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Printing Parameter Optimization of Flexible Strain Sensor for Maximum Strain Level Analysis

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ABSTRACT

This study explores the optimization of printing parameters for Flexible Strain Sensors (FSS) produced using fused deposition modeling. The experimental design utilizes a Taguchi L18 orthogonal array to assess the impact of five parameters—substrate material, sensor thickness, printing temperature, printing speed, and layer height—on the maximum tensile strain (elongation at break) of the printed sensors. The findings indicate that thermoplastic polyurethane (TPU) significantly enhances strain capability compared to polylactic acid (PLA). The optimal parameter combination consists of a sensor thickness of 0.3 mm, a printing temperature of 210 °C, and a printing speed of 40 mm/s, with variations in layer height having a minimal influence. Validation testing confirmed the optimization results, achieving a maximum tensile strain of 26.3% with strong agreement between predicted and experimental responses.

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1. INTRODUCTION

Additive manufacturing has become a key enabling technology in modern manufacturing due to its flexibility in producing customized and geometrically complex components. Additive manufacturing enables the creation of complex structures with reduced material waste and lower energy consumption compared to conventional manufacturing methods. Beyond design freedom, its successful industrial adoption depends on the ability to establish robust process parameters that ensure repeatable performance and minimize variability. From an Industrial Engineering perspective, this challenge is closely related to process standardization, process capability improvement, and quality consistency in production systems. This capability is vital in industries where customization and complexity are prerequisites, such as aerospace (Khorasani et al., 2022; Schiller, 2015; Shapiro et al., 2016), automotive (Sarvankar & Yewale, 2019; Vasco, 2021; Zhao et al., 2023), and healthcare (Ghomi et al., 2021; Giannatsis & Dedoussis, 2009; Rodríguez-Salvador & Garcia-Garcia, 2018). In the healthcare sector, for instance, 3D printing has enabled the rapid production of tailored prosthetics and implants (Munsch, 2017; Savsani et al., 2023), significantly improving patient outcomes and the efficiency of medical procedures. The technology has also been instrumental in developing sensor technologies, including strain sensors (Liu et al., 2022).

In addition to biomedical applications, 3D printing has supported the development of embedded sensing technologies for structural and functional monitoring.

Flexible strain sensors (FSS), in particular, have emerged as a promising class of printed devices due to their ability to conform to dynamic surfaces and capture real-time mechanical deformation. However, ensuring consistent performance of such functional devices under varying production conditions remains a key manufacturing challenge, particularly when transitioning from prototyping to repeatable production environments.

Although significant progress has been made in developing novel materials for FSS, the influence of fabrication process parameters on sensor performance remains underexplored. Fused deposition modeling (FDM), as one of the most accessible and widely adopted additive manufacturing techniques, offers several advantages, including material versatility, cost-efficiency, and design flexibility. However, the mechanical and functional properties of FDM-printed components are highly sensitive to processing parameters such as printing temperature, speed, layer height, and material selection. Variations in these parameters can introduce inconsistencies in interlayer bonding and structural integrity (Demir, 2025; Gajjar et al., 2025; Hasan et al., 2024), directly affecting strain performance and overall product reliability.

To address such variability, robust design and quality engineering approaches have been widely adopted in manufacturing to improve process reliability and product consistency. The Taguchi method provides a structured experimental framework for systematically evaluating multiple process parameters while minimizing experimental effort (Mitra, 2011; Roy, 2001). Owing to its effectiveness in identifying critical factors and establishing optimal operating conditions, the method has been extensively applied in manufacturing process optimization.

Despite the growing use of FDM in sensor fabrication, studies investigating how these printing parameters affect sensor performance are still limited. In most cases, fixed values are used without systematic optimization. This lack of structured parameter design presents a manufacturing challenge, particularly in ensuring process stability and product quality for functional printed devices. This gap highlights the need for a more rigorous approach to identify optimal parameter combinations that enhance sensor functionality.

Accordingly, this study aims to address this gap by optimizing FDM printing parameters to improve the strain performance of flexible strain sensors. Using the Taguchi method, the research evaluates the influence of substrate material, sensor thickness, printing temperature, printing speed, and layer height on the sensor's strain capacity. This work provides a systematic evaluation of multiple process parameters and establishes a relative hierarchy of their influence on strain performance. This enables the identification of dominant and non-dominant factors, offering insight into which parameters should be prioritized in process design and which allow greater operational flexibility. Beyond parameter optimization, this study also aims to provide a structured understanding of parameter sensitivity to support process standardization and improve manufacturing reliability in additive manufacturing environments. By identifying critical parameter sensitivities and establishing robust printing conditions, this study contributes to manufacturing process optimization and supports more reliable production of functional components within additive manufacturing environments.

2. LITERATURE REVIEW

The continuous advancement of 3D printing technology has expanded its applications from rapid prototyping (RP) to the fabrication of functional devices. Gong et al. (2023), for instance, demonstrated the utility of 3D asphalt printing for road maintenance by integrating 3D laser scanning and digital modeling to expedite repairs. Beyond prototyping, 3D printing has also been employed in the production of medical devices using elastomeric materials like silicone and polyurethane, highlighting its potential for producing functional components for daily use despite existing technical limitations (Duran et al., 2023).

