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EFFECT OF PROCESS PARAMETERS ON MECHANICAL PROPERTIES OF THE 3D PRINTED SILK-PLA SPECIMENS FABRICATED VIA FUSED DEPOSITION MODELING.

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ABSTRACT

Fused deposition modeling (FMD) is considered one of the most common additive manufacturing methods for creating prototypes and small functional parts. Many researchers have studied Polylactic acid (PLA), Polycarbonate (PC), and Acrylonitrile butadiene styrene (ABS) as a material for fused deposition modeling printing. Among them, Polylactic Acid (PLA) is considered one of the most popular thermoplastic materials due to its low cost and biodegradable properties. In this study, silk PLA material was used. In Fused deposition modeling (FMD), the selection of printing parameters plays a pivotal role in determining the overall quality and integrity of the 3D-printed products. These parameters significantly influence the quality and strength of 3-D printed products. This study investigates the mechanical properties of silk-PLA printed specimens under different printing conditions, such as layer thickness, nozzle temperature, and print speed. All the tensile specimens were tested using ASTM D638 to characterize Young's modulus and ultimate tensile strength. The thickness of the layers of tensile specimens was set to 0.1 mm, 0.15 mm, and 0.2 mm. The temperatures of the nozzle used during printing varied from 200°C, 210°C, and 220°C, whereas print speeds of 100 mm/s, 120 mm/s, and 140 mm/s were considered. The other printing parameters were kept consistent for all specimens. The result indicates tensile strength generally increases with increasing temperature of the nozzle, up to 220°C; however, a decline was observed in the average Young's modulus value when the thickness of the layer increased from 0.10 mm to 0.20 mm. According to the results of the ANOVA analysis, the interaction between layer thickness, nozzle temperature, and printing speed significantly affects the tensile strength and Young's modulus of Silk-PLA. This study reveals that nozzle temperature is the most critical parameter regarding the ultimate tensile strength and Young's modulus, providing crucial insights for optimizing 3D printing parameters.

Keywords: Additive Manufacturing, fused deposition modeling (FDM), mechanical properties, silk polylactic acid (PLA), analysis of variance (ANOVA).

1. INTRODUCTION

The rapid advancement of technology in the 21st century has significantly revolutionized various sectors, particularly in the realm of manufacturing. One such example is Additive Manufacturing (AM), commonly known as 3D printing. Additive manufacturing produces a part layer by layer, which differs from traditional manufacturing, like the CNC machining process that removes materials from bulk materials. 3D printing minimizes material waste and can print intricate shapes, thereby conserving raw materials throughout the printing process.

In 3D printing, printing parameters are considered one of the most crucial factors in the creation of high-quality 3D printed products [1]. By optimizing these parameters, the 3D-printed parts can have better surface quality, cost-effectiveness, and enhanced mechanical performance [2] making FDM process parameters a major research area. Different parameters influence 3D-printed structures, such as layer height, which has a significant effect on the ultimate tensile strength and printing duration, whereas the extrusion temperature is vital for determining the elastic modulus [3]. Vaibhav Bhosale and coworkers [4] explored the relationship between different process parameters and their effect on mechanical properties. According to their findings, layer height, and infill percentage, as process parameters, are vital for determining the strength and surface roughness. By printing with a thinner layer thickness, FDM's tensile strength and surface roughness improved. Tianyun Yao et al. [5] analyzed the maximum tensile strength of 3D-printed PLA materials at seven distinct angles and three different layer thicknesses. They discovered that increased layer thickness, from 0.1mm to 0.3mm, leads to lower tensile strength. The same conclusion was reported by V. Durga Prasada and

coworkers [6], who looked into the different printing parameters of FDM 3D printing. The thickness of layers has a significant impact on tensile strength, as demonstrated by their research. A layer thickness of 0.1mm resulted in the maximum tensile strength being recorded. examined how layer thickness affects the impact property of 3D-printed PLA, according to Tahseen Fadhil and co-authors [7]. Their findings show that layer thickness significantly influences the FDM process, affecting the strength and impact resistance of the final product. Magri and his team [8] examined how different extruder temperatures affect mechanical characteristics. Their observation was that the maximum tensile properties of PLA parts were achieved by elevating the nozzle temperature to 230°C. Furthermore, the work by Yang et al. [9], and Heidari-Rarani et al. [10] supported the significance of optimizing the printing speed for FMD 3D printing to improve the mechanical characteristics of PLA samples. Both of this researcher's investigations examined the way in which the combination of FDM printing speed and other parameters impact PLA printed materials and the conclusion has been reached that optimizing printing speed is essential for achieving better mechanical properties in FDM-printed PLA parts. Moreover, some researchers studied the feasibility of FDM printing speed when it exceeded 100 mm/s for Polylactic Acid (PLA). Similarly, Nabavi-Kivi and coworkers [11] reported that the most significant elongation and strongest tensile strength can be obtained by printing at 70 mm/s.

