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Experimental study and optimisation of flexural properties of 3D-printed polylactic acid for energy-storing-and-returning prosthetic foot

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Abstract
A prosthetic foot with energy-storing-and-returning capabilities requires high strength to prevent damage, high rigidity for stability, and low weight for user comfort. Therefore, efforts are needed to optimise the properties of the 3D-printed prosthetic foot. Based on the literature review, a research gap remains in understanding the complex interactions among 3D printing parameters that improve flexural properties, minimise mass, and reduce printing time. This study investigated how infill density, layer thickness, shell thickness, and their interaction affect the flexural strength-to-mass ratio, flexural modulus of elasticity, strain, and required printing time of the 3D-printed product. The experimental parameter ranges are infill density (40–60%), layer thickness (0.2–0.3 mm), and shell thickness (0.8–1.6 mm). A case study was conducted to optimise these parameters using the Response Surface Methodology with the Box-Behnken Design. The experimental data were fitted to a quadratic model, and Analysis of Variance determined the significance of individual factors. A gradient-based algorithm then identified the optimal parameter combinations. Results indicated that shell thickness was the most influential factor on the flexural strength-to-mass ratio and flexural modulus. Additionally, the interaction between layer height and shell thickness significantly affected strain, while infill density impacted printing time. The optimal values obtained were 32.5722 MPa/gram for the flexural strength-to-mass ratio, 2727.06 MPa for the modulus, 0.0522 for the strain, and 757.7788 seconds for the printing time. The novelty of this research lies in presenting how the interaction between shell thickness, layer thickness, and infill density affects process productivity and material efficiency while preserving product performance.

Keywords:
3D Printing;
Flexural Properties;
Optimisation;
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INTRODUCTION

Polylactic Acid (PLA) is commonly utilised in three-dimensional (3D) printing due to its biodegradability and biocompatibility. It is also environmentally friendly, easy to print, and affordable. However, PLA has relatively low mechanical strength compared to other polymers. Therefore, many researchers have improved the mechanical strength of 3D-printed PLA by modifying materials, adjusting printing process parameters, and performing post-processing.

Flexural strength is a crucial mechanical property of the 3D-printed PLA product. Flexural strength refers to the ability of a 3D-printed product to withstand maximum flexural stress before it breaks. Another important property is the flexural modulus of elasticity, which indicates the material's resistance to bending. The ductility of the 3D-printed product is also another important mechanical property. Ductility is the ability of a material to undergo permanent plastic deformation before breaking. This property is usually measured by the percentage elongation or strain of the material.

Flexural properties are the key factors in a variety of 3D-printed PLA products. For example, various sports equipment and prosthetic feet require a combination of maximum flexural properties. An energy-storing-and-returning type of prosthetic foot is subjected to compression, flexural, shear, and torsional stresses when used for standing, walking, or squatting. Therefore, this prosthetic foot must have enough strength to resist damage and enough rigidity and lightness to bring comfort to its user.

The flexural modulus of elasticity of a 3D-printed product is inversely proportional to its ductility. As the modulus of elasticity of the 3D-printed product increases, the elongation percentage decreases. Therefore, efforts are needed to optimise the flexural properties of the 3D-printed product to achieve maximum flexural strength, stiffness, and ductility while minimising mass and reducing printing time.

Main parameters and their influence

First, this research investigates the influence of several key parameters of the 3D printing process on the flexural strength-to-mass ratio, the flexural modulus of elasticity, the strain, and the required printing time of a 3D-printed product. A literature review was conducted to identify the key parameters of 3D printing. Based on the results, various 3D printing parameters influence the flexural properties of a 3D-printed product. A higher printing temperature parameter results in lower flexural strength and flexural modulus of the 3D-printed product. The printing temperature refers to the temperature of the 3D printer's nozzle, which heats the PLA material during the printing process. According to Aboulmajd et al., the printing temperature has a greater influence than printing speed and orientation [1]. Next, printing speed refers to the speed of movement of the nozzle and printing table during the printing process. This printing speed affects the flexural strength of 3D-printed PLA, as different printing speeds can result in varying cooling rates [2][3].

