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3D PRINTING PROCESS PARAMETERS OPTIMIZATION FOR CONDUCTIVE POLYMER USING FRACTIONAL FACTORIAL DESIGN APPROACH

Zaidan Faraby Zulkarnain, Aini Zuhra Abdul Kadir *, Muhd Ikmal Isyraf Mohd Maulana, Nor Akmal Fadil, Nurul Husna Mohd Yusoff
Faculty of Mechanical Engineering, Universiti Teknologi Malaysia,
81310 UTM Johor Bahru, Johor, Malaysia.
* Corresponding author: ainizuhra@utm.my

ABSTRACT

Conductive polymer filaments have gained increasing attention in fused deposition modelling (FDM) due to their potential applications in printed electronics and functional components. In this study, the electrical conductivity of commercially available conductive polylactic acid (PLA) filament was optimized by investigating the influence of key FDM process parameters. A two-level fractional factorial design was employed to evaluate the effects of nozzle temperature, printing speed, infill density, and layer height on the electrical conductivity of the 3D-printed specimens. A total of 24 samples were fabricated using a Bambu Lab X1 Carbon 3D printer and conductivity measurements were conducted using a two-point probe method. Statistical analysis using analysis of variance (ANOVA) revealed that the overall model was statistically significant ($p=0.024$), with a layer height identified as the most significant parameter affecting electrical conductivity ($F=18.55$ and $p=0.001$). Response optimization analysis determined an optimal printing condition consisting of a nozzle temperature of 200 °C, printing speed of 60 mm/s, infill density of 100%, and layer height of 0.3 mm, yielding a predicted electrical conductivity of 2.77 S/m. These results demonstrate that systematic optimization of FDM printing parameters can effectively enhance the electrical performance of conductive PLA components without modifying material composition.

KEYWORD

Conductive PLA, fused deposition modeling, electrical conductivity, fractional factorial design, process optimization

INTRODUCTION

Additive manufacturing particularly fused deposition modelling (FDM), is widely used for producing polymer-based components due to its cost-effectiveness, design flexibility, and capability to fabricate complex geometries (Sun, 2023). Initially adopted primarily for prototyping and structural applications, recent advances in functional polymer composites have extended the use of FDM toward electrically functional components such as sensors and printed electrodes (Faria et al., 2024). This development is driven by conductive polymer composites, especially polylactic acid (PLA) reinforced with conductive fillers like carbon black, carbon nanotubes, and graphene which provide electrical pathways within the printed structures (Naboulsi et al., 2025).

Despite progress in materials formulation, studies have emphasized that printing process parameters significantly influence the final electrical performance of FDM-printed functional parts. Variations in processing conditions influence interlayer bonding quality, filament fusion, and the continuity of conductive pathways, which collectively govern the electrical behaviour of printed components (Ibrahim & Salman, 2025).

Building on this understanding, several studies have investigated the effects of printing parameters on the electrical conductivity of conductive polymers. Rocha et al. (2022) reported that printing parameters such as layer height, nozzle temperature, printing speed, and infill pattern can alter resistivity and electrochemical response of printed conductive composites. Bugdayci et al. (2025) highlighted the importance of process parameter control for functional composites in FDM, suggesting that optimizing these variables are critical for performance beyond structural integrity. Tirado-Garcia et al. (2021) demonstrated that the incorporation of conductive fillers within PLA and the control of printing conditions affected the formation of conductive pathways and the resulting electrical behaviour in 3D-printed components. In addition, experimental investigations on graphene and carbonaceous fillers in extrusion printing also report strong dependence of measured conductivity on print settings and sample geometry (Shajahan, 2024).

Despite these findings, a major challenge remains in efficiently evaluating the combined effects of multiple printing parameters. Many existing studies employ a one factor at a time approach, which does not capture interaction effects and requires a large number of experimental runs. In contrast, statistical design of experiments (DoE) techniques, particularly fractional factorial design provides a resource-efficient DoE framework for screening and optimizing multiple parameters simultaneously. This approach enables the identification of dominant factors and key interactions while minimizing experimental effort (Glogowsky et al., 2024).

In this study, a structured experimental approach was adopted to investigate the influence of key FDM printing parameters on the electrical conductivity of a commercially available conductive PLA filament. Electrical conductivity was selected as the primary response variable, as it directly reflects the functional performance of conductive printed components. The objective of this work is to evaluate the relative significance of selected process parameters and to identify an optimal printing condition that enhances electrical performance, providing practical insight for functional applications of conductive polymer 3D printing.

MATERIAL AND METHODOLOGY

Materials

A commercially available conductive polylactic acid (PLA) filament, Protopasta Conductive PLA, with a nominal diameter of 1.75 mm was used in this study. The filament consists of a PLA matrix loaded with conductive carbon-based fillers to impart electrical conductivity. According to the manufacturer's specifications, the recommend extrusion temperature range for the filament is 195-230 °C. The material was used as received without any additional drying, treatment, or modification prior to printing.

