	180	50
4	4	1	1	200	50
5	5	-1	1	175.86	45
6	6	-1	1	204.14	45
7	7	-1	1	190	37.93
8	8	-1	1	190	52.07
9	9	0	1	190	45
10	10	0	1	190	45
11	11	0	1	190	45
12	12	0	1	190	45
13	13	0	1	190	45

3. RESULTS AND DISCUSSION

3.1 *Tensile Test Data*

Table 2. Tensile strength test data results

No.	Specimen		Tensile Strength (kgf/mm^2)			Elongation (%)			Average Tensile of Sample 1,2,3	Average Elongation of Sample 1,2,3
	Temperature (°C)	Print Speed (mm/m)	1	2	3	1	2	3		
1	180	40	1.85	1.76	1.88	550	855	928	1.83	777.67
2	200	40	1.67	1.7	1.64	822	781	465	1.67	689.33
3	180	50	1.67	1.83	1.71	1021	892	865	1.74	926
4	200	50	1.45	1.68	1.69	837	910	829	1.61	858.67
5	175.86	45	1.6	1.69	1.63	812	900	813	1.64	841.67
6	204.15	45	1.87	1.7	1.7	730	804	748	1.76	760.67
7	190	37.92	1.64	1.75	1.76	812	819	772	1.72	801
8	190	52.08	1.77	1.88	1.76	890	966	909	1.80	921.67
9	190	45	1.94	2.17	2.03	1108	1170	1026	2.05	1101.33
10	190	45	1.71	2.27	2.14	937	1013	1045	2.04	998.33
11	190	45	1.85	2.28	2.64	905	1061	945	2.26	970.33
12	190	45	2.33	2.47	2.21	996	997	967	2.34	986.67
13	190	45	2.26	2.05	2.21	1070	976	955	2.17	1000.33

From Table 2, it can be observed that the highest tensile strength of TPU filament is 2.34 kgf, the lowest is 1.61 kgf, and the average tensile strength is 1.89 kgf. The elongation of TPU filament has an average of 894.96%.

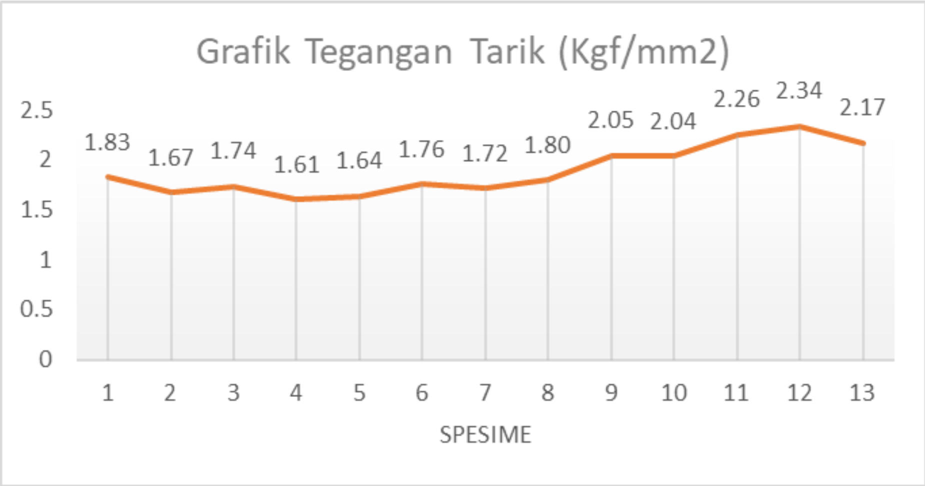

Figure 11. Graph of tensile stress of TPU filament

In Figure 11, it can be seen that the highest tensile stress of the filament is in specimen no. 12 with a tensile stress of 2.34 kgf/mm^2.