Researchers have made many attempts to enhance the mechanical properties and quality of 3D-printed parts. Until now, many research studies considered printing speeds to be less than 100 mm/s [12, 13]. However, this study explored higher printing speeds, like 120mm/s and 140mm/s, which can be valuable findings for PLA materials by providing insights into the limits of the PLA materials and can help in understanding the modifications in the printing speeds with other process parameters.

2. MATERIALS AND METHODS

Polylactic Acid, also known as PLA, is an eco-friendly thermoplastic polymer originating from renewable sources, like corn starch or sugarcane [14]. In this work, instead of pure PLA filament, silk-PLA material with a density of 1.24 g/cm3 was considered and has a diameter of 1.75 mm. The tensile specimen was created using CAD software following the specifications of ASTM D638 as shown in Figure 1.

All specimens were printed using the FDM Intamsys FUNMAT HT 3D printer as shown in Figure 2(a). Printed 27 different types of specimens separated by a plastic bag as shown in Figure. 2 (b), and included a silica gel packet in each plastic bag to absorb any excess moisture that might change the material properties of the tensile specimens. Apart from changing the thickness of layers, temperature of the nozzle, and print speed from Table 1, other parameters like the infill density of 100%, build plate temperature of 40°C, raster angle of 45°, chamber temperature of 25°C, and the printing orientation are kept constant for all specimens according to the Table 2.
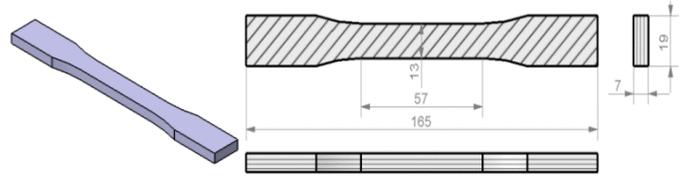

FIGURE 1: ASTM D638 TYPE-I TENSILE TESTING SPECIMENS (UNITS IN MILLIMETERS) [15].

(a)   (b)

FIGURE 2: (A) INTAMSYS FUNMAT HT 3D PRINTER, (B) 27 TYPES DIFFERENT PARAMETERS PRINTED TENSILE SPECIMEN.

TABLE 1: 3D PRINTING PROCESS PARAMETERS AND LEVELS

Parameters	Notation	Level 1	Level 2	Level 3
Layer thickness	L(mm)	L1- 0.1	L2- 0.15	L3- 0.2
Nozzle Temperature	T(°C)	T1-200	T2- 210	T3-220
Printing Speed	P(mm/s)	P1-100	P2-120	P3-140

TABLE 2: FIXED PROCESS PARAMETER

Parameters	Set value
Build plate temperature	40 °C
Chamber temperature	25 °C
Raster angle	45 °
Printing pattern	Lines
Infill density	100%
Nozzle diameter	0.4 mm

3. RESULTS AND DISCUSSION

3.1. Tensile Testing

Tensile testing was conducted on the MTS E42 Universal Testing Machine (Figure 3), which has up to 5 KN load capacity. According to the ASTM D638 standard [16] Type-I, five specimens were printed in each orientation, and a total of 135 specimens (Figure 7) were tested at a 5 mm/min rate.
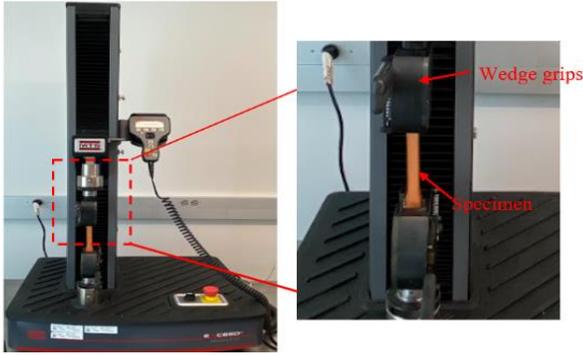

FIGURE 3: MTS E42 UNIVERSAL TESTING MACHINE DURING TENSILE TESTING.

