EFFECT OF PROCESS PARAMETERS ON TENSILE STRENGTH OF 3D PRINTED PLA PARTS

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ABSTRACT: Additive Manufacturing (AM), known as 3D printing, has transformed industrial production through precise layer-by-layer material deposition. However, the primary issue often encountered during the fabrication of parts using Fused Deposition Modeling (FDM) is the inferior mechanical characteristics resulting from processing parameters. This study investigates the effect and interaction of various process parameters (infill density, temperature, layer height) on the tensile strength of 3D-printed PLA parts using Analysis of Variance (ANOVA). Utilizing a fractional factorial design, four-parameter runs with three factors at two levels each were created. The main plot effect indicates that infill density and print temperature are the most significant factors, and the interaction plots reveal a notable correlation between printing temperature and layer height. A linear regression model has been developed to predict the tensile strength. The selected process parameters influence the strength, but only infill density (85.03%) and print temperature (8.8%) are statistically significant. The microstructure analysis showed a good agreement between the experimental and statistical data, where 100% infill density at different temperatures and layer height settings offer excellent interlayer adhesion and fewer voids than the 50% infill density. The presented methodology can be used as a pre-processing approach to optimize desired mechanical properties in material extrusion 3D printing.

KEYWORDS: *Fused Deposition Modeling (FDM); 3D Printing; Polylactic Acid (PLA); Tensile Strength; ANOVA*

1.0 INTRODUCTION

3D printing technology has revolutionized the manufacturing industry by enabling the production of complex and customized parts with ease. PLA (Polylactic Acid) is a commonly used material in 3D printing due to its biodegradability, cost-effectiveness, and favourable mechanical properties [1]. However, the quality and performance of PLA 3D-printed parts rely heavily on printing parameters such as printing temperature, infill density, and layer height [2][3][4][5]. While prior research has explored the influence of individual printing parameters on the mechanical properties of PLA prints, a comprehensive analysis considering multiple parameters on the tensile strength of PLA 3D prints is still lacking. Currently, insufficient models effectively represent the relationship between printing parameters, bonding mechanism, and tensile strength of PLA 3D-printed parts.

To address this knowledge gap, a fractional factorial design-based mathematical model is developed to systematically evaluate the impacts of printing parameters on bonding mechanisms and tensile strength. By quantifying the effects of variables such as layer height, printing temperature, and infill density, a mathematical model can guide the selection of optimal parameter settings to achieve desired mechanical properties in PLA 3D-printed parts [6]. Additionally, the study endeavored to advance predictive capabilities in 3D printing by developing a mathematical model for accurately foreseeing and optimizing the tensile strength of PLA-based 3D-printed parts through regression analysis. By the end of the study, more informed adjustments may be made to optimize parameters and promote progress in manufacturing dependable and high-performing 3D-printed structures using PLA. Therefore, this study aims to investigate the impact of three parameters - infill density, print temperature, and layer height on the tensile strength of 3D printed specimens and to understand the relationship between these parameters. In addition, a mathematical model to predict the tensile strength of 3D-printed parts made with PLA material is developed using regression analysis.

2.0 METHODOLOGY

The experimental design for this work was based on the fractional factorial design. Three factors with two levels were set. The proposed number of runs was four, and with nine replications, 36 completely randomized specimens were produced. Table 1 shows the factors and their levels.

Table 1: 3D printing process parameters

Filament Material	PLA		
Default parameter	Printing speed: 60 mm/s [7] Platform temperature: 60°C [8] Printing orientation: 0° [9]		
Factors and their levels	Temperature (°C)	Infill Density (%)	Layer Height (mm)
	200	50	0.1
	220	100	0.3
Set of parameters	Set (A) 220°C, 50%, 0.1mm Set (B) 200°C, 50%, 0.3mm Set (C) 200°C, 100%, 0.1mm Set (D) 220°C, 100%, 0.3mm		

The tensile test specimens were designed in accordance with the American Society for Testing and Materials (ASTM) standard D638 (Standard Test Method for Tensile Properties of Plastics) Type IV standard, as depicted in Figure 1. Ultimaker S5 Pro was used for the 3D printing.