3.2 *Hardness Test Result Data*

Table 3. Hardness test results data

No.	Specimen		Hardness (HRR)			Average Hardness of Sample 1,2,3
	Temperature (°C)	Print Speed (mm/m)	1	2	3	
1	180	40	35	21	58	38
2	200	40	81	10	22	37.67
3	180	50	55	53	65	57.67
4	200	50	45	49	52	48.67
5	175.86	45	58	56	67	60.33
6	204.15	45	73	63	82	72.67
7	190	37.92	84	50	75	69.67
8	190	52.08	53.5	57	65	58.5
9	190	45	84	51.5	66.5	67.33
10	190	45	86	46	74	68.67
11	190	45	40	68	42	50
12	190	45	19	31	80	43.33
13	190	45	43	53	25	40.33

From Table 3, it can be seen that the maximum hardness value of TPU is 72.67, the minimum hardness value of TPU is 37.67, and the average hardness of TPU is 54.83.

3.3 *Density Test Results Data*

Table 4. Density test results data

No	Spesimen			Volume (v)	Massa (m)	Density (ρ)
	P	L	T			
1	18.8	18.2	2	684.32	0.68	0.000994
2	18.6	18	2	669.6	0.65	0.000971
3	18.8	18.3	2	688.08	0.62	0.000901
4	18.6	18.2	2	677.04	0.61	0.000901
5	18.7	18	2	673.2	0.63	0.000936

So, from the density calculations conducted, the average density of TPU filament is 0.000994 g/mm^3, which is converted to 0.994 g/cm^3.

3.4 *Data Processing with Minitab Using Method Response Surface Methodology (RSM)*

3.4.1 *Main Effect Plot Graph*

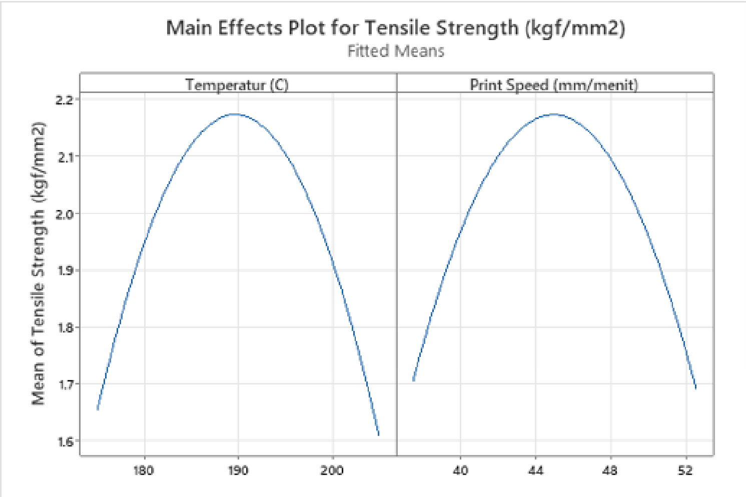

Figure 12. Main effect plot graph of tensile strength

Figure 12 shows that the higher the temperature, the lower the tensile strength, and similarly, the higher the printing speed, the lower the tensile strength.

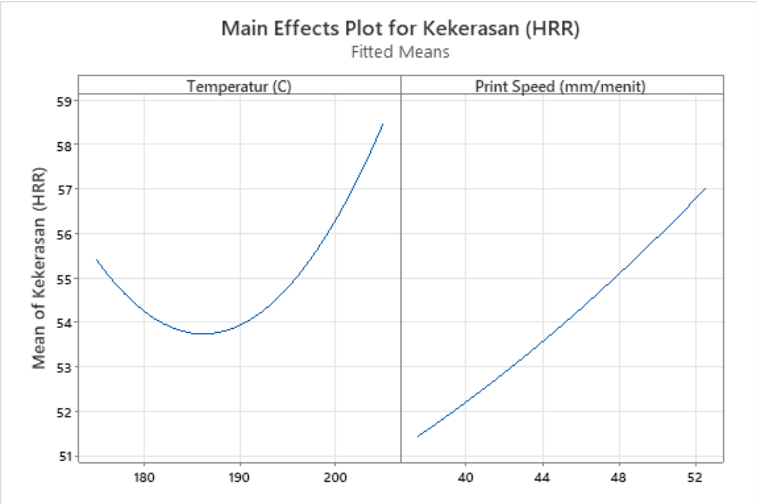

Figure 13. Main effect plot of hardness graph

From Figure 13, it can be observed that the hardness value increases as the temperature and printing speed increase.

