



A Study of Optimum Conditions for the Production of a Prototype of Nakhon Si Thammarat's Niello with 3D Printing

Pongpun Ratchapakdee¹, Rungrote Jeendoung¹, Kamonpong Jamkamon², Chatpon Phimpha³,
Banthita Poosabmee Ponatong^{1*}

¹ Department of Industrial Technology, Faculty of Science and Technology, Rajamangala University of Technology Srivijaya, Nakhon Si Thammarat, Thailand; pongpun.r@rmutsv.ac.th (PR); rungrote.j@rmutsv.ac.th (RJ); banthita.p@rmutsv.ac.th (BPP)

² Department of Industrial Engineering, Faculty of Engineering, Rajamangala University of Technology Krungthep, Bangkok, Thailand; kamonpong26@gmail.com

³ Department of Industrial Engineering, Faculty of industrial Education, Rajamangala University of Technology Suvarnabhumi, Suphanburi, Thailand; chatpon.p@rmutsb.ac.th

*Correspondence: banthita.p@rmutsv.ac.th

Article history

Received 29.12.2025

Accepted 11.05.2026

Available online 30.06.2026

Keywords

3D printing,
Polylactic acid,
Tensile strength,
Surface roughness.

Abstract

This study employed a Box–Behnken Design for experimental planning and analyzed the results using Response Surface Methodology (RSM). The process parameters considered were print temperature, print speed, and infill density. Experimental results revealed that the optimal printing conditions for achieving the highest tensile strength, as determined by RSM, were a print temperature of 240 °C a print speed of 30 mm/s, and an infill density of 80%. Under these conditions, the printed specimens exhibited 36.16 MPa as the maximum tensile strength and 4.96 µm as the minimum surface roughness. The anticipated values were compared with the actual experimental data to verify the accuracy of the experimental model and response predictions. The results showed strong agreement between the predicted and experimental values, with average prediction errors of only 1.11 for tensile strength and 0.93 for surface roughness, confirming the reliability of the developed model.

DOI: 10.30657/pea.2026.32.30

1. Introduction

3D printing is a manufacturing technique that builds three-dimensional objects by layering material in a manner similar to traditional printing processes. Classified as an additive manufacturing method, it is widely used for rapid prototyping (Yuan et al, 2019). A digital 3D model made using specialized software is the first step in the process, which defines the object's parameters and is then divided into thin layers with a cross-section. The printer constructs the object sequentially from the base upwards, depositing material layer by layer. This layered approach allows us to produce highly complex objects with complex geometries without molds, which significantly reduces production costs and lead times. Fundamentally, the workflow involves designing the object using software for computer-aided design (CAD). The design is then saved in a file format, typically with a .STL (Stereolithography) extension, that guides the printer in fabricating the object.

The 3D model file is first imported into the printer's software, where various printing parameters are configured. These parameters determine how the digital model is sliced into thin, two-dimensional layers, depending on factors such as resolution and layer thickness. The final object is then constructed by sequentially printing these layers on top of each another. The method of printing begins with a plastic filament fed into the printer's extruder. Within the extruder, a heating element melts the filament, converting it from a solid to a condition of molten. The molten plastic is thus extruded through a nozzle and deposited in horizontal layers, beginning at the object's base and working your way up until the entire form is finished (Shahrubudin et al, 2019). Thermoplastic materials are commonly used in 3D printing using fused deposition modeling (FDM). These plastics harden as they cool, allowing the printer to build objects by applying layer after layer of molten material. Each new layer fuses with the previous one, gradually forming the complete three-dimensional structure. The



procedure starts with a computer-generated model that is cut into thin, horizontal layers using specialized software. After that, the printer builds the thing layer by layer, beginning at the bottom and working its way up. This layer-by-layer fabrication enables the production of complex and detailed geometries without the need for molds, which significantly reduces manufacturing costs. Since the object is built nearly entirely from the initial material without cutting, drilling, or subtractive machining, material waste is minimized. As a result, 3D printing technology has rapidly evolved, spawning numerous new printing techniques (Aliheidari et al, 2017). Its ability to quickly produce intricate shapes has made it especially valuable. Among these technologies, FDM stands out as one of the most widely adopted methods due to its cost efficiency and ease of use and maintenance. It is extensively applied in rapid prototyping (Prater et al, 2019; Ranganathan et al, 2019) and has been utilized across various sectors, such as the automotive, medical device, aerospace, and even food industries (Novakova-Marcincinova et al, 2014; Garg & Bhattacharya, 2017; Zhang et al, 2017; Liu et al, 2018; Prater et al, 2019; Jannet et al, 2024). Fused Deposition Modelling is a 3D printing technology developed by Stratasys (Akhoundi & Behraves, 2019) that utilizes safe, non-toxic materials. This additive manufacturing technique involves melting thermoplastic filaments to fabricate three-dimensional objects layer by layer. A polymer filament is first fed into the printer to start the process, where it is heated until it reaches a molten state and is extruded through a nozzle (Guduru & Srinivasu, 2020). The nozzle travels in both the X and Z dimensions, and the construction platform moves along the Y-axis, allowing precise deposition of material in each layer. Printing starts at the base platform and gradually builds the object upward. After completing each layer, the nozzle raises by the layer's thickness to begin printing the next one. The distance between the platform and the nozzle at this raised position corresponds to the thickness of each printed layer, as shown in Figure 1.

Nakhon Si Thammarat niello ware is a distinguished traditional craft from Nakhon Si Thammarat province in Thailand. It has enjoyed longstanding popularity and continues to play a significant role in supporting the livelihoods and economic stability of local families and communities. In spite of its cultural and economic significance, the production process faces several notable obstacles. Much of the manufacturing still relies on traditional methods and manual labour, particularly during the prototype stage, which involves crafting models from green or blue wax. These wax prototypes are essential for creating molds used in metal casting. However, this stage is labour-intensive and requires skilled artisans, as shaping and finishing of the prototypes demand both precision and time. Consequently, there is often variation in the quality of the finished products compared to the original designs, which increases production costs. Moreover, the lack of integration of modern technology into the production process presents an additional barrier. Therefore, addressing the challenges associated with prototype fabrication remains critical for improving the efficiency and quality of Nakhon Si Thammarat niello ware production.