The flexural properties of 3D-printed PLA are also influenced by the build orientation. Build orientation refers to the position and direction of an object when it is printed on the table of a 3D printer. Printing in an on-edge orientation will produce better flexural strength compared to a flat-type orientation [4]. Moreover, layer thickness also affects the flexural strength of the 3D-printed PLA [3, 5, 6, 7, 8]. The thickness of each layer of printed material is referred to as layer thickness. Reducing the layer thickness increases the flexural strength of the 3D-printed PLA. Another parameter that affects the flexural strength and modulus of the 3D-printed PLA is the shell thickness, which refers to the thickness of the wall or outermost layer printed around the object. The flexural strength increases to some extent as the shell thickness increases [8][9].

Then, infill density, or the percentage of material that fills the inside of the printed object, also affects the flexural properties of the 3D-printed PLA. Increasing the infill density increases the flexural strength and flexural modulus of 3D-printed PLA [5, 10, 11 , 12]. In addition, infill width also affects the flexural strength and modulus of the 3D-printed PLA [13]. Infill width is the thickness of each raster extruded by the nozzle of the 3D printer in building an object. Different infill patterns have different effects on the flexural strength and flexural modulus of the 3D-printed PLA [11, 14 – 17]. A closer and homogeneous infill pattern type results in higher strength and stiffness. Infill angle also affects the flexural strength and modulus of 3D-printed PLA [13, 18, 19]. The infill angle is the direction of the material raster that fills the inside of the printed object. The value of the infill angle typically ranges from 0° to 90°.

Based on the previous works by the researchers mentioned above, the flexural properties of a 3D-printed product are influenced by several factors, including printing temperature, printing speed, build orientation, layer thickness, infill density, infill width, infill pattern, infill angle, and shell thickness.

Limitations of previous research

Previous research found that flexural strength and flexural modulus are affected by the infill density parameter. The mass of the 3D-printed PLA and the time of the printing process are both primarily influenced by the infill density [20]. Based on research by Hodzic and Adi Pandzic, flexural strength increases linearly with the increase in infill density for all types of infill patterns [11]. However, the change in flexural modulus value that occurs when there is a change in infill density is not significant at the high infill density. The flexural modulus value differs slightly between 80% and 100% infill density. It shows that the infill density value still needs to be optimised to obtain certain flexural properties.

Additionally, layer thickness is a significant factor influencing flexural strength. Layer thickness is a more effective factor than infill density in increasing flexural strength [7]. Layer thickness can be used to restore the flexural strength value when the infill density needs to be decreased to reduce the mass of the 3D-printed product. However, a lower layer thickness will significantly increase the printing time. The optimal values of layer thickness and infill density for achieving the maximum flexural strength, the lowest mass, and the shortest printing time of the 3D-printed product have not yet been investigated.

According to Chokshi and Suteja, shell thickness is a factor that affects flexural strength more significantly than layer thickness. The thicker the printed wall, the stiffer the 3D-printed product [8][9]. As a result, it can withstand higher flexural loads. The shell thickness also affects the flexural modulus [21]. The higher the shell thickness, the thicker the wall will be. Larger wall thickness reduces the cavity in the 3D-printed product, which should be filled with material using various filling patterns. It is hypothesised that by increasing the values of shell and layer thickness, the infill density can be reduced, leading to a decrease in the mass and printing time of the 3D-printed product, while still achieving the necessary flexural properties. The interaction between 3D printing parameters and material efficiency, process productivity, and product performance requires further exploration.

Despite existing studies emphasising the need to investigate the effect of 3D printing parameters on material efficiency and performance, a research gap remains in understanding the complex interactions among infill density, layer thickness, and shell thickness to optimise flexural properties, minimise mass, and reduce printing time.

The purpose of this research is to investigate the effect of infill density, layer thickness, and shell thickness parameters and their interaction on the flexural properties of the 3D-printed product. This research focuses on the ratio of flexural strength to mass, the flexural modulus of elasticity, the strain, and the required printing time of the 3D-printed product. As a case study, the research optimises the 3D printing parameters in manufacturing a particular component as a research object. The parameters are optimised to obtain the maximum ratio of flexural strength to mass, the flexural modulus of elasticity, and strain in the shortest printing time.