Specimen fabrication

All specimens were fabricated using Bambu Lab X1 Carbon FDM 3D printer. The specimen geometry was designed using SolidWorks software and sliced using Bambu Studio. A total of 24 specimens were produced based on a two-level fractional factorial experimental design.

Four key printing parameters were selected as independent variables which are nozzle temperature at 200 °C and 220 °C, printing speed at 40 mm/s and 80 mm/s, infill density at 50% and 100%, and layer height at 0.2 mm and 0.4 mm. These parameters were chosen due to their known influence on filament melting behaviour, interlayer bonding quality, and internal structure formation in FDM-printed parts.

All other parameters were kept constant throughout the experiments to isolate the effects of the selected variables. These constant parameters included a nozzle diameter of 0.4 mm, a build plate temperature of 60 °C, raster orientation of 0°, and fixed cooling fan settings.

Electrical conductivity measurement

Electrical conductivity was evaluated using a two-point probe method. Electrical resistance measurements were obtained by placing the probes at fixed and consistent locations along the length of each printed specimen to ensure repeatability. The measured resistance values were then used to calculate and compare the electrical conductivity of specimens produced under different combinations of printing parameters.

Experimental design and data analysis

A-two level fractional factorial design was employed investigate the effects of multiple printing parameters while minimizing the number of experimental runs. Statistical analysis was performed using Minitab software. Analysis of variance (ANOVA) was conducted at 95% confidence level to identify statistically significant printing parameters affecting electrical conductivity. Main effects trends were analysed and response optimization was performed to determine the combination of printing parameters that maximized electrical conductivity.

RESULT AND DISCUSSION

The electrical conductivity results obtained from the 24 printed specimens demonstrate that FDM printing parameters have a statistically significant influence on the electrical performance of conductive PLA parts, as evidenced by the ANOVA results presented in Table 1. The ANOVA indicates that the overall model was found to be statistically significant at a 95% confidence level (p= 0.024), indicating that at least one of the investigated printing parameters affects electrical conductivity.

ANOVA results revealed that layer height was the most significant parameter unfluencing electrical conductivity, with an F-value of 18.55 and a p-value of 0.001. In contrast, nozzle temperature (p=0.507), printing speed (p=0.439), and infill density (p=0.398) did not show statistically significant effects within the investigated parameter ranges. Additionally, two-way interaction effects between the printing parameters were found to be statistically insignificant (p=0.527), suggesting that the electrical conductivity was primarily governed by the main effects rather than interaction effects.

Table 1: Analysis of Variance (ANOVA) for electrical conductivity of FDM-printed conductive PLA parts.

Source	**DF**	**F-Value**	**P-Value**
Nozzle Temperature	1	0.46	0.507
Printing Speed	1	0.63	0.439
Infill Density	1	0.75	0.398
Layer Height	1	18.55	0.001
2-way Interactions	3	0.77	0.527
Model	7	3.24	0.024

Quantitatively, specimens printed with a larger layer height exhibited higher electrical conductivity compared to those printed with a smaller layer height. The increase in layer height led to an improvement in conductivity from approximately 2.16 S/m to 3.37 S/m, as indicated by the optimized model prediction and its 95% confidence interval. This behaviour can be attributed to enhanced interlayer contact and reduced interfacial resistance between deposited layers, which facilitate the formation of more continuous conductive pathways within the printed structure.

Response optimization analysis was performed to identify the printing condition that maximized electrical conductivity. The optimal parameter combination was determined to be a nozzle temperature of 200 °C, printing speed of 60 mm/s, infill density of 100%, and layer height of 0.3 mm. Under these conditions, the predicted electrical conductivity was 2.77 S/m, demonstrating an improvement of approximately 25-30% compared to the lowest-performing parameter combination. These results confirm that systematic optimization of FDM printing parameters is effective for enhancing the electrical performance of conductive PLA components.

CONCLUSION

This study demonstrated that FDM printing parameters significantly influence the electrical conductivity of conductive PLA components. Statistical analysis using analysis of variance confirmed that the overall model was significant at a 95% confidence level (p=0.024). Among the investigated parameters, layer height was identified as the most significant factor affecting electrical conductivity, with an F-value of 18.55 and a p-value of 0.001. Other parameters such as nozzle temperature, printing speed, and infill density exhibited no statistically significant effects within the studied ranges. Response optimization analysis indicated that an optimal printing condition consisting of a nozzle temperature of 200 °C, printing speed of 60 mm/s, infill density of 100%, and layer height of 0.3 mm yielded a predicted electrical conductivity of 2.77 S/m, corresponding to an improvement of approximately 25-30% compared to the lowest-performing parameter combination. These findings highlight the importance of statistically guided process parameter optimization for enhancing the electrical performance of conductive PLA components fabricated using standard FDM systems.

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