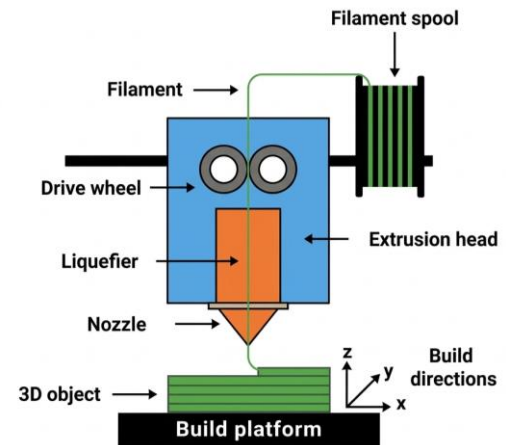


Fig. 1. The method of printing using fused deposition modeling

Technology for 3D printing has advanced quickly in the last few years and has attracted considerable attention across diverse fields such as industry, medicine, biomedical science, engineering, and fundamental research. The jewellery industry, in particular, has embraced this technology extensively, especially in the development of prototypes. Numerous studies have examined the use of Digital Light Processing (DLP) printing, concentrating on how process variables affect important characteristics of printed items made of resin, including dimensional accuracy, hardness, and surface roughness (Hanon & Zsidai, 2023; Huynh et al, 2025). For example, research has investigated the effects of specific using print variables regarding the tensile of strength and surface texture of photopolymer resin parts produced through DLP, aiming to quantify the contribution of each parameter to variations in mechanical performance (Sukindar et al, 2024). A review of the existing literature reveals a gap in studies specifically focused on using Fused Deposition Modelling (FDM) for producing jewellery prototypes, particularly within the framework of traditional crafts. Currently, the excellence of FDM-printed parts remains insufficient for direct use in production environments, especially when high surface quality and fine detail are required. Previous research has primarily examined how key process the mechanical properties are influenced by factors and surface finish of printed components, with the aim of optimizing settings for general manufacturing purposes (Markiz et al, 2020; Selvam et al, 2022; Jawad et al, 2025; Ranganathan et al, 2020; Srinidhi et al, 2021;). This research aims to determine the ideal circumstances for fabricating niello ware prototypes using FDM-based 3D printing. The objective is to integrate modern manufacturing technology into the traditional craft of Nakhon Si Thammarat niello ware, thereby supporting the preservation of local artisanal knowledge and craftsmanship in Nakhon Si Thammarat province, Thailand. The findings are expected to provide practical guidelines for improving the efficiency and quality of niello ware production. By streamlining the process and enhancing product standards, the research aims to strengthen the competitiveness and increase the business potential of niello ware products in both domestic and international markets.

This research attempts to identify the optimal conditions for producing PLA-based prototypes of niello ware using 3D printing technology with fused deposition modeling (FDM). The experimental procedure was designed using the combination of Box–Behnken Design (BBD) with Response Surface Methodology (RSM) to systematically evaluate the impact of three crucial process factors: print temperature, print speed, and infill density. To guarantee the accuracy and repeatability of the findings, each condition of the experiment was tested in triplicate. The primary response variables assessed were surface roughness (Ra) and tensile strength. During the course of the tests, certain parameters were held constant, including a linear printing pattern, a fixed layer thickness of 0.2 mm, and an X-axis printing orientation that is constant. The study's goal is to examine the connection between printing settings and the mechanical and surface quality characteristics, in order to generate data that can inform the production of high-quality niello ware prototypes. The findings are expected to contribute to the advancement of traditional craftsmanship in Nakhon Si Thammarat by integrating modern additive manufacturing techniques into the design and fabrication process.

2. Material and Methods

2.1 Materials

The data utilized in this research was Polylactic Acid (PLA) filament, supplied by the brand E-sun, with a nominal diameter of 1.75 mm. Before printing, the PLA filament is dried at 40°C for 8 hours using a filament dryer.

2.2 Preparation of test Specimens

The test specimens were modeled using SolidWorks, while Creality software was employed to slice the models and configure the parameters for printing. Fabrication was conducted on an Ender 5 Pro 3D printer utilizing Fused deposition modeling (FDM) technology using a 0.4 mm nozzle. A heated bed temperature of 60°C and a layer thickness of 0.2 mm were the printing parameters. A layer height of 0.2 mm was selected for FDM 3D printing using PLA, as it is considered the optimal value for balancing interlayer adhesion quality and printing stability (Hsueh et al, 2021). Throughout the experiments, certain parameters were maintained consistently, including a linear printing pattern and printing orientation along the X-axis. The raster pattern was applied with alternating layer orientations at +45° and 45° to enhance the mechanical properties (Dogru et al, 2021). In this experiment, the 3D printer was modified into a closed-enclosure configuration to maintain a stable thermal environment during printing. During the printing process, the nozzle temperature was monitored at 5-minute intervals using an infrared thermometer. The measured temperature has fluctuations within approximately $\pm 1^\circ\text{C}$ relative to the set temperature. The nozzle temperature was monitored using an infrared thermometer during the printing process. Temperature measurements were recorded at 5-minute intervals at a fixed location on the outer surface of the nozzle, approximately 5 mm above the nozzle tip. The measurement distance was maintained at approximately 50 mm. Prior to the

experiments; the infrared thermometer was calibrated according to the manufacturer's specifications.

2.3 Experimental Design

This research utilized the Box–Behnken Design (BBD) in combination with Response Surface Methodology (RSM) to structure the experimental framework. Prior to the formal experimental design, preliminary printing trials were conducted to identify feasible and stable operating ranges for the process parameters. Based on these trials, the selected ranges print temperature of 200–240 °C, infill density of 40–80%, and print speed of 30–70 mm/s were verified to produce stable extrusion, consistent layer deposition, and acceptable print quality without print failure. The study focused on three primary factors: Print Temperature, Infill Density, and Print Speed (Dong et al., 2018). These factors play a critical role in the filament's bonding and cooling process during layer deposition, which affects residual stresses and voids in the finished printed product. Improper selection of these parameters can adversely impact the printed components' structural integrity and mechanical strength (Zaldivar et al, 2017; Ravindrababu et al, 2018; Dave et al, 2022). Statistical analyses, including Analysis of Variance (ANOVA) and RSM, were employed to evaluate the main effects, interactions, and relationships between variables. The objective was to determine the optimal printing conditions for fabricating molds of traditional Nakhon Si Thammarat niello ware using a PLA filament extrusion system. The experiment was designed with three factor levels and each trial was replicated three times, as summarized in Table 1.

Table 1. Variables Used in the Experimental Design.

Factors	Level			Unit
Print Temperature (X_1)	200	220	240	(°C)
Infill Density (X_2)	40	60	80	(%)
Print Speed (X_3)	30	50	70	(mm/s)

2.4 Tensile Strength Testing

Tensile strength was found to be evaluated using samples modeled in SolidWorks, as illustrated in Figure 2. The slicing process was completed using Creality software. Mechanical testing was conducted with a SHIMADZU Universal Testing Machine (AGS-X model) with a load capacity of 100k. In accordance with ASTM D638 Type I standard, the test was conducted at a constant crosshead speed of 5 mm/min. (ASTM, 2014).