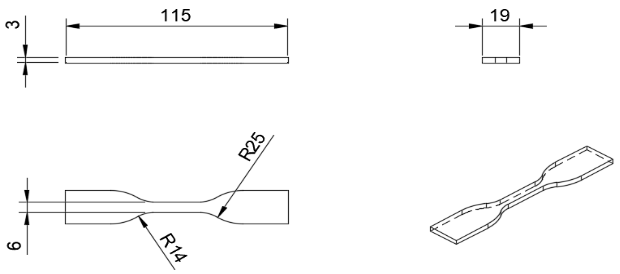
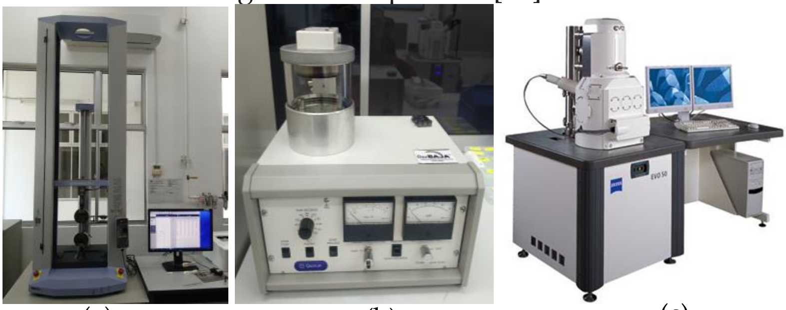


Figure 1: ASTM D638 Type IV specimen (all dimension in mm)

The tensile test was conducted by using the Shimadzu Universal Testing Machine (UTM), as depicted in Figure 2 (a), which is essential for determining a material's ultimate tensile strength (UTS), yield strength, and ductility [10]. The testing equipment has a 20 kN load cell and operates at a 5 mm/min testing speed. The 3D-printed fractured surface was sputter-coated with 10 nm palladium and gold using the

SC 7620 mini sputter coater [11], as indicated in Figure 2 (b). The microstructural study is essential to determine how the structural change occurs after assessing the influences of various factors [12][13]. The microstructural study was examined at magnifications of 50x, 100x, and 150x using a Carl Zeiss Evo 50 scanning electron microscope (SEM) equipped with a 10 kV acceleration voltage, as shown in Figure 2 (c). The ImageJ analyzer was used to measure the interlayer gap lengths in the SEM images for comparison [14].



(a) (b) (c)

Figure 2: (a) Shimadzu universal tensile testing machine (UTM) (b) SC 7620 mini sputter coater (c) SEM machine (Carl Zeiss Evo 50)

3.0 RESULTS AND DISCUSSION

The experimental tensile test results for all 36 specimens are shown in Table 2. Figure 3 depicts samples from the four set of parameters and the fracture happens mostly horizontal cut. According to the findings, the overall sample printed at a parameter set (D) of 220°C, 100%, and 0.3mm has the highest tensile strength (54.71 N/mm^2), followed by set (C) of 200°C, 100%, and 0.1mm (50.42 N/mm^2), indicating that 100% infill density offers better strength. On the other hand, 50% infill density for sets (A) and (B) shows the lowest tensile strength, with the average data of 42.92 N/mm^2 and 40.61 N/mm^2, respectively. The experimental tensile strength data indicates that infill density is the most influential factor.