3.4.2 *Interaction Plot*

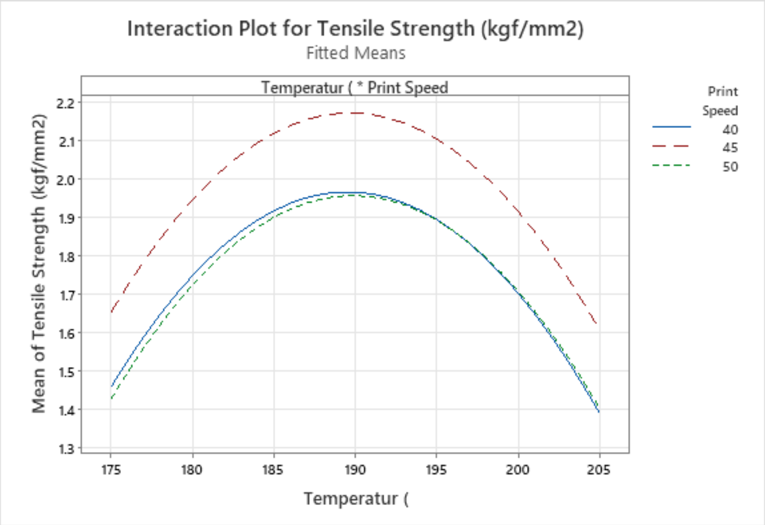

Figure 14. Interaction plot graph of tensile strength

From Figure 14, it can be observed that as the temperature increases, the tensile strength decreases.

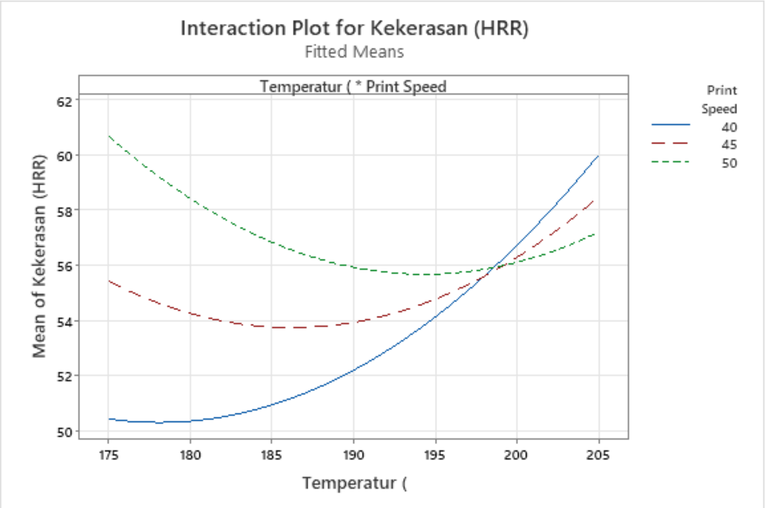

Figure 15. Hardness interaction plot graph

Figure 15 shows that as the temperature increases, and at a print speed of 40 mm/minute, the hardness also increases.

3.4.3 *Contour Plot*

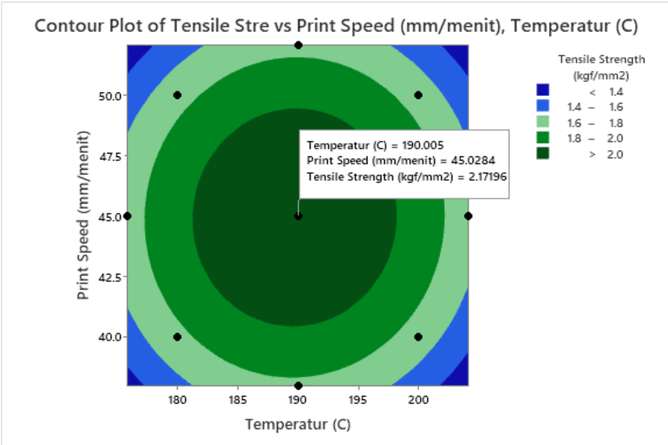

Figure 16. Contour plot of tensile strength

From figure 16, the optimum point for TPU filament tensile strength occurs at a temperature of 190°C, printing speed of 45.0284 mm/min, with a tensile strength of 2.17196 kgf/mm².