TABLE 3: RESULTS OF THE TENSILE EXPERIMENT

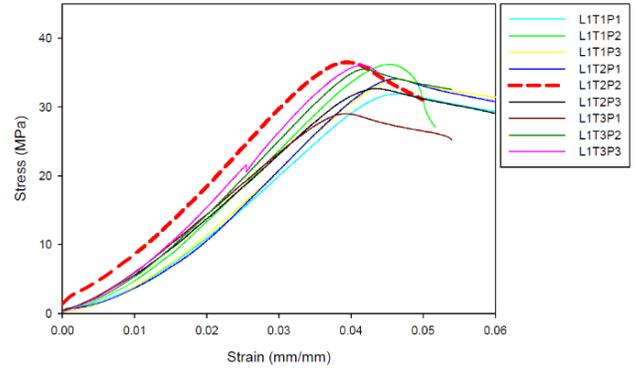| Sample No.	Code	Average Weight (g)	Mean Tensile Strength (MPa)	Young's modulus (MPa)
1.	L1T1P1	19.74	31.95	877.09
2.	L1T1P2	19.90	36.21	965.46
3.	L1T1P3	20.30	34.03	874.29
4.	L1T2P1	20.40	34.11	994.20
5.	L1T2P2	20.86	36.51	1054.51
6.	L1T2P3	20.52	32.67	893.71
7.	L1T3P1	20.22	29.05	854.71
8.	L1T3P2	20.90	35.49	1027.84
9.	L1T3P3	20.50	36.09	998.32
10.	L2T1P1	19.56	29.27	730.09
11.	L2T1P2	20.46	37.48	981.22
12.	L2T1P3	20.12	30.59	842.26
13.	L2T2P1	20.90	31.61	890.23
14.	L2T2P2	20.80	37.22	1001.89
15.	L2T2P3	20.52	37.45	999.00
16.	L2T3P1	20.66	36.91	982.06
17.	L2T3P2	20.80	37.77	999.60
18.	L2T3P3	20.74	37.48	920.42
19.	L3T1P1	20.90	36.79	785.40
20.	L3T1P2	20.00	25.79	687.84
21.	L3T1P3	20.78	32.59	779.73
22.	L3T2P1	20.78	36.23	900.71
23.	L3T2P2	20.94	37.70	972.30
24.	L3T2P3	21.22	35.87	1066.16
25.	L3T3P1	21.16	32.72	828.71
26.	L3T3P2	21.16	40.68	1041.69
27.	L3T3P3	21.12	37.00	941.55