The differences between this research and previous research can be summarised as follows:

- Previous research found that infill density affects flexural strength and modulus. However, its impact diminishes at high values (80%–100%). Therefore, this research examines lower infill density for further optimisation to achieve specific flexural properties.
- Previous research investigated the influence of layer thickness, shell thickness, and infill density in enhancing flexural properties. This research investigates the effect of and optimise the complex interactions between these parameters on the flexural properties and mass reduction, especially considering the trade-off with printing time.

The novelty of this research lies in presenting how the individual and the interaction among shell thickness, layer thickness, and infill density affect process productivity, material efficiency, and product performance. In addition, it offers insights for optimisation.

This research contributes to the field by developing a new model that describes the effect of the interaction among infill density, layer thickness, and shell thickness parameters on the printing time, flexural strength-to-mass ratio, flexural modulus, and strain of the 3D-printed product. In addition, this research presents a case study on how to adjust infill density, layer thickness, and shell thickness to enhance the productivity of 3D printing processes and material efficiency while maintaining structural integrity.

MATERIAL AND METHOD

Methods

Figure 1 illustrates the flow chart of this research, which aims to understand the influence of and optimise the interaction between 3D printing parameters on process productivity, material efficiency, and product performance.

The independent and dependent parameters of this research are illustrated in Figure 2. Three independent parameters with three levels are investigated in this research: infill density, layer height, and shell thickness. The dependent parameters or responses of this research are printing time, flexural strength-to-mass ratio, flexural modulus, and strain. Other parameters in the printing process are kept constant. The values of each parameter studied in this research can be seen in Table 1.

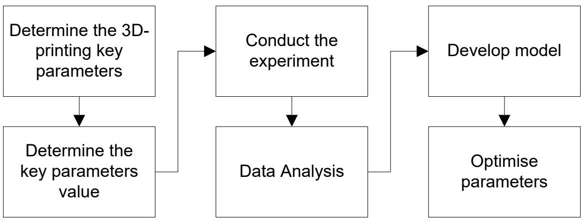

Figure 1. Flow Chart

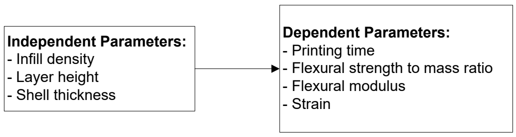

Figure 2. Independent and Dependent Research Parameters

The Response Surface Methodology with Box-Behnken Design is implemented to design the experiment. The method is also employed to model and analyse the influence of the independent parameter on the response. The Box-Behnken Design involves a set of experimental runs for three independent parameters, each with three levels and two replications. As a result, this research requires a total of thirty experimental runs. After the data from each run is collected and calculated, the experimental data are fitted to a model, which is typically a linear or quadratic model using regression analysis. Then, the Analysis of Variance statistical test is used to determine the significance of the model and its individual terms. After that, the model is used to generate a surface plot to illustrate how the response changes with varying parameters. Finally, the optimal conditions are identified by employing a gradient-based algorithm to find the combination of parameter levels that optimised the responses.

Experiment Procedures

This study uses a bending test specimen as the research object, printed with a 3D printing process. The specimen is made according to ISO 178 standards with dimensions of 80 ± 2 mm in length, 10 ± 0.2 mm in width, and 4 ± 0.2 mm in height, as shown in Figure 3. The process begins with using CAD software to create the bending test specimen model. Then, this model is saved in STL format, a common file type readable by slicer software. The slicing software is utilised to establish printing settings, divide the 3D model into thin layers, and produce G-code commands for the 3D printer. Subsequently, the 3D printer is employed to print the specimens. After that, the 3D-printed specimens are allowed to cool at room temperature to prevent warping.