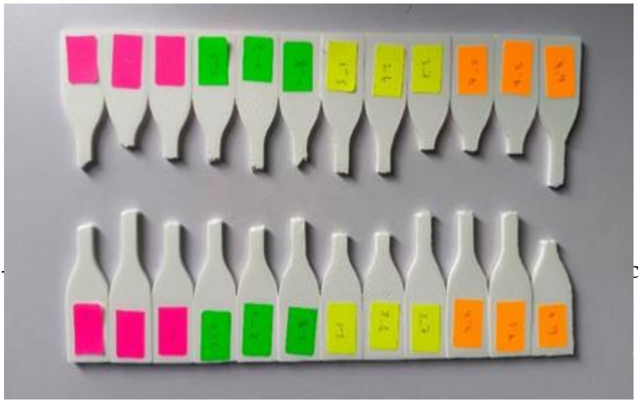


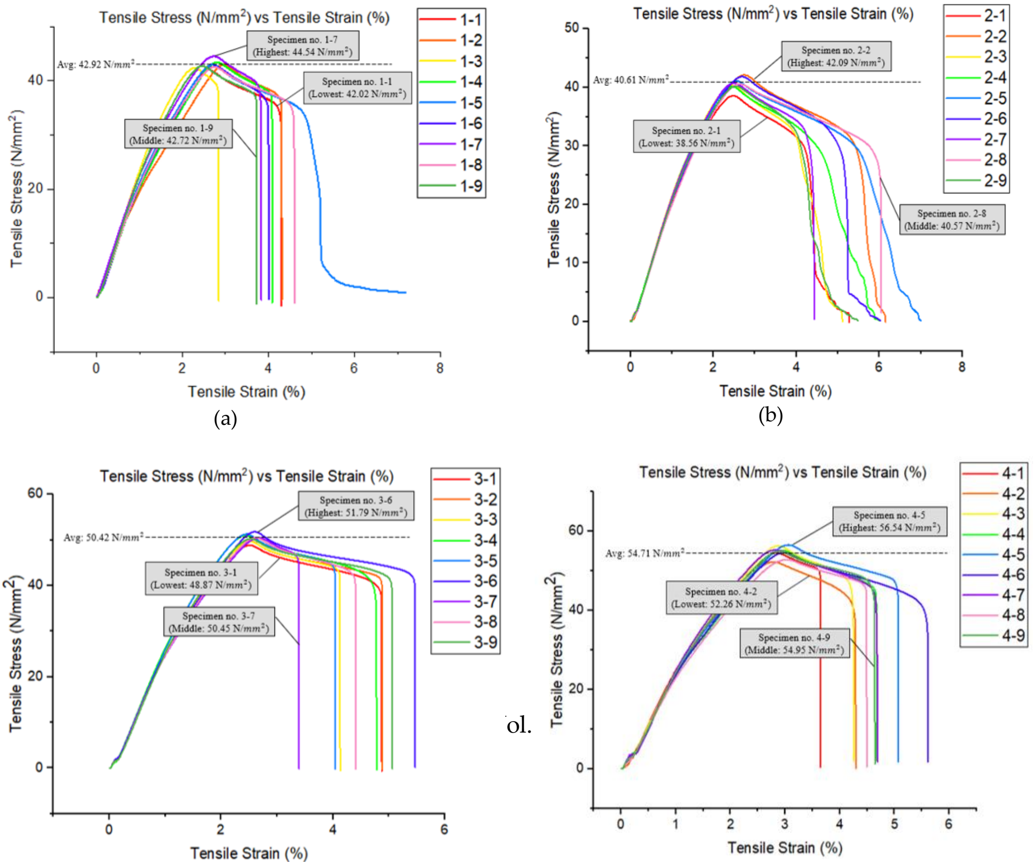
Figure 3: Tensile specimens after testing

Table 2: Tensile test result for all sets of parameters

Set	Parameter	Specimen No.	Tensile Force (N)	Tensile Strength (N/mm^2)
(A)	220°C, **50%,** 0.1mm	**1-1**	**756.35**	**42.02**
		1-2	774.16	43.01
		1-3	762.66	42.37
		1-4	781.10	43.39
		1-5	774.27	43.02
		1-6	767.70	42.65
		1-7	**801.77**	**44.54**
		1-8	765.98	42.55
		1-9	**769.05**	**42.72**
		Average	772.56	42.92
(B)	200°C, **50%,** 0.3mm	**2-1**	**694.11**	**38.56**
		2-2	**757.54**	**42.09**
		2-3	725.38	40.30
		2-4	722.68	40.15
		2-5	740.21	41.12
		2-6	752.89	41.83
		2-7	732.49	40.69
		2-8	**730.18**	**40.57**
		2-9	722.94	40.16
		Average	730.94	40.61
(C)	200°C, **100%,** 0.1mm	**3-1**	**879.71**	**48.87**
		3-2	897.66	49.87
		3-3	894.49	49.69
		3-4	918.30	51.02
		3-5	923.16	51.29
		3-6	**932.22**	**51.79**
		3-7	**908.16**	**50.45**
		3-8	909.20	50.51
		3-9	904.69	50.26
		Average	907.51	50.42
(D)	220°C, **100%,** 0.3mm	4-1	981.58	54.53
		4-2	**940.65**	**52.26**
		4-3	1014.51	56.36
		4-4	993.35	55.19