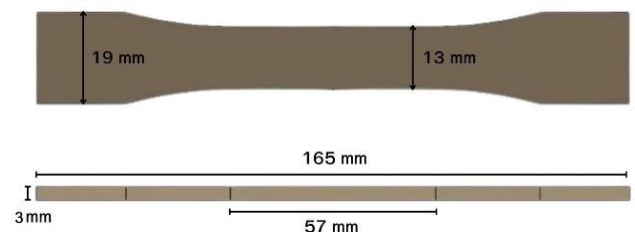


Fig. 2. ASTM D638 Type I Standard-Based Tensile Test Specimen

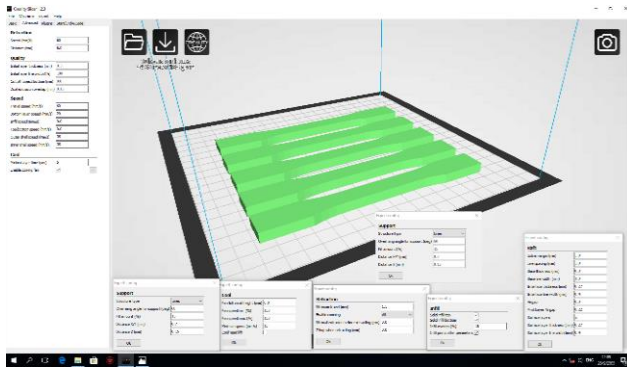


Fig. 3. Print Settings for Test Specimen

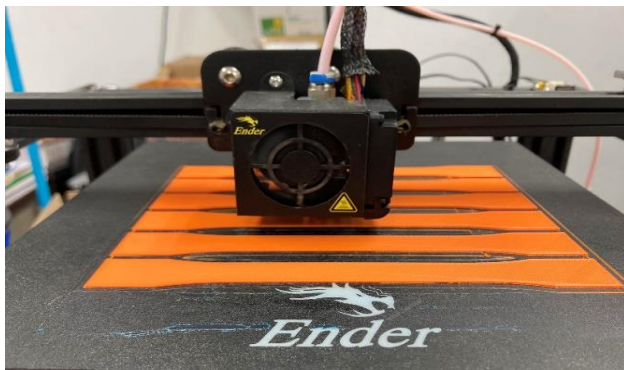


Fig. 4. Test Specimen Printed Using a 3D Printer

2.5 Surface Roughness Testing

Surface roughness was measured using a Mitutoyo SJ-210 surface roughness tester equipped with a stylus probe. The measurements were conducted over an evaluation length of 4.0 mm with a cut-off length of 0.8 mm and a traverse speed of 0.5 mm/s. All measurements were performed on the top surface of the specimens. For each specimen, surface roughness was measured at three locations: one at the center and two at positions 50 mm from the center on opposite sides. The average value of the three measurements was used for analysis. The roughness values were recorded as Ra (Arithmetic Average Roughness). Each specimen was tested after the printing process, and the results were averaged to support further analysis and help draw conclusions from the experiment.

3. Results

The experimental analysis was performed using the Box Behnken Design combined with Response Surface Methodology. Three independent variables including print temperature, print speed, and infill density were investigated, with each experimental run repeated three times. The primary response variables evaluated were surface roughness (Ra) and tensile strength. Regression models were then fitted to the data for each response, and their adequacy was assessed through statistical measures such as the regression p-value, the coefficient of determination (R squared), the corrected R squared, and the lack of fit p-value. The outcomes of these analyses are presented below.

3.1 Results of Tensile Strength and Surface Roughness Tests

This section presents the statistical analysis used to evaluate the experimental data and develop predictive models for tensile strength and surface roughness. The experimental design matrix and corresponding response values that form the basis of the analysis are summarized in Table 2. These data were subsequently used for residual diagnostics, analysis of variance (ANOVA), and regression modeling, as discussed in Sections 3.1.1 and 3.1.2.

Table 2. Experimental design matrix and measured responses

Run	Print temp (°C)	Infill density (%)	Print Speed (mm/s)	Tensile Strength (MPa)	Ra (mm)
1	220	80	70	31.29	8.95
2	220	60	50	26.11	8.04
3	240	60	30	30.22	5.18
4	240	60	70	24.12	7.15
5	240	80	50	33.01	6.20
6	220	60	50	26.20	8.13
7	200	60	70	21.46	11.33
8	240	40	50	20.95	6.20
9	200	80	50	31.44	10.07
10	220	80	30	35.41	6.94
11	220	40	30	20.66	7.33
12	220	60	50	26.15	8.11
13	200	60	30	25.83	9.23
14	220	40	70	15.11	9.36
15	200	40	50	17.06	12.32

3.1.1 Assessment of Model Adequacy

The model's validity was evaluated by checking the normality, independence, and homogeneity of variance in the data. The findings of the experiment were analyzed using statistical software, confirming that the data met all necessary assumptions for the analysis. The statistical findings are shown in Figure 5. During the experimental process, the validity and reliability of the collected data were assessed by evaluating the normality of the tensile strength distribution through a probability plot. The analysis yielded a p-value of 0.063, which exceeds the standard significance threshold ($\alpha = 0.05$). This indicates that the data do not significantly deviate from a normal distribution. As illustrated in Figure 5, the residuals' normal probability plot demonstrates how closely the data points match the reference line, with no apparent outliers, further supporting the assumption of normality (Myers & Montgomery, 1996). The residuals are uniformly and randomly distributed around the central horizontal line in the residuals versus fits graphic. There are no discernible patterns or trends, and all values fall within the expected control limits. This pattern suggests that the residuals are independent and the variance is homogeneously distributed (Janmanee & Ratchapakdee, 2024). Moreover, the residuals histogram exhibits a symmetric, bell-shaped curve, which is characteristic of a normal distribution. In the residuals versus fitted values plot, there is no evidence

of a funnel-shaped or megaphone-like pattern, indicating constant variance across the range of fitted values. To further assess the independence of the residuals, the residuals versus order plot was examined. The residuals appear to be randomly distributed, with no sequential patterns, no significant clustering, and no indication of systematic variation across the order of observations. There are no outliers, and no trends persist for more than five consecutive points, confirming the independence of the data points. In addition, the adjusted R^2 values remained close to the corresponding R^2 values, indicating that model complexity was appropriate relative to the data. Together with non-significant lack-of-fit tests and the absence of systematic residual patterns, these results indicate that the high R^2 values reflect strong predictive performance rather than overfitting. Overall, the statistical analyses confirm that the experimental data meet the assumptions of normality, independence, and constant variance. These characteristics validate the use of the data for predictive modeling and further statistical analysis.