Table 1. Parameter Values

Parameters	Value	Unit
Infill Density	40, 50, 60	%
Layer Height	0.2, 0.25, 0.3	mm
Shell Thickness	0.8, 1.2, 1.6	mm
Extruder Temperature	210	°C
Nozzle Diameter	0.4	mm
Infill Pattern	Triangular	
Bed Temperature	60	°C
Printing Speed	90	mm/s
Infill Angle	0	°
Printing Orientation	On-edge	

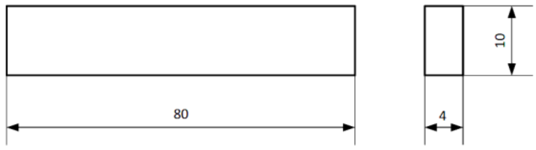

Figure 3. Dimension of Research Object in mm

During the printing process, the duration of printing is measured using a stopwatch. The mass of the specimen is measured by using a digital weight scale. Then, the dimensions of the specimen are measured using a calliper to ensure they meet the standard. Each specimen is then tested using a universal testing machine to measure its flexural properties, which are flexural force and deflection. Finally, the fractured surfaces are visually examined for significant air gaps, which could indicate flow interruptions during printing.

Tools and Materials

The material used to print the bending test specimen is Polylactic Acid (PLA) in the form of filament produced by CCTree. The slicing software used in this research is Slic3r, which is embedded in Repetier Host. The 3D printer used to print the specimens is the Anycubic Cobra, with a printing size of 220 x 220 x 250 mm. The printing time is measured using the Android-based stopwatch application on a cellular phone. The digital weight scale used is the Mettler Toledo type ME204E, with an accuracy of 0.001 grams. The dimensions of the specimen are measured using Mitutoyo callipers with 0.01 mm accuracy. The flexural properties testing machine used is the Universal Testing Machine (UTM) Tarno Grocki with a 10.000 kg capacity.

Parameters and Values

The dependent parameters of this research, along with their corresponding values, are determined based on the literature review. Jagadeesh et al. conducted a study that implemented a triangular infill pattern. According to their findings, the research demonstrates that the triangular infill pattern yields better tensile and flexural strength in 3D-printed objects compared to other infill patterns [22].

To find the optimal infill density, this research considered the available range of infill percentages. According to Hodzic and Adi Pandzic, the flexural modulus between 80% and 100% infill density does not show a significant difference [11]. The medium level for infill density was determined by selecting the median value of 50%. Meanwhile, the low and high levels were then set by decreasing and increasing the medium level by 10%.

According to the guidelines' recommendation, the minimum layer height is equal to half the nozzle diameter, and the maximum layer height should not exceed 80 % of the nozzle diameter. As this research employed nozzle diameters of 0.4 mm, the layer heights were set to 0.2 mm, 0.25 mm, and 0.3 mm, corresponding to the low, medium, and high levels.

The diameter of the nozzle generally determines the thickness of the shell. It is recommended to have a minimum shell thickness of two times the diameter of the nozzle. The thickness of the printed object limits the maximum shell thickness. The study established that the minimum shell thickness was twice the 0.4 mm nozzle diameter, which is equivalent to 0.8 mm. The maximum shell thickness was limited by the specimen width and set to 1.6 mm. To explore different shell thickness configurations, a medium level of 1.2 mm was chosen.

Analysis and Optimisation Procedures

The measured and calculated printing time, mass, flexural strength, flexural modulus, and strain data of each specimen are then analysed using statistics software. They are also used to generate the regression equation for four responses: the flexural strength and mass ratio, flexural modulus, strain, and printing time.

Before optimising the process parameters, the regression equation model for each response is analysed using the lack-of-fit test to determine whether it is a linear or quadratic model. Additionally, insignificant factors are eliminated one by one, leaving only the significant ones to be considered. Finally, the response optimiser and desirability function methods are used to optimise the four responses simultaneously.