		4-5	**1017.81**	**56.54**
		4-6	981.02	54.50
		4-7	994.27	55.24
		4-8	950.78	52.82
		4-9	**989.08**	**54.95**
		Average	984.78	54.71

Figure 4 illustrates the tensile graph for all parameter sets, with nine specimens for each set. As mentioned earlier, 100% infill density demonstrates better tensile strength (set C and D) than the 50% infill density (Set A and B). The graph depicts that a fully dense print generally has a higher Young's modulus (stiffer material) compared to a 50% infill. This means that the strain (deformation) will be less in a 100% infill object for a given stress, indicating higher stiffness. This can be seen in Figure 4b, where the strain value is slightly more (4.5 – 7%) than 100% infill density in Figures 4c and 4d, respectively. As for the 100% infill density, the onset of plastic deformation occurs at a higher stress level, and the ultimate strength and fracture point are higher, indicating that the material can absorb more energy before breaking. The material can withstand higher loads before permanently deforming.



(a)

(b)

ol.

(c) (d)

Figure 4: Comparison of stress-strain graph (a) set A, (b) set B, (c) set C and (d) set D

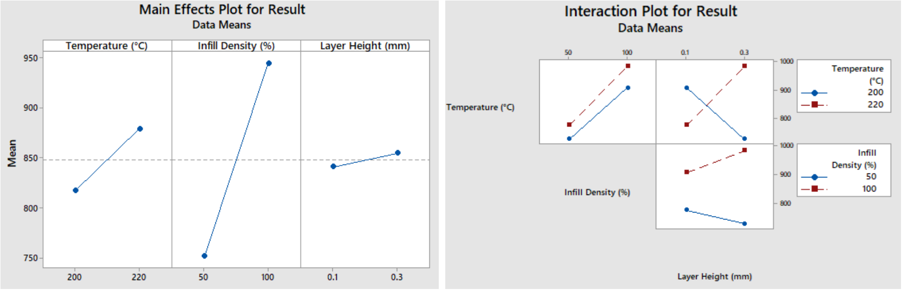
An analysis of variance (ANOVA) was used for the statistical analysis to determine the effect of 3D printing parameters on output parameters based on experimental test results. ANOVA at the 95% confidence interval [15] was applied. Table 3 presents the result of the analysis. It was determined that the most effective 3D printing parameter for tensile strength was infill density with an additive ratio of 85.03%. Infill density and temperature are significant since the p-value is less than 0.05, while the layer height factor is not significant, as the p-value is more than 0.05. This supported the findings from Ambati and Ambatipudi [2], and Sandanamsamy et al. [16], which highlighted that infill density and printing temperature are critical in FDM 3D printing. However, the statistical finding which revealed that the layer height is not significant somehow contradicted the finding from Giri et al. [17], which highlighted that when layer height exceeds the value of 0.2 mm, a decrease in the tensile strength of the sample will be observed. In fact, in this study, the layer height of 0.3mm shows an excellent tensile strength compared to the 0.1mm with 100% infill density. The fact that print temperature is more dominant than the layer height is observed in this experimental work. Therefore, 100% infill density must be used to ensure good tensile strength, and the optimal print temperature must be set according to the material.

Furthermore, the R^2 value of the ANOVA analysis for the tensile strength parameter was calculated as 1.00, indicating that the regression equations are highly successful in predicting tensile strength. Infill density emerges as the most influential factor (85.03%), followed by printing temperature (8.80%). However, layer height is not found to be significant and does not affect tensile strength.