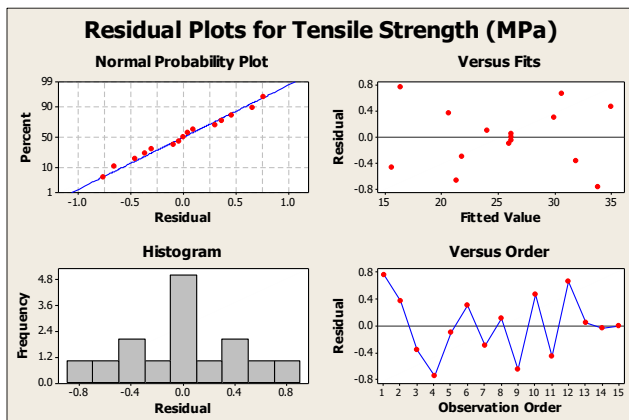


Fig. 5. Analysis of Model Validity for the Experiment

3.1.2 Regression equation, analysis of variance, and response results of tensile strength and surface roughness

The appropriate regression model for all response variables was selected based on several key statistical indicators, including the coefficient of determination (R^2), adjusted R^2 , the p-value for regression, and the p-value for lack of fit, all evaluated at a 95% confidence level with a significance level of 0.05. Following validation of the experimental data, the full quadratic regression model emerged as the best representation of the relationship between factors and responses, as illustrated in Tables 3 and 4. Although the interaction and quadratic terms were not statistically significant at the 95% confidence level, the full quadratic model was retained in accordance with standard Response Surface Methodology practice for Box–Behnken designs, to ensure response surface continuity and robustness for optimization purposes. The analysis of variance revealed that the regression p-values for both tensile strength and surface roughness were 0.00, indicating that the models are highly significant. The primary factors considered printing temperature (X_1), infill density (X_2), and

printing speed (X_3) were shown to have a statistically significant influence on the tensile strength and surface roughness responses at the 95% confidence level. Furthermore, the lack-of-fit tests yielded p-values of 0.19 for tensile strength and 0.08 for surface roughness. Since these values exceed 0.05, the lack of fit is not significant, verifying that the models fit the experimental data sufficiently. The models demonstrated excellent explanatory power, with R^2 values of 99.40% and 98.78% for tensile strength and surface roughness respectively, and adjusted R^2 values of 98.33% and 96.59%, underscoring the robustness of the regression equations.

Table 3. Analysis of Variance (ANOVA) for Tensile Strength Values

Source	DF	Seq SS	Adj SS	F	P
Regression	9	485.28	485.28	92.33	0.00
Linear	3	481.68	481.68	274.9	0.00
Square	3	1.00	1.00	0.57	0.66
Interaction	3	2.605	2.605	1.49	0.33
Residual Error	5	2.92	2.92		
Lack-of-Fit	3	2.916	2.916	1.38	0.19
Pure Error	2	0.004	0.004		
Total	14	488.2			
$R^2 = 99.40\%$ $R^2(\text{adj}) = 98.33\%$					

Table 4. ANOVA Results for Surface Roughness

Source	DF	Seq SS	Adj SS	F	P
Regression	9	53.031	53.031	45.01	0.00
Linear	3	50.88	50.88	129.6	0.00
Square	3	0.8802	0.8802	2.24	0.2
Interaction	3	1.2699	1.2699	3.23	0.12
Residual Error	5	0.6546	0.6546		
Lack-of-Fit	3	0.6501	0.6501	97.03	0.08
Pure Error	2	0.0045	0.0045		
Total	14	53.685			
$R^2 = 98.78\%$ $R^2(\text{adj}) = 96.59\%$					

From Table 3, the analysis of the tensile strength of the specimens using the Box–Behnken Design (BBD) with a response surface regression model showed that the main effects of the three primary factors, namely print temperature, infill density, and print speed, had a statistically significant influence on the tensile strength of the specimens ($P < 0.05$). In contrast, all interaction effects were found to be statistically insignificant ($P > 0.05$). Similarly, the curvature or quadratic terms of the model were also not statistically significant ($P > 0.05$). The regression model demonstrated a high coefficient of determination, with an R -squared (R^2) value of 99.40%, indicating that the model could explain nearly all of the variability observed in the data from the experimental, with the model shows a coefficient of determination that is acceptable, indicating a good fit. The complete quadratic equation for tensile stress is shown in Equation (1).

$$y_{TS} = -83.695 + 0.6308X_1 + 0.6821X_2 + 0.1513X_3 - 0.000935X_1^2 - 0.000410X_2^2 - 0.000929X_3^2 - 0.00145X_1X_2 - 0.001081X_1X_3 + 0.000894X_2X_3 \quad (1)$$

From Table 4, the analysis of the surface roughness (Ra) of the samples uses a response surface regression model based on the Box–Behnken Design (BBD), indicating that the main effects of the three primary factors, namely print temperature, infill density, and print speed, had a statistically significant influence on Ra ($P < 0.05$). Most of the interaction effects were found to be statistically insignificant ($P > 0.05$), except for the relationship between print temperature ($^{\circ}\text{C}$) and infill density (%), which had an impact on surface roughness that is statistically significant ($P < 0.05$). For the curvature analysis, It was discovered that the model was not important ($P > 0.05$). The regression model demonstrated a high coefficient of determination, with an R-squared (R^2) value of 98.78%, demonstrating that the model could explain nearly all of the variability observed in the experimental data. Equation (2) shows the complete quadratic model for surface roughness.

$$y_{\text{Ra}} = 91.6744 - 0.5691X_1 - 0.4068X_2 + 0.1222X_3 + 0.000852X_1^2 + 0.000658X_2^2 - 0.000529X_3^2 + 0.001406X_1X_2 - 0.000081X_1X_3 - 0.000013X_2X_3 \quad (2)$$

The use of Equations (1) and (2) is limited to the following parameter ranges: print temperature (X_1) of 200–240 $^{\circ}\text{C}$, infill density (X_2) of 40–80%, and print speed (X_3) of 30–70 mm/s.

3.2 Analysis of Optimal Printing Conditions for the Prototype of Nakhon Si Thammarat Niello Ware

This study aimed to optimize the printing conditions for the Nakhon Si Thammarat niello ware prototype fabricated via material extrusion (fused filament fabrication). Tensile strength and surface roughness were used as key evaluation criteria. The optimization process involved response surface methodology, complemented by a detailed microstructural analysis. The results of this study are outlined below.

Figures 6 and 7 display response surface plots that explore the combined impact of print temperature, infill density, and print speed on tensile strength and surface roughness. The findings reveal that increasing print temperature and infill density lead to improvements in both tensile strength and surface finish. In contrast, higher printing speeds cause a decline in these properties (Naveed, 2021).

There is a clear correlation between Infill Density and Print Temperature, with increases in both parameters leading to improvements in tensile strength and surface finish. These factors have been identified as key influences on the mechanical and surface characteristics of 3D-printed components. Considering the response surface analysis, the optimal printing conditions for producing a niello ware prototype maximizing tensile strength while minimizing surface roughness were found to be a Print Temperature (X_1) of 240 $^{\circ}\text{C}$, an Infill Density (X_2) of 80%, and a Printing Speed (X_3) of 30 mm/sec.