RESULTS AND DISCUSSION

The printing time (PT), flexural strength-to-mass ratio (FSMR), flexural modulus (FM), and strain (S) data for various combinations of infill density (ID), shell thickness (ST), and layer height (LH) parameters are presented in Table 2 and Table 3. Based on the analysis results and the lack-of-fit test from these data, the regression equations for flexural strength and mass ratio, flexural modulus, and strains are linear models. In the meantime, the regression equation of printing time is a quadratic model. Then, based on the elimination process of insignificant factors, the factor that significantly affects the flexural strength-to-mass ratio and flexural modulus is shell thickness. The shell thickness and the interaction between layer height and shell thickness have a significant influence on the strain. In addition, infill density, layer height, shell thickness, and the combination of infill density and shell thickness have a significant role in affecting printing time. The regression equations for the flexural strength-to-mass ratio, flexural modulus, strain, and printing time are presented in (1) through (4). The equations describe the effect of interaction among parameters on the responses. The influence of each factor on each response can also be visualised using a Pareto Chart. Pareto Charts for the flexural strength-and-mass ratio response, flexural modulus, strains, and printing time are shown in Figures 4 through 7.

$$FSMR = 26.72 + 0.051 \times ID - 26.8 \times LH + 6.76 \times ST \quad (1)$$

$$FM = 3497 + 13.3 \times ID - 871 \times LH - 818\ ST \quad (2)$$

$$S = 0.0651 + 0.000045 \times ID - 0.2502 \times LH - 0.0210 \times ST + 0.1940 \times LH \times ST \quad (3)$$

$$PT = 2080 + 9.72 \times ID - 8233 \times LH - 176 \times ST + 9273 \times LH \times LH + 130.8 \times ST \times ST - 3.37 \times ID \times ST \quad (4)$$

Table 2. Experiment Data Printing Time and Flexural Strength-and-Mass Ratio

No	ID (%)	ST (mm)	LH (mm)	PT (sec)	FSMR (MPa/gram)
1	40	1.2	0.20	1006	33.29
2	40	1.2	0.20	1004	30.86
3	40	0.8	0.25	828	21.67
4	40	0.8	0.25	829	20.56
5	40	1.6	0.25	804	38.56
6	40	1.6	0.25	807	29.75
7	40	1.2	0.30	672	28.95
8	40	1.2	0.30	659	31.90
9	50	0.8	0.20	1093	38.93
10	50	0.8	0.20	1091	28.14
11	50	1.6	0.20	1100	31.62
12	50	1.6	0.20	1100	31.88
13	50	1.2	0.25	867	29.05
14	50	1.2	0.25	863	38.56
15	50	1.2	0.25	865	29.43
16	50	1.2	0.25	865	31.23
17	50	1.2	0.25	868	32.14
18	50	1.2	0.25	861	36.88
19	50	0.8	0.30	724	26.79
20	50	0.8	0.30	724	21.01
21	50	1.6	0.30	705	34.78
22	50	1.6	0.30	730	31.15
23	60	1.2	0.20	1107	30.04
24	60	1.2	0.20	1107	29.78
25	60	0.8	0.25	986	29.63
26	60	0.8	0.25	984	31.75
27	60	1.6	0.25	913	36.12
28	60	1.6	0.25	903	27.88
29	60	1.2	0.30	747	29.04
30	60	1.2	0.30	770	29.49

Table 3. Experiment Data Flexural Modulus and Strain

No	ID (%)	ST (mm)	LH (mm)	FM (MPa)	S
1	40	1.2	0.20	3353	0.03439863
2	40	1.2	0.20	2671	0.03990234
3	40	0.8	0.25	2601	0.02559434
4	40	0.8	0.25	2604	0.02436328
5	40	1.6	0.25	2965	0.05021484
6	40	1.6	0.25	2478	0.04657940
7	40	1.2	0.30	2487	0.03990234
8	40	1.2	0.30	3101	0.03439863
9	50	0.8	0.20	3497	0.03613594
10	50	0.8	0.20	2670	0.03412617
11	50	1.6	0.20	2413	0.05124639
12	50	1.6	0.20	2502	0.04892578
13	50	1.2	0.25	2989	0.03422490
14	50	1.2	0.25	3723	0.03732422
15	50	1.2	0.25	2785	0.03732422
16	50	1.2	0.25	3256	0.03439863
17	50	1.2	0.25	3057	0.03676436
18	50	1.2	0.25	3494	0.03825732
19	50	0.8	0.30	3822	0.02246191
20	50	0.8	0.30	3231	0.02072813
21	50	1.6	0.30	2530	0.05213262
22	50	1.6	0.30	2310	0.05200100
23	60	1.2	0.20	3009	0.03603516
24	60	1.2	0.20	3325	0.03362432
25	60	0.8	0.25	3836	0.02700879
26	60	0.8	0.25	3569	0.03092139
27	60	1.6	0.25	3221	0.04460801
28	60	1.6	0.25	2174	0.05150391
29	60	1.2	0.30	2498	0.04057354
30	60	1.2	0.30	2765	0.03822715