Table 3: Results of ANOVA for tensile strength

Source	DF	% Contribution	Adj SS	Adj MS	F-Value	P-Value
Temperature (°C)	1.000	8.80	35.745	35.745	12.28	0.008
Infill Density (%)	1.000	85.03	345.265	345.265	118.60	0.000
Layer Height (mm)	1.000	0.43	1.735	1.735	0.60	0.462
Error	8.000	5.74	23.288	2.911		

Total	11.000	100.00	406.033			
R^2		1.00				



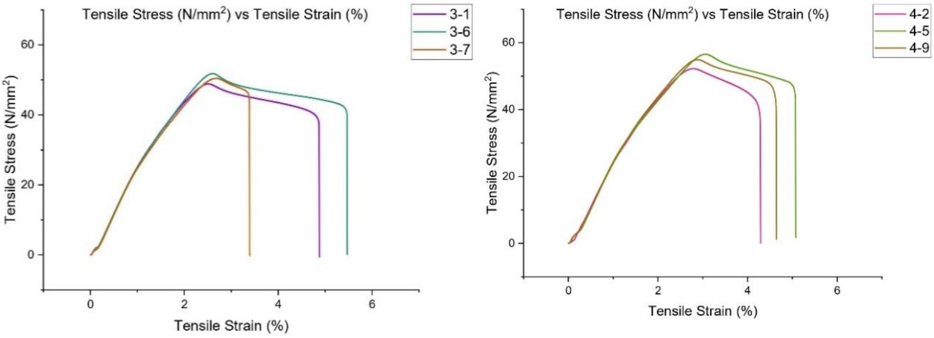
(a) (b)

Figure 5: (a) Main effect plot (b) Interaction plot

The main plot and interaction effects are plotted using ANOVA to further illustrate the relationship between these factors. Figure 5 (a) shows the main effect plot of all factors (infill density, print temperature, layer height). According to the main effect plot, infill density is the most significant effect, followed by the print temperature, with the layer height being less influential. The signal-to-noise (S/N) ratio is more significant for the infill density, which supported the finding from Venkateswar et al. [18]. The results also supported Gunasekaran et al. [19], who suggested that the samples printed at a higher percentage of infill density showed a considerable increase in tensile strength compared to the control group. These factors independently have a significant effect on the response variable (tensile strength), which means changes in infill density and temperature directly influence the tensile strength. However, the significant effect of layer height, as suggested by Shahsikumar et al. [20], is not evident. Layer height does not significantly affect the tensile strength, which means changes in layer height alone do not produce a statistically significant difference in the tensile strength. Other factor, such as printing orientation [21], or pre-preparation of the material [22], may contribute to the variation of the results. This main effect plot validated the experimental test results, which show that 100% infill density presented the first and second highest stress values and had the most significant effect compared to temperature and layer height.

Figure 5 (b) illustrates the interaction plot, highlighting a more substantial interaction between printing temperature and layer height.

Although layer thickness alone does not significantly affect the response variable, its interaction with temperature does. This suggests that the effect of temperature on the tensile strength depends on the level of layer height and vice versa. When the infill density is 100%, different layer heights and temperature settings result in a distinct tensile strength value, as depicted in Figure 5. Notably, the higher temperature in parameter set (D) at 220°C (Figure 5b) leads to a superior tensile strength compared to parameter set (C) (Figure 5a), conforming to the main effect plot, where the layer height is the least significant factor. The layer height effect is not so apparent due to the slight variation of the tensile strength concerning the two levels of the factor, which are 0.1 mm and 0.3 mm. This confirms that their levels affect the tensile strength (response variable) of these two factors (print temperature and layer height). Therefore, the effect of those process parameters (infill density, print temperature, and layer height) in tensile strength is finally understood, where infill density and print temperature will directly influence the strength, and there is an interaction between temperature and layer height. In this sense, varying the print temperature and layer height at certain levels will vary the tensile strength, and to avoid this, we can make them constant by choosing the optimal setting for each, as proposed by other researchers, with a finer layer height and the print temperature for PLA in the range of 210-220°C.