FIGURE 4: STRESS-STRAIN CURVE FOR SAMPLES 1 TO 9 (LAYER THICKNESS-0.1MM)
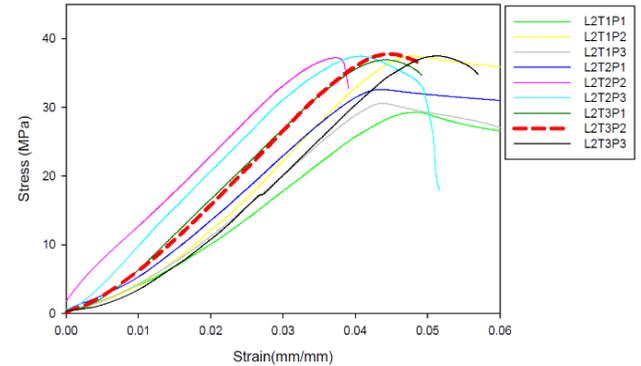

FIGURE 5: STRESS-STRAIN CURVE FOR SAMPLES 10 TO 18 (LAYER THICKNESS-0.15MM)
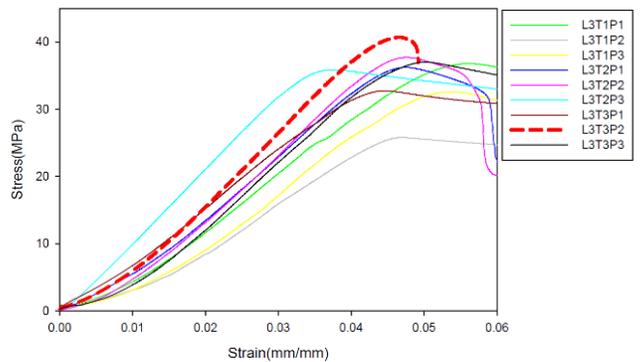

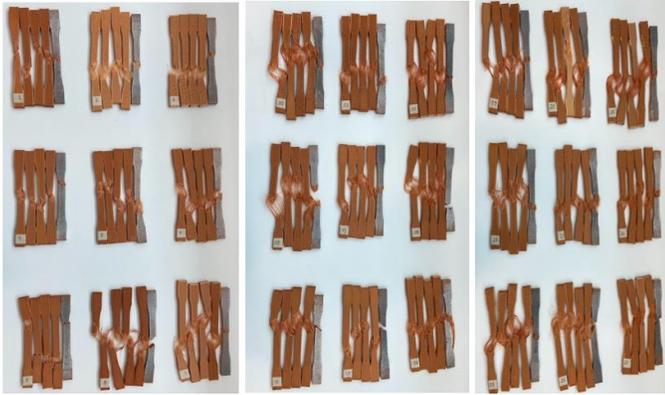**FIGURE 6:** STRESS-STRAIN CURVE FOR SAMPLES 19 TO 27 (LAYER THICKNESS-0.2MM)

FIGURE 7: TWENTY-SEVEN (27) DIFFERENT PARAMETERS IN A TOTAL OF 135 FRACTURED SPECIMENS AFTER TENSILE TESTING.

All tensile experiment data is recorded in Table 3. The average weight of the printed specimen is 20.59g. Figures 4, 5, and 6 demonstrate the sample of nine for each graph when the layer thickness is fixed at 0.1 mm, 0.15mm, and 0.2mm, respectively. Sample 26 (Figure 5) L3T3P2, a layer thickness of 0.2mm, temperature of the nozzle at 220°C, and print speed of 120mm/s has the highest tensile strength of 40.68 MPa, and this is the highest tensile strength recorded across all tested samples. In contrast, sample 20 (Figure 5) L3T1P3, a thickness of each layer at 0.2mm, a nozzle temperature of 200°C, and a printing speed of 120 mm/s, demonstrates the lowest tensile strength, measuring 25.79 MPa, which is approximately 36.60% lower than that of Sample 26. Moreover, the highest Young's modulus, 1066.16 MPa, was observed in sample 24, with a layer height of 0.2 mm, nozzle temperature of 210°C, and print speed of 140 mm/s.

3.2 Analysis of Variance

Analysis of Variance, commonly referred to as ANOVA, is a statistical approach used to examine variations between the mean values of groups within a sample. The ANOVA was performed by employing the MINITAB 17 software to identify the effect of three different printing parameters on the ultimate tensile strength and Young's modulus of the 3D-printed Silk-PLA material. All the data obtained was within the 95% confidence interval.

3.2.1 Main effects plots

Figure 8 depicts the main effect plot for ultimate tensile strength. The process parameters are displayed on a horizontal axis, while the mean ultimate tensile strength is shown on the vertical axis. The trend line for the layer thickness is nearly horizontal; therefore, layer thickness has no statistically significant impact on UTS within the range examined. However, the nozzle temperature trend line displays a positive slope, suggesting that ultimate tensile strength (UTS) rises as the nozzle

temperature increases from 200 °C to 240°C. This relationship is statistically significant.
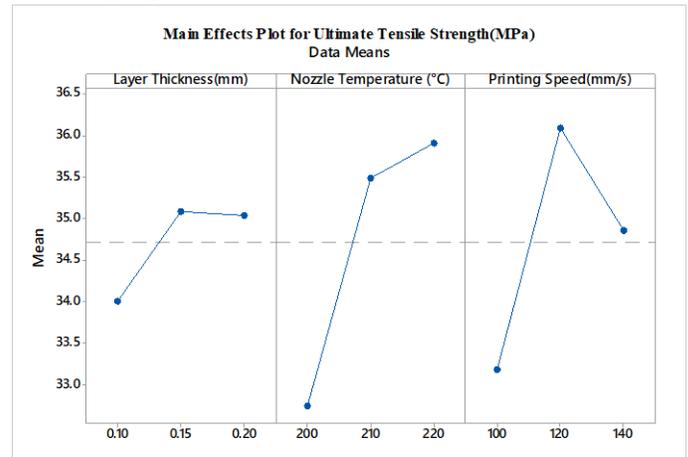