Surface Plot of Tensile Strength vs Infill density, Print temp

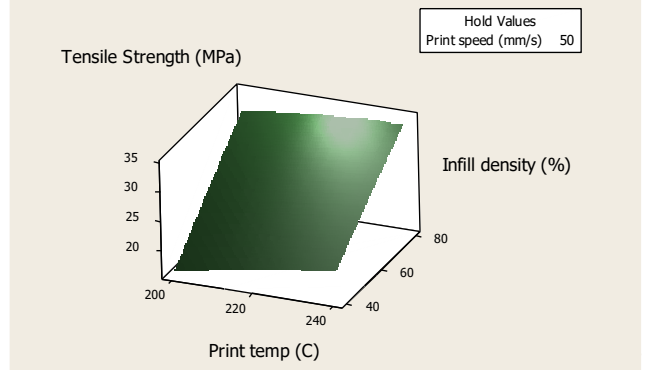


Fig. 6. Response surface plot showing the combined effects of print temperature, infill density, and print speed on tensile strength.

Surface Plot of Ra vs Infill density, Print temp

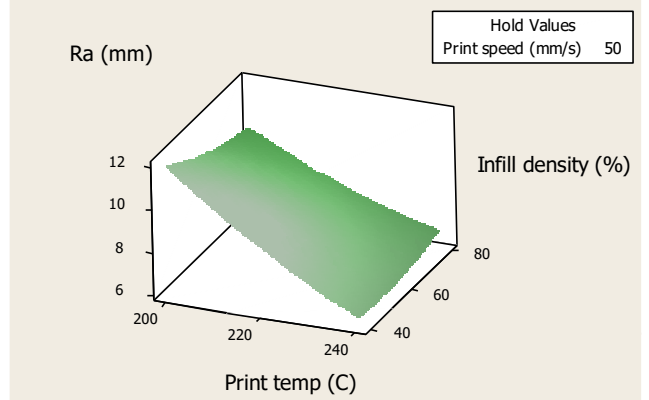


Fig. 7. Response surface plot showing the combined effects of print temperature, infill density, and print speed on surface roughness.

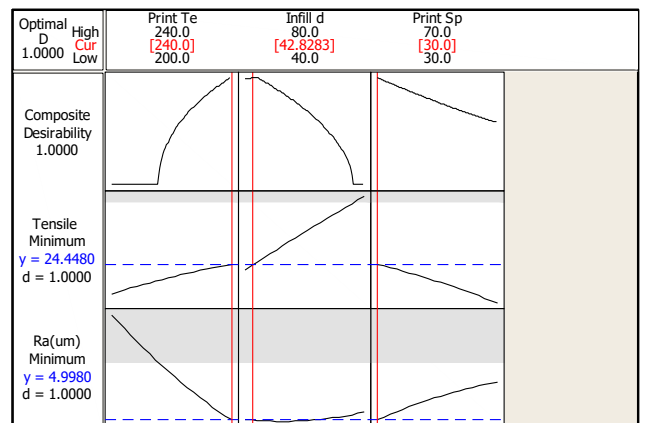


Fig. 8. Optimization results for printing the Nakhon Si Thammarat niello ware prototype.

Under these conditions, the printed part achieved a tensile strength of 36.16 MPa (Sangkharat & Techawinyutham, 2024) and the lowest recorded surface roughness, with a Ra value of 4.96 μm . The process window around the optimal condition was quantitatively defined by allowing a maximum reduction of 5% in tensile strength and a maximum increase of 5% in surface roughness relative to the optimal values. This tolerance level was selected to represent a realistic manufacturing margin that accommodates minor process fluctuations while maintaining mechanical and surface performance close to the optimum condition. The optimal parameters were identified as a print temperature of 240 °C, a printing speed of 30 mm/s, and an infill density of 80%, yielding a tensile strength of 36.16 MPa and a surface roughness of 4.96 μm . Therefore, the acceptable performance limits were defined as tensile strength ≥ 34.35 MPa and surface roughness ≤ 5.21 μm . Using the regression equations, each parameter was varied around the optimal point while keeping the other parameters constant to determine the allowable deviation range, which defines the practical process window. These findings are consistent with the results reported by Janmanee and Ratchapakdee (Janmanee & Ratchapakdee, 2024).



Fig. 9. Final ring prototype manufactured under optimal process parameters.



Fig. 10. Bracelet prototype printed under optimal experimental conditions.

Table 5. Comparison of Errors in Resistance, Tensile Force, and Surface Roughness Between Calculated and Experimental Results

No.	Tensile Strength			Surface roughness		
	Target	Test	Error	Target	Test	Error
1	29.43	30.60	1.17	7.51	8.31	0.8
2	29.43	30.45	1.02	7.51	8.32	0.9
3	29.43	30.57	1.14	7.51	8.52	1.01
Average Error			1.11	0.93		

According to Table 5, the differences in tensile strength and surface roughness between the calculated and experimental values were evaluated using three printed samples. The specimens were manufactured using the Fused Deposition Modeling (FDM) process under specific conditions: 60% infill density, a printing speed of 50 mm/s, and a printing temperature of 220 °C. These samples underwent tensile and surface roughness testing. On average, the results showed a small error of just 1.11 for tensile strength and 0.93 for surface roughness. The statistical significance of the differences was evaluated using a paired t-test, yielding p-values of 0.887 for tensile strength and 0.921 for surface roughness. Based on these results, there is no statistically significant difference between the calculated and experimental values for both properties (Srivabut et al, 2022).

3.3 Microstructure Investigations

The morphology of the fracture surface and cross-section of the tensile test specimens fabricated using the Fused Deposition Modeling (FDM) process was examined. The morphological characteristics were investigated using a scanning electron microscope (JEOL, model JSM-6510LV). The samples were coated with a thin layer of gold–palladium to prevent electrostatic charging and to improve image resolution during SEM examination. The microstructural images were captured at magnifications of 75x and 100x under an accelerating voltage of 20 kV.

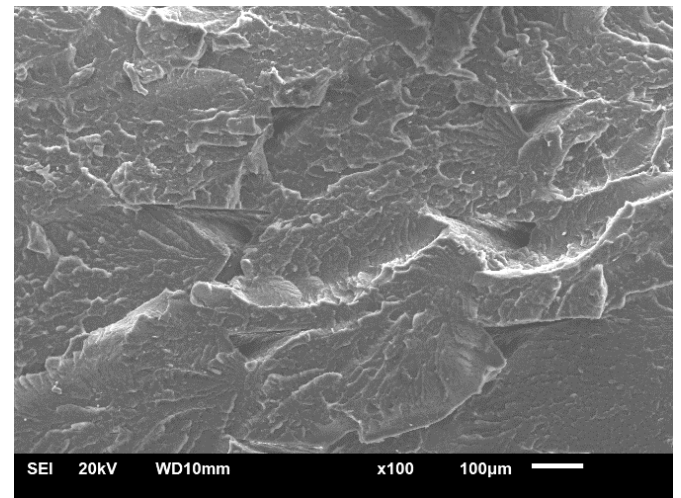


Fig. 11. SEM image of the fracture surface of a specimen with print temperature 240 °C, infill density 80%, and printing speed 30 mm/s.