(a) (b)

Figure 5: Comparison between same 100% infill density but different temperature and layer height printed at (a) 200°C, 0.1mm (set C); (b) 220°C, 0.3mm (set D)

Minitab software was used to develop the Multiple Linear Regression Predictive Model for the Ultimate Tensile Strength (UTS). Table 4 tabulates the regression analysis result. Figure 6 shows the regression plot.

Table 4: Regression Table for Ultimate Tensile Strength (UTS

Predictor	Coefficient	Standard Error coefficient	T-Value	P-Value
Constant	47.114	0.493	95.660	0.000
Temperature (°C)	-1.726	0.493	-3.500	0.008
Infill Density (%)	-5.364	0.493	-10.890	0.000
Layer Height (mm)	-0.380	0.493	-0.770	0.462

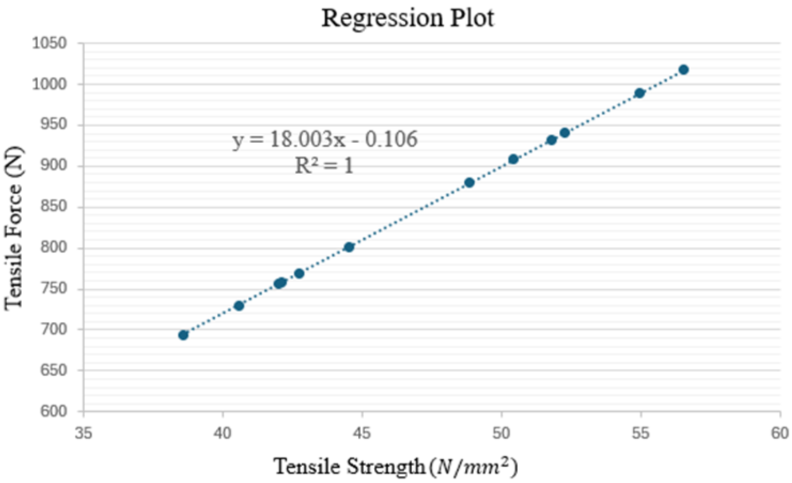
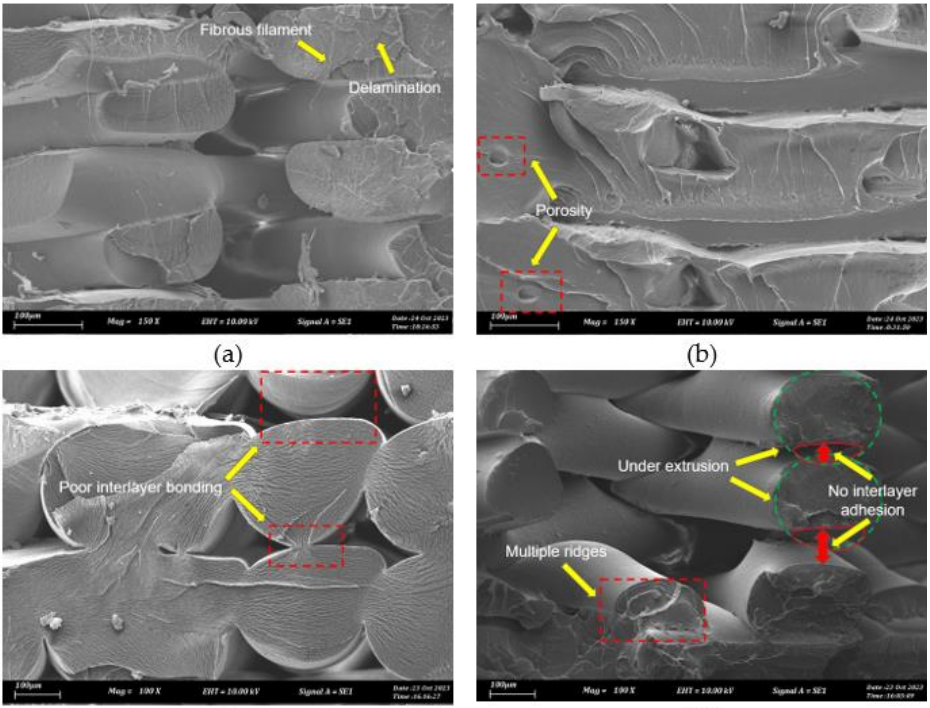