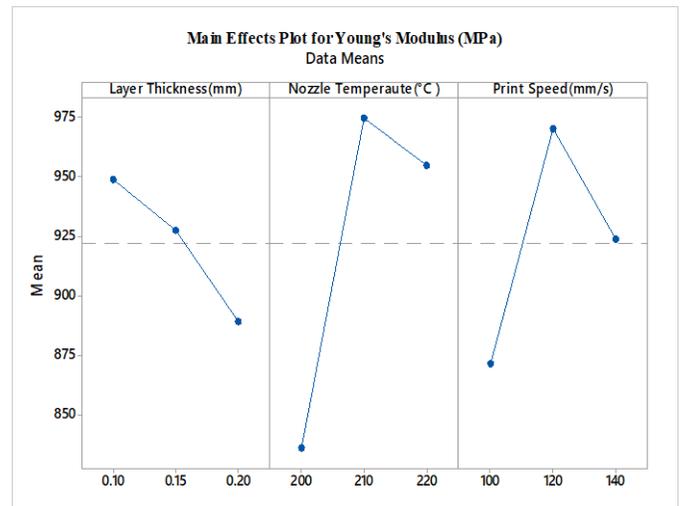**FIGURE 8:** MAIN EFFECTS PLOT FOR ULTIMATE TENSILE STRENGTH.

FIGURE 9: MAIN EFFECTS PLOT FOR YOUNG'S MODULUS

The plot of the main effects of Young's modulus is given in Figure 9. The graph shows a decrease in the average Young's Modulus value as the layer thickness increases from 0.10 mm to 0.20 mm. The thickness of the layer was 0.10mm, which led to the observation of the best Young's Modulus. It is observed that the temperature of the nozzle significantly affects Young's modulus, i.e., when nozzle temperature increases 200°C to 210°C, it has the highest Young's modulus, but it drops gradually when nozzle temperature increases to 220°C. Therefore, the nozzle temperature rises to 210°C, which can significantly increase Young's modulus. The correlation between printing speed and Young's Modulus demonstrates an initial rise as the printing speed increases from 100 mm/s to 120 mm/s,

subsequently decreasing at 140 mm/s printing speed and reaching close to the mean value.
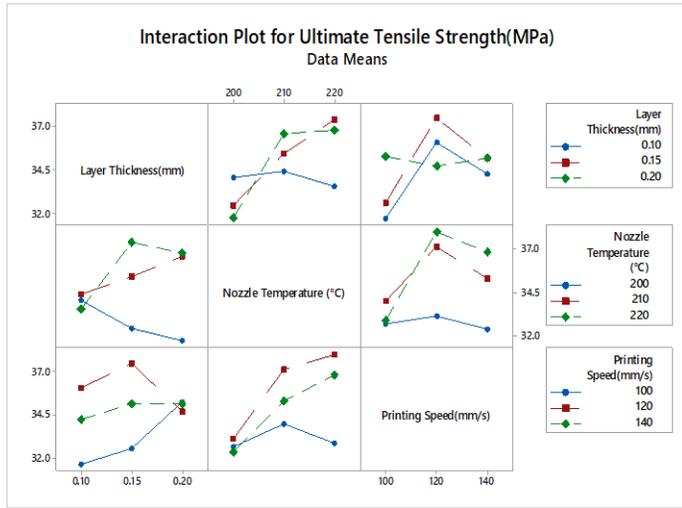

FIGURE 10: INTERACTION PLOT BETWEEN THE SIGNIFICANT PARAMETERS FOR ULTIMATE TENSILE STRENGTH.
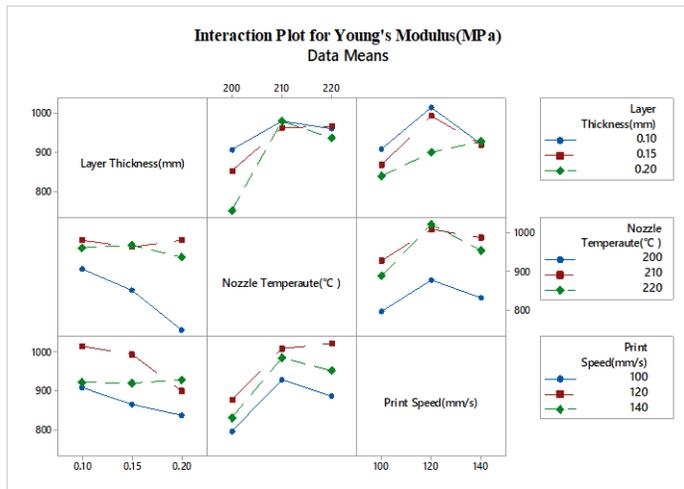

FIGURE 11: INTERACTION PLOT BETWEEN THE SIGNIFICANT PARAMETERS FOR YOUNG'S MODULUS.