Based on Figure 4, shell thickness has the most significant influence on the flexural strength-and-mass ratio of the 3D-printed specimen. It happens because the shell thickness affects the magnitude of the moment of inertia of the cross-sectional area of the printed specimen. The moment of inertia increases as the shell thickness grows larger. Consequently, the bending moment resistance and flexural strength of the printed specimen also increase. This finding aligns with previous research, which states that the shell thickness affects flexural strength and modulus due to better compaction and density at the surfaces [23].

The mass of the 3D-printed specimen is also affected by the shell thickness. Greater shell thickness leads to an increase in the printed specimen shell volume. As a result, the mass of the printed specimen increases with increasing shell thickness. The report by Bedan et al. shows the same result [24]. Based on the experimental results, the influence of shell thickness on flexural strength is greater than its influence on mass. Therefore, the flexural strength-and-mass ratio of the 3D-printed specimen increases as the shell thickness increases. Meanwhile, infill density does not significantly affect the flexural strength-and-mass ratio of the printed specimen. The volume of the inside cavity in the printed specimen that needs to be filled by adjusting the infill density is small. As a result, the changes in infill density do not affect the mass. However, increasing the layer height has a greater impact compared to adjusting the infill density, as it results in a larger void between the layers, ultimately reducing the flexural strength and mass of the printed specimen.

Figure 5 shows that the flexural modulus is significantly affected by shell thickness. The reason is that the shell thickness influences both the magnitude of the moment of inertia of the cross-sectional area and, consequently, the deflection of the printed specimen. The greater the shell thickness, the greater the ratio of the required force and deflection decreases. As a result, the flexural modulus decreases. Other researcher reports a similar result related to the influence of shell thickness on the flexural strength and modulus of 3D-printed objects [25].

The strain is affected by the shell thickness and the interaction between layer height and shell thickness, as shown in Figure 6. Increasing the shell thickness allows the printed specimen to handle a higher maximum deflection, which in turn increases the strain on the specimen. Furthermore, the strain of the printed specimen can be influenced by the interaction between shell thickness and layer height. Using a lower layer height produces a printed specimen that is more homogeneous. When a lower layer height is combined with a higher shell thickness, it increases the strain of the printed specimen. Other researchers also indicate that shell thickness significantly impacts the strain in 3D-printed products [26][27].

Figure 7 illustrates that layer height is the most significant factor affecting printing time. The smaller the layer height, the more layers that must be deposited. As a result, the required printing time is longer. It is in accordance with the research by Suteja et al. [9]. Additionally, infill density also affects printing time, as it determines the printed volume of the specimen's internal cavity. The greater the infill density, the larger the volume of the cavity that must be filled. As a result, the printing process requires more time. The research by Suteja shows a similar result [28]. The thickness of the shells and their interaction with the infill density also affect the required printing time, as the volume of the cavity inside the printed specimen is influenced by the shell thickness. The greater the thickness of the shell, the smaller the volume of cavities that must be filled. As a result, the time needed for printing the specimen is shorter. This finding is consistent with that reported by Chintakula, who also observed similar outcomes in their study related to the effect of shell thickness on the printing time [29].