Figure 6: Regression plot for the tensile strength

For the microstructural study, three specimens were carefully selected within each parameter set based on tensile force values, representing the lowest, middle, and highest results, as indicated in Table 3. Figure 7 depicts SEM analysis of the fractured PLA specimens, which revealed distinct defects, shedding light on the interplay between printing parameters and structural integrity. The presence of fibrous filaments, delamination, and porosity in specimens printed at 200°C with 100% infill and 0.1mm layer height suggests a complex relationship between these parameters. The elevated temperature might have led to excessive filament flow, resulting in the formation of fibrous structures. In contrast, potential under extrusion and insufficient material flow could contribute to delamination and porosity. Poor interlayer bonding observed in specimens printed at 200°C with 50% infill and 0.3mm layer height indicates challenges in achieving adequate fusion between layers, potentially exacerbated by the more considerable layer height. Under extrusion in specimens printed at 220°C with 50% infill and 0.1mm layer height may be attributed to the higher temperature affecting material flow dynamics. Then, the absence of interlayer adhesion between specimen layers may be attributed to insufficient material flow or inadequate bonding of successive layers, particularly under the finer layer height parameter of 0.1mm during the 3D printing process. Multiple ridges in identical specimens suggest a potential influence of temperature and layer height on surface irregularities. This nuanced understanding highlights the importance of carefully selecting and optimizing printing parameters to mitigate specific defects and enhance the overall structural integrity of 3D-printed PLA specimens.



(a) (b) (c) (d)

Figure 7: Fractured surface of specimen printed with (a) 200°C, 100%, 0.1mm; (b) 220°C, 100%, 0.3mm; (c) 200°C, 50%, 0.3mm; (d) 220°C, 50%, 0.1mm

Therefore, in comparison of 100% and 50% infill density, we can see that the fracture surface of the 100% infill density (Figures 7a and 7b) shows better layer adhesion and fewer voids compared to the 50% infill density (Figure 7c and 7b). The finding can be correlated to the statistical and experimental data discussed earlier, where specimens with higher tensile strength (100% density) offer good interlayer adhesion and fewer voids compared to the 50% infill density.

Therefore, to relate the finding to this work's aim, the infill density selection affects the tensile strength, and the combination of various process parameters will also influence the microstructure. Therefore, we propose using 100% infill density and optimal printing temperature based on the material used (in this case, 220°C for PLA), making the layer height constant, and choosing the finer layer height, like 0.1 mm.

4.0 CONCLUSION

To conclude, infill density shows the most significant effect (85.03%), followed by the print temperature (8.8%). On the other hand, layer height is not significant. However, there is an interaction between layer height and print temperature, and the variation of these two factors will contribute to the variation of the tensile strength. The experimental and statistical data have validated the finding, and the microstructural analysis also confirms a better layer adhesion and fewer voids in the sample of 100% infill density compared to the 50% infill density. Therefore, one must choose 100% infill density, with the optimal print temperature for each thermoplastic material (in this case 220°C for PLA), and avoid varying the layer height and print temperature, as there is an interaction between these factors. As suggested by many researchers, finer layer height should be chosen for excellent interlayer adhesion if strength is the main aim of the printing. The presented methodology can be used as a pre-processing approach to optimize desired mechanical properties in material extrusion 3D printing.

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AUTHOR CONTRIBUTIONS

R.A. Hamid: Writing and Data Analysis; N.P. Lee: Experimental Works; S. Maidin: Proof-reading; N. Hajar: Mathematical Modelling; T. Ito: Reviewing

CONFLICTS OF INTEREST

The manuscript has not been published elsewhere and is not under consideration by other journals. All authors have approved the review, agree with its submission, and declare no conflict of interest on the manuscript.

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