3.2.2 Interaction plots

The interaction plot is a powerful tool for identifying how multiple factors influence a response variable simultaneously. Figure 10 and Figure 11 show an interaction plot for ultimate tensile strength (MPa) and Young's modulus (MPa) with data means focusing on the effects of layer thickness, nozzle temperature, and print speed on the tensile strength of Silk-PLA printed material. In an interaction plot, parallel lines indicate the

absence of any interaction, whereas different slope lines indicate that interaction might be present. Figure 10 shows that tensile strength varies with nozzle temperature changes. Additionally, Figure 11 shows that the interaction lines between print speed and nozzle temperature are almost parallel, suggesting a lack of interaction between these two factors.
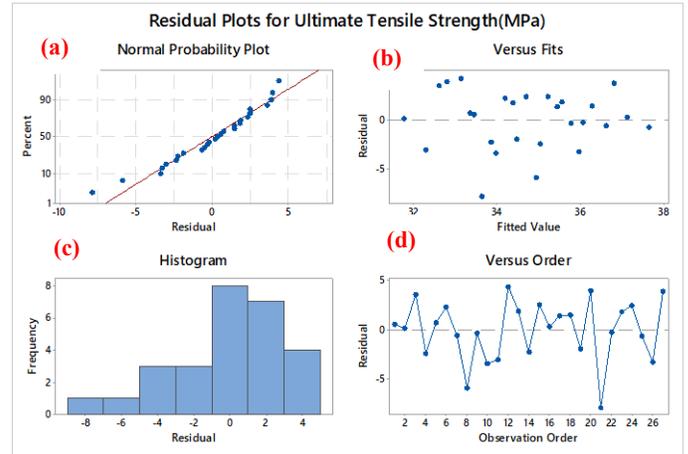

FIGURE 12: PLOT OF ULTIMATE TENSILE STRENGTH AT 95% OF CONFIDENCE INTERVAL A) NORMAL PLOT FOR RESIDUALS, (B) VERSUS ORDER PLOT FOR RESIDUALS, (C) HISTOGRAM PLOT FOR RESIDUALS, AND (D) VERSUS FITS PLOT FOR RESIDUALS.
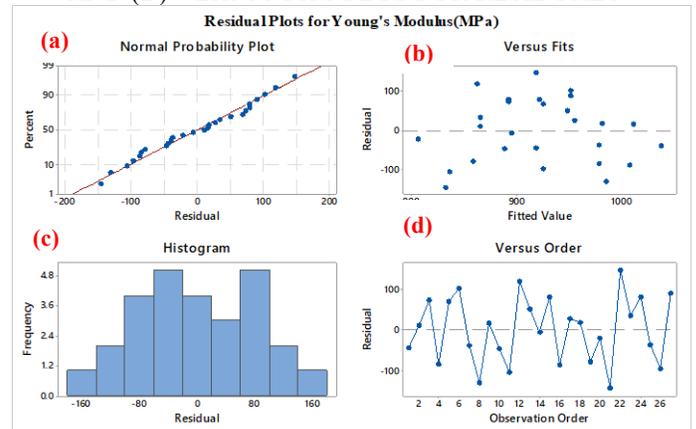

FIGURE 13: PLOT OF YOUNG'S MODULUS AT 95% OF CONFIDENCE INTERVAL; A) NORMAL PLOT FOR RESIDUALS, (B) VERSUS ORDER PLOT FOR RESIDUALS, (C) HISTOGRAM ORDER PLOT FOR RESIDUALS, AND (D) VERSUS FITS PLOT FOR RESIDUALS

3.2.3 Residuals plots

The normal probability plot and the histogram are used to test the assumption of normality of the residuals. Figures 12(a) and 13(a) show a plot of ultimate tensile strength and Young's modulus in the residuals that mostly follow the line and have a mean close to zero. It means that the residuals are approximately

normally distributed. Fig.12(c) and Fig. 13 (c) histogram plots provide the visual representation of the distribution of residuals. The plot of residuals vs. fits in Fig. 12(b) and Fig. 13 (b) helps assess the validity of the assumption regarding the constant variance of the residuals, and the absence of a pattern indicates that the residuals are likely independent. There has been no unexpected change in residuals over time, as revealed by Fig.12 (d) and Fig.13 (d) residuals versus observation order.