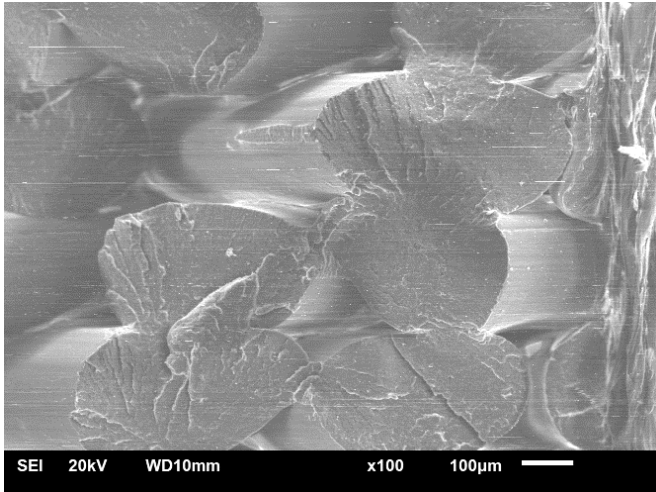


Fig. 12. SEM image of the cross-section of a specimen with print temperature 240 °C, infill density 80%, and printing speed 30 mm/s.

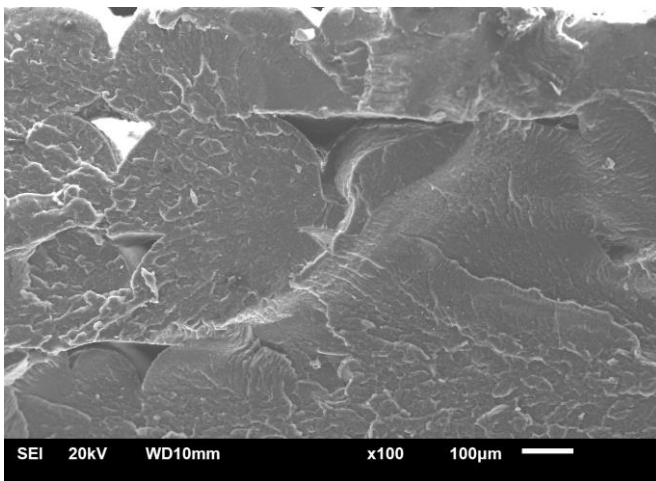


Fig. 13. SEM image of the fracture surface of a specimen with print temperature 200 °C, infill density 40%, and printing speed 70 mm/s.

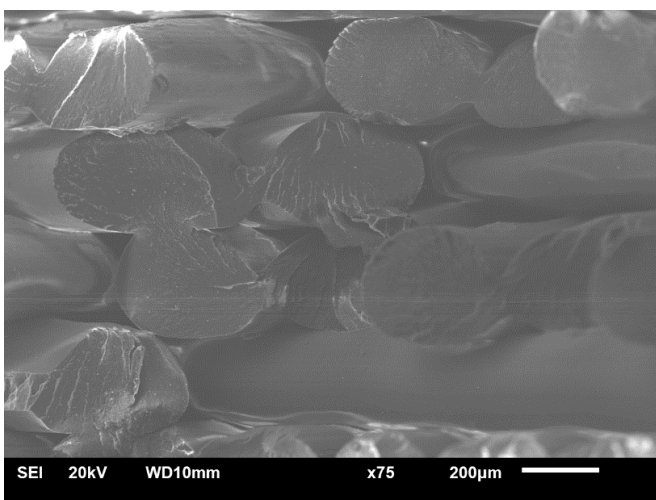


Fig. 14. SEM image of the cross-section of a specimen with print temperature 200 °C, infill density 40%, and printing speed 70 mm/s.

Figure 11 presents a scanning electron microscope (SEM) image of the fracture surface of a tensile test specimen, while Figure 12 shows the SEM image of its cross-section. The specimens were manufactured using the Fused Deposition Modeling (FDM) process under specific conditions: 80% infill density, a printing speed of 30 mm/s, and a printing temperature of 240 °C. These parameters yielded the highest tensile strength and the lowest surface roughness among the tested configurations, resulting in a smooth and uniform external surface free from visible defects. The enhanced mechanical performance and surface quality are attributed to the combination of a high printing temperature, high infill density, and low printing speed, which together promote better fusion between layers. Improved interlayer adhesion results in a more compact and homogeneous internal structure, reducing the likelihood of warping and delamination. The SEM images support this observation, showing fewer voids and more consistent bonding between the deposited filaments. Regarding Figures 13 and 14, the specimens printed under the conditions of a 200°C printing temperature, 40% infill density, and a 70 mm/s feed rate clearly show significant internal voids or cavities between layers. This is due to insufficient filament melting and poor interlayer adhesion, which results in a higher surface roughness on the exterior of the specimen. These results are in agreement with previous studies (Guduru & Srinivasu, 2020; Moradi et al, 2021), which report that stronger interlayer bonding contributes to greater dimensional stability and mechanical strength. Improved fusion between layers not only minimizes deformation during and after printing but also contributes to the overall integrity and surface quality of the printed part.

4. Discussion

The findings from this study demonstrate that print temperature and infill density significantly influence the mechanical properties and surface quality of 3D-printed parts. Specifically, increasing both parameters led to improvements in tensile strength and surface smoothness, while higher feed rates were associated with a reduction in tensile strength. The optimal combination of parameters was identified as a print temperature of 240°C, printing speed of 30mm/s, and infill density of 80 %. In these circumstances, the printed specimen achieved a maximum tensile strength of 36.16MPa and a minimum surface roughness of 4.96µm. The relationship between tensile strength and surface roughness can also be interpreted directly from the regression equations. The linear coefficients indicate that increasing print temperature and infill density increases tensile strength while simultaneously reducing surface roughness within the investigated range, explaining the absence of a strong trade-off between these two responses. In contrast, the printing speed leads to a decrease in tensile strength but tends to increase surface roughness, indicating a potential trade-off between mechanical performance and surface quality that must be balanced through parameter optimization. In addition to identifying the optimal parameter combination, the regression model also en-

ables an assessment of process robustness around the optimum. A practical process window can be defined by allowing a 5% reduction in tensile strength relative to the predicted maximum value. Using the regression equation, the allowable $\pm$ deviations of individual process parameters can be estimated by varying one factor at a time around the optimal setting while holding the remaining parameters constant. This approach provides insight into the sensitivity of tensile strength to parameter fluctuations and supports practical implementation of the optimized printing conditions.