Based on the literature, PLA is a material with a high modulus of elasticity [30]. However, a hollow printed specimen will have a lower modulus of elasticity. By increasing the thickness of the shell, the outer structure of the printed object becomes more rigid so that the stress is distributed evenly. As a result, the PLA-printed specimens have a higher flexural modulus and strength. Additionally, PLA, which has a rigid molecular structure, tends to exhibit brittle properties [31]. By lowering the layer height, the adhesion between layers becomes stronger, improving the ability of PLA-printed specimens to absorb deformation before breaking. As a result, a decrease in layer height along with an increase in shell thickness can increase the strain.

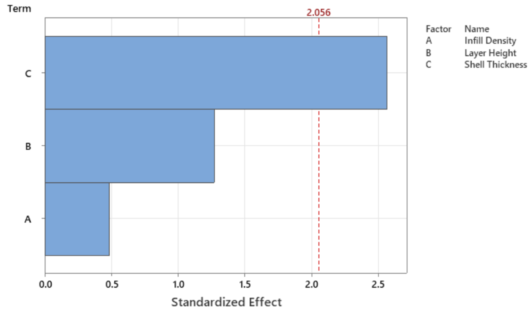

Figure 4. Pareto Chart of Flexural Strength-and-Mass Ratio

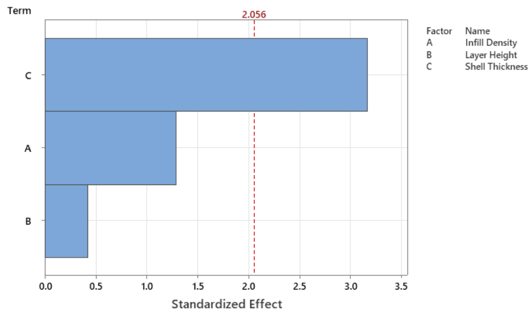

Figure 5. Pareto Chart of Flexural Modulus

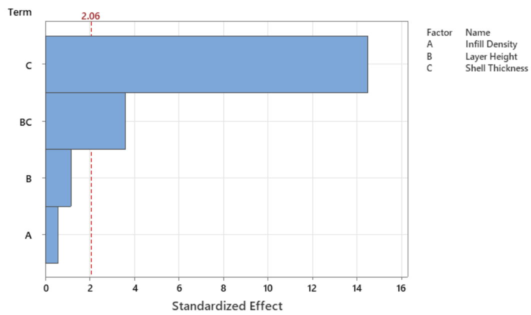

Figure 6. Pareto Chart of Strain

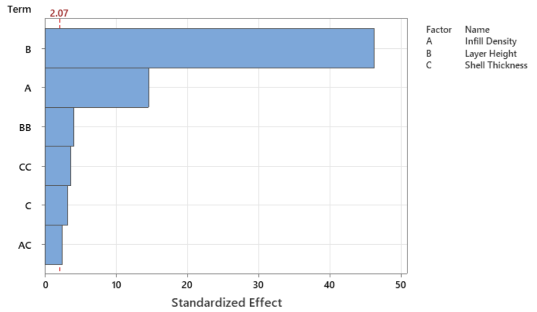

Figure 7. Pareto Chart of Printing Time

To demonstrate that 3D printing parameters can enhance the productivity of the process without compromising structural integrity, a process optimisation is implemented by printing the bending test specimen according to ISO 178 standards. Regression equations for the flexural strength-and-mass ratio, flexural modulus, strains, and printing time are optimised using the response optimiser and the composite desirability function approach. The desired response is a maximum flexural strength-and-mass ratio, flexural modulus, and strain with the fastest printing time.

Figure 8 shows the results of the optimisation process. The largest composite desirability data were achieved when using a value of the infill density parameter equal to 60%, a layer height of 0.3 mm, and a shell thickness of 1.6 mm. The shell thickness is determined by multiplying the nozzle diameter, so it should be either 0.8 mm, 1.2 mm, or 1.6 mm in value. Of the three values, the largest composite desirability value is obtained at a shell thickness of 1.6 mm. By implementing the optimal values of parameters, the flexural strength-and-mass ratio obtained is 32.5722 MPa/gram. Then the optimal values of flexural modulus, strain, and printing time, respectively, are 2727.06 MPa, 0.0522, and 757.7788 seconds.