TABLE 4: ANALYSIS OF THE VARIANCE TABLE FOR TENSILE STRENGTH

Source	DF	Seq SS	Adj SS	Adj MS	F-Value	P-Value
Regression	3	62.555	62.555	20.852	2.04	0.137
Layer Thickness	1	4.773	4.773	4.773	0.47	0.501
Nozzle Temperature	1	45.065	45.065	45.065	4.41	0.047
Print Speed	1	12.718	45.065	12.718	1.24	0.276
Error	23	235.287	235.287	10.230		
Total	26	297.843				

DF (Degrees of Freedom); Seq SS (Sequential Sum of Squares); Adj MS (Adjusted Mean Square); F-Value (F statistic); P-Value (Probability value)

Table 4 shows ANOVA in the tensile test results section in the MINITAB. In ANOVA analysis, the p-value (probability value) reveals the significant influence of parameters on the output, in this case, ultimate tensile strength. The process parameter, which has a p-value lower than 0.05, is considered statistically significant [17, 18, 22]. Table 4 indicates that the nozzle temperature has a probability value of 0.047, which is less than 0.05, and this is considered the statistically significant parameter for ultimate tensile strength. However, layer thickness has a p-value of 0.501, and print speed has a p-value of 0.276, which is insignificant to tensile strength.

ANOVA analysis is also carried out on Young's modulus to gain insight into the importance of the process parameters. From Table 5, layer thickness (L) has a probability value of 0.155, and printing speed (P) has a probability value of 0.208. Therefore, layer thickness and printing speed have p-values higher than 0.05, indicating they do not significantly impact Young's modulus under the conditions studied. However, the nozzle temperature (T) has a probability of 0.007, which is less than the considered P value of 0.005 and has a significant parameter for Young's modulus of the material.

TABLE 5: ANALYSIS OF THE VARIANCE TABLE FOR YOUNG'S MODULUS

Source	DF	Seq SS	Adj SS	Adj MS	F-Value	P-Value
Regression	3	92139	92139	30713	4.16	0.017
Layer Thickness	1	15963	15963	15963	2.16	0.155
Nozzle Temperature	1	63786	63786	63786	8.64	0.007
Print Speed	1	12389	12389	12389	1.68	0.208
Error	23	169724	169724	7379		
Total	26	261863				

4. CONCLUSION

This study experimentally investigated the impact of various 3D printing parameters on the mechanical characteristics of silk-PLA material. Process parameters, such as layer height, nozzle temperature, and printing speed, are considered and the mechanical characteristics such as Young's modulus and ultimate tensile strength were measured and analyzed in this study. Until now many studies have explored the optimization of process parameters for FDM 3D printing, but relatively little focus on investigating higher printing speeds for PLA-printed materials. Therefore, this research aims to establish a clear correlation between process parameters like higher printing speed, nozzle temperature, layer thickness, and the mechanical characteristics of silk PLA materials.

The following conclusion can be drawn from this study-

I. The ANOVA table reveals that the nozzle temperature is the key factor significantly impacting the ultimate tensile strength and Young's modulus.
II. Considering the obtained P value from ANOVA, printing speed and layer thickness have no critical influence on the responses of the ultimate tensile strength.
III. Higher nozzle temperatures may enhance the material's performance by improving layer adhesion, leading to an increase in tensile stress capacity, which agrees with [19, 20, 21].
IV. The highest tensile strength of 40.68 MPa is achieved with the optimal combination of process parameters at testing sample 26 when a layer thickness of 0.2mm, temperature of the nozzle at 220°C, and print speed of 120mm/s.

Future studies can be conducted on the image-based strain analysis method known as DIC to analyze the full field displacement and strain measurements, and scanning electron

microscopy (SEM) images of fracture surfaces to understand process parameters that affect failure modes. Understanding these modifications in the process parameters will lead to enhanced product quality, reduced costs, and improved mechanical performance of 3D-printed parts.

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