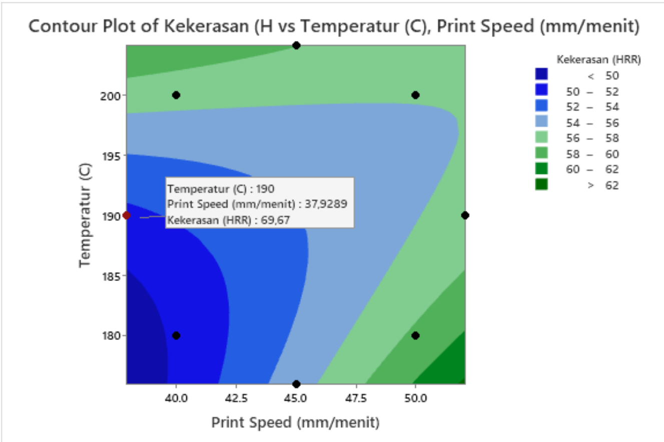

Figure 17. Contour plot graph of tensile strength

Figure 17 shows that the optimum point for TPU filament hardness occurs at a temperature of 190 °C and a printing speed of 37.9289 mm/minute, with a hardness of 69.67 HRR.

3.4.4 *Analyze Optimization*

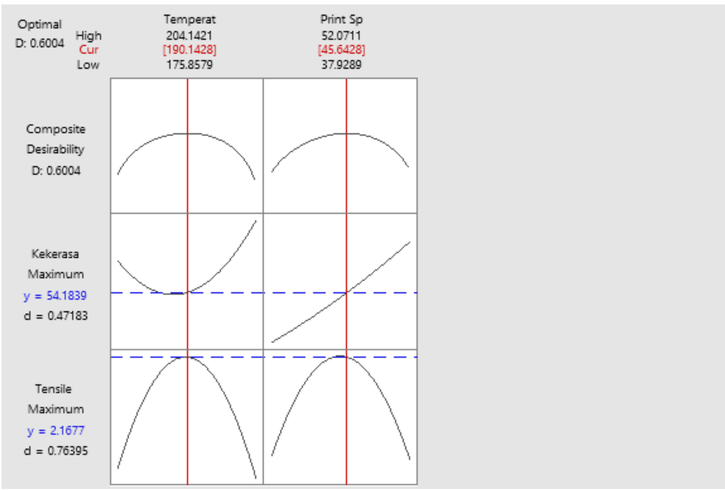

Figure 18. Analyze optimization

In the Response Surface Methodology (RSM) system, simulations are conducted to determine the optimal parameters that can produce optimal print quality. This optimization prediction can be seen in Figure 4.8, where the optimal temperature is 190.1428 ℃ and the optimal print speed is 45.6428 mm/minute. With these parameter settings, the tensile strength reaches 2.1677 kgf/mm² and the hardness reaches 54.1839 HRR.

4. CONCLUSION

By using the Response Surface Method (RSM) Central Composite Design, the parameters for achieving maximum tensile strength were found to be at a temperature of approximately 190°C and a printing speed of 45 mm/minute, resulting in a tensile strength of 2.34 kgf/mm². Additionally, the parameters for achieving maximum hardness were at a high printing temperature of 214.15°C and a printing speed of 45 mm/minute, resulting in a hardness of 72.67 HRR. In this RSM method, it is recommended to use the optimal parameters of a temperature of 190.1428°C and a printing speed of 45.6428 mm/minute for the specimen, which results in a tensile strength of 2.1677 kgf/mm² and a hardness of 54.1839 HRR.

REFERENCES

[1] Muhammad Nizar Arvila Putra *et al.*, "Sampah Plastik sebagai Ancaman terhadap Lingkungan," *Akt. J. Ilmu Pendidikan, Polit. dan Sos. Indones.*, vol. 2, no. 1, pp. 154–165, 2024, doi: 10.62383/aktivisme.v2i1.725.

[2] I. Akbar, Z. Sirwansyah Suzen, and I. Idiar, "Analisis Proses 3D Printing terhadap Pengujian Impak Metode Charpy Pada Material PLA+," *J. Syntax Admiration*, vol. 2, no. 8, pp. 1480–1493, Aug. 2021, doi: 10.46799/jsa.v2i8.297.