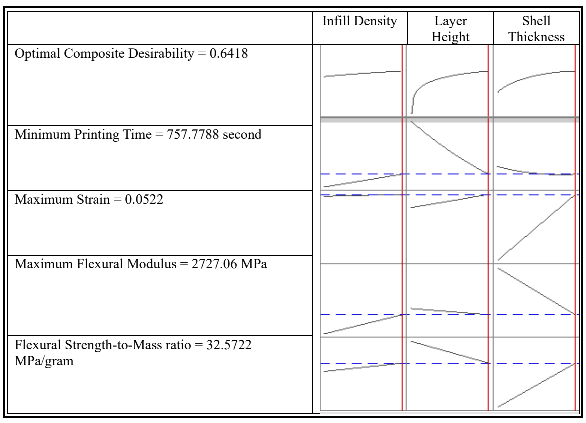

Figure 8. Optimisation Result

The optimal values of the flexural strength, modulus of flexural elasticity, and strains are compared to the maximum value based on the Finite Element Method simulation under static conditions for the load equal to the average user mass [32, 33, 34]. Based on the comparison result, the optimal values obtained still meet the requirements for an energy-storing-and-returning prosthetic foot. Compared to the results of previous research by Atakok et al., which required a 0.25 mm layer height and 70% infill density, this study achieved equivalent flexural strength while reducing printing time using a lower infill density and larger layer height [7]. It is also shown that the value of infill density and subsequently the printing time can be reduced by increasing the value of layer thickness. Compared to research by Mansor et al., which used 100% infill density, 0.15 mm layer height, and 2 mm shell thickness, this research achieved higher flexural strength and lower printing time by using a lower shell thickness and infill density [25]. Thus, this research demonstrates improvements in the flexural properties of 3D-printed PLA, as well as the printing time, which can be utilised in the energy-storing-and-returning prosthetic foot. In addition, previous research primarily focused on enhancing mechanical performance through individual parameters such as infill density or raster angle. This research integrates multiple influential factors, which are layer thickness, infill density, and shell thickness, to optimise responses.

CONCLUSION

This research demonstrates that shell thickness is the most significant factor influencing the flexural strength-to-mass ratio and flexural modulus. The shell thickness and the interaction between layer height and shell thickness have a significant influence on the strain. Additionally, the infill density, layer height, shell thickness, and the interaction between infill density and shell thickness have a significant impact on printing time. This research has performed statistical validation through regression modeling and Analysis of Variance (ANOVA). The flexural strength-to-mass ratio, flexural modulus, and strain exhibit linear relationships with the studied parameters, while printing time follows a quadratic model.

The physical mechanism underlying this effect is primarily attributed to the moment of inertia of the specimen cross-section, which increases with shell thickness, thereby enhancing flexural strength and stiffness. As the moment of inertia increases, the printed specimen undergoes an increase in bending moment resistance and flexural strength. However, this increase also contributes to higher mass, because the thicker shell increases the volume of the printed specimen shell. When the shell thickness is increased, there is a decrease in flexural modulus because the ratio of the required force and deflection is reduced. A larger shell thickness increases the maximum deflection that can be held, thereby increasing the strain of the printed specimen. Using a smaller layer height and greater shell thickness increases the strain of the printed specimen. In addition, a lower layer height and shell thickness, along with higher infill density, increase the required printing time because they need more layers and volumes to be printed. These findings align with prior studies that emphasise the role of the infill density, layer thickness, and shell thickness in improving mechanical properties while further advancing the understanding of parameter interactions, especially considering the trade-off with printing time.

The optimal values of the investigated parameters have been determined. The infill density, layer height, and shell thickness should be set at 60 %, 0.3 mm, and 1.6 mm, respectively, for optimal results. By implementing this value of parameters, the flexural strength-and-mass ratio obtained is 32.5722 MPa/gram. Then, the optimal values of flexural modulus, strain, and printing time are 2727.06 MPa, 0.0522, and 757.7788 seconds, respectively.

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