These results can be explained by the improved thermal behavior and material deposition achieved under high-temperature and low-speed conditions. At elevated temperatures, the extruded filament melts more thoroughly, promoting better interlayer diffusion and adhesion. Similarly, a slower feed rate allows more time for bonding between layers, while a higher infill density reduces internal voids, leading to a more cohesive and compact internal structure (Sangkharat & Techawinyutham, 2024). This enhanced bonding minimizes warping and shrinkage as the material cools (Shunmugam et al, 2024), and the gradual thermal gradient associated with low-speed printing further reduces residual stress. Together, these factors contribute to the observed improvements in tensile performance and surface quality. These outcomes are in line with prior studies (Akpakpavi et al, 2023; Fadillah et al, 2023), which have also emphasized the role of interlayer fusion and thermal control in optimizing the quality of FDM-printed components.

5. Conclusion

Employing Response Surface Methodology (RSM), the study identified the optimal printing parameters for attaining the maximum tensile strength in components that are 3D printed. The ideal settings were determined to be a print temperature of 240 °C, a print speed of 30 mm/s, and an infill density of 80%. Under these conditions, the maximum tensile strength of the test specimens was 36.16 MPa, and the lowest surface roughness was 4.96 μm . These improvements are primarily attributed to more consistent filament melting and stronger interlayer bonding. Additionally, the increased infill density reduces internal voids, enhancing filament adhesion and thereby improving the mechanical performance of the printed parts. To verify the accuracy of the model predictions, specimens were fabricated under the predicted optimal conditions and experimentally tested. The observed results closely matched the predicted values, with mean errors of only 1.11 for tensile strength and 0.93 for surface roughness. This strong agreement confirms that the predictive models are both reliable and effective, providing a valuable tool for optimizing process parameters in 3D printing to improve part quality. While the present study focuses on tensile strength and surface roughness as key indicators of mechanical performance and surface quality, additional prototype-level characteristics such as dimensional accuracy, detail resolution, and surface behavior in functional regions are also important for comprehensive prototype evaluation. These aspects are

identified as directions for future work to further extend the applicability of the proposed optimization approach.

Acknowledgements

Under Contract No. 203952, Thailand Science Research and Innovation (TSRI) provided financial assistance for this work. Additional support in the form of research equipment was kindly supplied by Rajamangala University of Technology Rattanakosin's Faculty of Engineering and Rajamangala University of Technology Srivijaya's Faculty of Science and Technology.

Reference

- Akhoundi, B., & Behraves, A.H., 2019. Effect of filling pattern on the tensile and flexural mechanical properties of FDM 3D printed products. *Experimental Mechanics*, 59(6), 883-897. DOI: 10.1007/s11340-018-00467-y.
- Akpakpavi, M.K., Sackey, S.M., & Asante-Afrifa, M.K., 2023. Optimisation of process parameters on tensile strength of 3D printed polylactic acid (PLA) parts: ASTM D638 type-IV. *African Journal of Applied Research*, 9(2), 104-123. DOI: 10.26437/ajar.v9i2.564.
- Aliheidari, N., Tripuraneni, R., Ameli A., & Nadimpalli, S., 2017. Fracture resistance measurement of fused deposition modeling 3D printed polymers. *Polymer Testing*, 60, 94-101. DOI: 10.1016/j.polymertesting.2017.03.016.
- ASTM: American Society for Testing and Materials., 2014. ASTM D638: standard test method for tensile properties of plastics. West Conshohocken: ASTM.
- Dave, H.K., Prajapati, A.R., Rajpurohit, S.R., Patadiya, N.H., & Raval, H.K., 2022. Investigation on tensile strength and failure modes of FDM printed part using in-house fabricated PLA filament. *Advances in materials and processing technologies*, 8(1), 576-597. DOI: 10.1080/2374068X.2020.1829951.
- Dogru, A., Sozen, A., Naser, G., & Ozgur Seydibeyoglu M., 2021. Effects of aging and infill pattern on mechanical properties of hemp reinforced PLA composite produced by fused filament fabrication (FFF). *Applied Science and Engineering Progress*, 14(4), 651-660. DOI: 10.14416/j.asep.2021.08.007.
- Dong, G., Wijaya, G., Tang, Y., & Zhao, Y. F., 2018. Optimizing process parameters of fused deposition modeling by Taguchi method for the fabrication of lattice structures. *Additive Manufacturing*, 19, 62-72. DOI: 10.1016/j.addma.2017.11.004.
- Fadillah, F., Suryanto, H., & Suprayitno, S., 2023. Study on effect of 3D printing parameters on surface roughness and tensile strength using analysis of variance. *Mechanical Engineering*, 7(2), 96-105. DOI: 10.17977/um016v7i22023p096.
- Garg, A., & Bhattacharya, A., 2017. An insight to the failure of FDM parts under tensile loading: finite element analysis and experimental study. *International Journal of Mechanical Sciences*, 120, 225-236. DOI: 10.1016/j.ijmecsci.2016.11.032.
- Guduru, K.K., & Srinivasu, G., 2020. Effect of post treatment on tensile properties of carbon reinforced PLA composite by 3D printing. *Materials Today: Proceedings*, 33, 5403-5407. DOI: 10.1016/j.matpr.2020.03.128.
- Hanon, M.M., & Zsidai, L., 2023. Investigation on the accuracy, hardness, and surface roughness of photopolymerization 3D printing technique objects, *Proceedings of the 36th Conference of the polymer processing society (PPS)36*, 2607(1). DOI: 10.1063/5.0135763.
- Hsueh, M. H., Lai, C. J., Wang, S. H., Zeng, Y. S., Hsieh, C. H., Pan, C. Y., & Huang, W. C. (2021). Effect of printing parameters on the thermal and mechanical properties of 3d-printed pla and petg, using fused deposition modeling. *Polymers*, 13(11), 1758. DOI: 10.3390/polym13111758.
- Huynh, H.N., Huynh, Q.T., & Bui, T.H., 2025. Improve the surface roughness of resin 3D printed products using RSM Method. *Journal of Physics: Conference Series*, 2949(1). DOI: 10.1088/1742-6596/2949/1/012031.
- Ismail, K.I., Pang, R., Ahmed R., & Yap, T.C., 2023. Tensile properties of in situ 3D printed glass fiber-reinforced PLA. *Polymers*, 15(16), 3436. DOI: 10.3390/polym15163436.
- Janmanee, P., & Ratchapakdee, P., 2024. Comparison of artificial neural