[3] A. Setiawan, P. Studi DIII Aeronautika, and S. Yogyakarta, "PENGARUH PARAMETER PROSES EKTRUSI 3D PRINTER TERHADAP SIFAT MEKANIS CETAK KOMPONEN BERBAHAN FILAMENT PLA (Poly Lactide Acid)," 2017.

[4] Z. Sirwansyah Suzen and P. Manufaktur Negeri Bangka Belitung, "Optimasi Parameter Produk 3D Printing Terhadap Kuat Tarik Menggunakan Filamen TPU (Thermoplastic Polyurethane)," vol. 01, no. 2, 2023.

[5] S. Zakaria, R. Stighfarrinata, P. Studi, T. Industri, and U. Bojonegoro, "E -ISSN : 2746-0835 Volume 3 No 4 (2022) JUSTI (Jurnal Sistem Dan Teknik Industri) OPTIMASI PARAMETER PROSES 3D PRINTING TERHADAP KUAT TARIK E -ISSN : 2746-0835 Volume 3 No 4 (2022) JUSTI (Jurnal Sistem Dan Teknik Industri)," vol. 3, no. 4, pp. 538–545, 2022.

[6] S. Riskiawan, H. Delima, and H. Andami, "Optimasi Parameter Pencetakan dan Evaluasi Sifat Mekanis Filamen Poliuretan Termoplastik dalam Pencetakan 3D," vol. 30, no. 2, pp. 96–107, 2025, doi: 10.5614/MESIN.2025.30.2.2.Optimasi.

[7] D. Mahandika and H. Sukma, "Analisa Hasil Cetak 3D Printer Terhadap Pengujian Tarik Material ABS+ dengan Variasi Densitas Infill."

[8] "Universitas Gadjah Mada, 2020 | Diunduh dari http://etd.repository.ugm.ac.id/," p. 379076, 2020.

[9] T. Gulo, D. Mardiyana, and Z. Sulaiman, "Pengaruh Variasi Print Speed dan Nozzle Temperature Terhadap Kekerasan Produk 3D Printer Filamen TPU 95A," pp. 86–91, 2024.

[10] H. Hasdiansah and Z. S. Suzen, "Pengaruh Geometri Infill terhadap Kekuatan Tarik Spesimen Uji Tarik ASTM D638 Type IV Menggunakan Filamen PLA+ Sugoi," *J. Rekayasa Mesin*, vol. 16, no. 2, p. 140, 2021, doi: 10.32497/jrm.v16i2.2343.

[11] L. Nulhakim, A. I. Tauvana, and S. Syafrizal, "Able To Pull Polylactid Acid (Pla) Material Anet Et4 3D Printing Machine Product Results," *Kreator*, vol. 11, no. 1, pp. 18–23, 2024, doi: 10.46961/kreator.v11i1.1222.

[12] R. D. Salindeho, J. Soukota, and R. Poeng, "Pemodelan pengujian tarik untuk menganalisis sifat mekanik material," *J. Online Poros Tek. Mesin*, vol. 2, no. 2, pp. 88–98, 2018.

[13] R. B. Widiantoro and Y. R. Fauzi, "Analisis Komparatif Metode Pengujian Kekerasan: Rockwell Dan Vickers Pada Heat-Treated HighSpeed Steel (Baja Kecepatan Tinggi Yang Diolah Panas)," *Semin. Nas. Penelit.*, pp. 67–71, 2024.

[14] W. Soedarmadji and N. Islamuddin, "Analisa Uji Tekan, Kerapatan Densitas Dan Mikrostruktur Terhadap Komposit Bahan Baku Teakwood Serbuk Gergaji Kayu," *J. Mech. Manuf. Technol.*, vol. 1, no. 2, pp. 58–65, 2020.

[15] I. Sendawati, A. Asri, and B. S. Nugroho, "Analisis Pengaruh Densitas Pada Kualitas Papan Komposit Berbahan Baku Limbah Kayu Jabon dan Serat Bundung (Scirpus grossus)," *Prism. Fis.*, vol. 10, no. 1, p. 33, 2022, doi: 10.26418/pf.v10i1.53428.