- network and response surface methodology in predicting the tensile strength and optimization of 3D printed objects. *Engineering and Applied Science Research*, 51(6), 704-715. URL: <https://ph01.tci-thaijo.org/index.php/easr/article/view/255880>.
- Jannet, S., Soundararajan, R., Kandavalli, S. R., & Raja, R., 2024. Wear and friction behavior on extrusion-based 3D printed short carbon fiber reinforced PETG composites with annealing and laser treated effects. *Journal of The Institution of Engineers (India): Series D*, 1-10. DOI: 10.1007/s40033-024-00794-6.
- Jawad, H.H., Kordani, N., Bagheri, A., & Derazkola, H.A., 2025. Optimization of 3D printing parameters for enhanced mechanical strength: effects of glass fiber reinforcement and fill ratio using RSM and ANOVA. *Journal of Composites Science*, 9(2), 63. DOI: 10.3390/jcs9020063.
- Liu, J., Gaynor, A.T., Chen, S., Kang, Z., Suresh, K., Takezawa, A., Li, L., Kato, J., Tang, J., Wang, C.C.L., Cheng, L., Liang, X., & To, A.C., 2018. Current and future trends in topology optimization for additive manufacturing. *Structural and Multidisciplinary Optimization*, 57(6), 2457-2483. DOI: 10.1007/s00158-018-1994-3.
- Novakova-Marcincinova, L., Novak-Marcincin, J., & Janak, M., 2014. Precision manufacturing process of parts realized by FDM rapid proto-typing. In *Key Engineering Materials*, 581, 292–297. DOI: 10.4028/www.scientific.net/kem.581.292.
- Moradi, M., Aminzadeh, A., Rahmatbadi, D., & Hakimi, A., 2021. Experimental investigation on mechanical characterization of 3D printed PLA produced by fused deposition modeling (FDM). *Materials Research Express*, 8(3), 035304. DOI: 10.1088/2053-1591/abe8f3.
- Myers, R.H., Montgomery, D.C., 1996. Response surface methodology, 1031-1032. DOI:10.1080/15458830.1996.11770760.
- Markiz, N., Horváth, E., & Ficzer, P., 2020. Influence of printing direction on 3D printed ABS specimens. *Production Engineering Archives*, 26(3), 127-130. DOI:10.30657/pea.2020.26.24.
- Naveed, N., 2021. Investigate the effects of process parameters on material properties and microstructural changes of 3D-printed specimens using fused deposition modelling (FDM). *Materials Technology*, 36(5), 317-330. DOI:10.1080/10667857.2020.1758475.
- Prater, T., Werkheiser, N., Ledbetter, F., Timucin, D., Wheeler, K., & Snyder, M., 2019. 3D printing in zero g technology demonstration mission: Complete experimental results and summary of related material modeling efforts. *The International Journal of Advanced Manufacturing Technology*, 101(1), 391-417. DOI:10.1007/s00170-018-2827-7.
- Ranganathan, S., Thangaraj, H.N.R.S., Vasudevan, A.K., & Shanmugan, D.K., 2019. Analogy of thermal properties of Polyamide 6 reinforced with glass fiber and glass beads through FDM process (No. 2019-28-0137). *SAE Technical Paper*. DOI: 10.4271/2019-28-0137.
- Ranganathan, S., Kumar K, S., Gopal, S., & Palanivelu, R., 2020. Enhancing the tribological properties PETG and CFPETG composites fabricated by FDM via various infill density and annealing (No. 2020-28-0429). *SAE Technical Paper*. DOI:10.4271/2020-28-0429.
- Ravindrababu, S., Govdeli, Y., Wong, Z. W., & Kayacan, E., 2018. Evaluation of the influence of build and print orientations of unmanned aerial vehicle parts fabricated using fused deposition modeling process. *Journal of Manufacturing Processes*, 34, 659-666. DOI:10.1016/j.jmapro.2018.07.007.
- Sangkharat, T., & Techawinyutham, L., 2024. Development of screw-based 3D printing machine and process experiments for short fiber reinforced polymer composites. *Applied Science and Engineering Progress*, 17(2), 7184-7184. DOI: 10.14416/j.asep.2023.11.005.
- Selvam, A., Mayilswamy, S., Whenish, R., Naresh, K., Shanmugam, V., & Das, O., 2022. Multi-objective optimization and prediction of surface roughness and printing time in FFF printed ABS polymer. *Scientific Reports*, 12(1), 16887. DOI: 10.1038/s41598-022-20782-8.
- Shahrubudin, N., Lee, T. C., & Ramlan, R. J. P. M., 2019. An overview on 3D printing technology: Technological, materials, and applications. *Procedia Manufacturing*, 35, 1286-1296. DOI: 10.1016/j.promfg.2019.06.089.
- Shunmugam, M.N., Sankaranarayanan, S., Pandiarajan, N., Parthipan, B.K., & Pandiarajan, B., 2024. Enhancing mechanical properties of PLA filaments through orange peel powder reinforcement: Optimization of 3D printing parameters. *Applied Science and Engineering Progress*, 17(4), 7536. DOI: 10.14416/j.asep.2024.08.011.
- Srinidhi, M.S., Soundararajan, R., Satishkumar, K.S., & Suresh, S., 2021. Enhancing the FDM infill pattern outcomes of mechanical behavior for as-built and annealed PETG and CFPETG composites parts. *Materials Today: Proceedings*, 45, 7208–7212. DOI: 10.1016/j.matpr.2021.02.417.
- Srivabut, C., Ratanawilai, T., & Hiziroglu, S., 2022. Response surface optimization and statistical analysis of composites made from calcium carbonate filler-added recycled polypropylene and rubberwood fiber. *Journal of Thermoplastic Composite Materials*, 35(3), 391-415. DOI: 10.1177/0892705719889988.
- Sukindar, N. A., Khata, M. T. A. H. M., Yasir, A. S. H. M., Zawawi, M. F., Kamaruddin, S., & Ab Aziz, A. A., 2024. Effect of the printing parameters on the tensile strength and surface roughness of a photopolymer resin using DLP 3D printing. *Malaysian Journal of Microscopy*, 20(1), 189-200.
- Yuan, L., Ding, S., & Wen, C., 2019. Additive manufacturing technology for porous metal implant applications and triple minimal surface structures: A review. *Bioactive Materials*, 4, 56-70. DOI: 10.1016/j.bioactmat.2018.12.003.
- Zaldivar, R.J., Witkin, D.B., McLouth, T., Patel, D.N., Schmitt, K., & Nokes, J.P., 2017. Influence of processing and orientation print effects on the mechanical and thermal behavior of 3D-printed ULTEM® 9085 material. *Additive Manufacturing*, 13, 71-80. DOI: 10.1016/j.addma.2016.11.007.
- Zhang, P., Liu, J., & To, A. C., 2017. Role of anisotropic properties on topology optimization of additive manufactured load bearing structures. *Scripta Materialia*, 135, 148-152. DOI: 10.1016/j.scrip-ta-mat.2016.10.021