Among the various functionalized devices enabled by 3D printing, strain sensors—particularly flexible strain sensors (FSS)—have drawn considerable interest. Strain sensors manufactured through additive manufacturing can be customized in size, sensitivity, and functionality to fit specific applications. For example, in wearable technology, sensors need to be highly flexible and durable to withstand constant movement and bending. Flexible strain sensors (FSS) have increasingly gained attention, as they offer greater stretchability compared to conventional strain sensors (Smith, 2018). FSS can be used in health monitoring (Guo et al., 2022; Kohestanian et al., 2023; Li et al., 2022; H. Liu et al., 2021), human-machine interfaces (Cheng et al., 2023; Feng et al., 2023; Yan et al., 2023), and soft robotics (Ma et al., 2023).

To meet the functional requirements of FSS—particularly a high strain range—the choice of material is crucial. Various material combinations have been proposed in the literature, including thermoplastic polyurethane (TPU) combined with carbon nanotubes (CNTs) (Chen et al., 2022; Xiang et al., 2019), TPU-CNT composites (Poompiew et al., 2023), carbon nanotube-polydimethylsiloxane (CNT-PDMS) composites (Yan et al., 2023), gelatin and carbon black (Hardman et al., 2021), polyurethane-based systems (Yang et al., 2021), and polydimethylsiloxane (PDMS) combined with carbon black and CNTs (Ma et al., 2023). Similarly, another study combined thermoplastic polyurethane (TPU) with CNTs to print flexible sensors, incorporating CNTs into the sensors using high-energy ultrasonic waves (Li et al., 2022). Other studies have incorporated materials such as Multi-Walled Carbon Nanotubes (MWCNT) (Bai et al., 2022; Christ et al., 2017) and graphene (Alsharari et al., 2018; Qian et al., 2022) into the sensor structure.

However, the complexity of fabricating these composite materials poses a significant challenge. For instance, Yan et al. (2023) emphasized the need for precise control over evaporation conditions when preparing CNT-based composites, while Feng et al. (2023) described the time-intensive process required to synthesize polyvinyl alcohol-based hydrogel sensors. To circumvent these complexities, some researchers have opted for more accessible and ready-to-use materials. Zhao et al. (2020) demonstrated a simplified fabrication approach using commercial polydimethylsiloxane (PDMS), conductive silicone rubber (CSR) with silver-coated glass fiber (AGF), and carbon fiber (CF), which were mixed without the need for complex synthesis steps. Similarly, Guo et al. (2022) fabricated sensors using commercially available TPU filaments and infused CNTs via high-energy ultrasonic waves.

In terms of manufacturing processes, 3D printing technologies such as fused deposition modeling (FDM), direct ink writing (DIW), and digital light processing (DLP) have been widely adopted for FSS fabrication (Hardman et al., 2021; Poompiew et al., 2023). Among these, FDM stands out due to its affordability, accessibility, and compatibility with a broad range of thermoplastic materials. Yan et al. (2023) noted that FDM offers high fabrication flexibility with relatively simple equipment and low cost, making it attractive for rapid and customizable sensor manufacturing.

Prior studies have also demonstrated that FDM processing parameters play a critical role in determining the mechanical performance and structural integrity of printed components (Demir, 2025; Gajjar et al., 2025; Hasan et al., 2024). Variables such as printing temperature, layer height, and deposition speed influence interlayer bonding, porosity, and overall mechanical behavior, thereby motivating the need for systematic parameter evaluation in functional applications.

Despite the widespread use of FDM in sensor fabrication, most studies have used fixed printing parameters without exploring their impact on sensor performance. For example, a previous study used predetermined settings for printing temperature, infill density, and speed without evaluating how these factors influence sensor strain performance (Smith, 2018). Given that printing parameters directly affect the mechanical and structural properties of FDM-printed objects, optimization is critical for ensuring reliable and functional strain sensors.

To systematically address parameter variability, Design of Experiments (DOE) approaches have been widely employed in manufacturing research. The Taguchi method, a robust design technique, enables efficient identification of critical factors while reducing experimental effort and improving process consistency (Mitra, 2011; Roy, 2001). Its effectiveness in manufacturing optimization has led to broad adoption across engineering applications where performance reliability is essential.

Prior studies demonstrate the expanding capability of additive manufacturing to fabricate flexible strain sensors using diverse material systems and printing technologies (L. Liu et al., 2021; Nyabadza et al., 2021; Xie et al., 2026). However, most studies predominantly emphasize material development and device functionality, while the role of process parameters is often treated as secondary and remains insufficiently explored systematically. In many cases, process parameters are fixed or selected based on trial-and-error, limiting the ability to understand parameter sensitivity and their relative contribution to performance variability.

Furthermore, limited efforts have been made to translate experimental findings into structured insights that support process optimization and manufacturing decision-making. These gaps underscore the need for a statistically grounded optimization strategy to identify critical parameters and support consistent production outcomes.

To fill this research gap, the present study focuses on optimizing FDM printing parameters to enhance the strain capacity of flexible strain sensors. Using commercially available Polylactic Acid (PLA), TPU, and conductive Acrylonitrile Butadiene Styrene (ABS) filaments, the study applies the Taguchi method to systematically evaluate parameter effects and identify the optimal configuration for maximizing strain performance.

3. METHODOLOGY

3.1. Materials

The study evaluated filaments of PLA and TPU as the sensor substrate alternative, and conductive ABS as the sensor sensing material. PLA and TPU filaments were sourced from Esun, featuring a diameter of 1.75 mm with a tolerance of ± 0.05 mm. The conductive ABS filament, provided by R3Dmaker, also measured 1.75 mm in diameter but with a tighter tolerance of ± 0.02 mm. These materials were selected for their high flexibility, durability, and conductive properties suitable for flexible electronics applications.

3.2. Design of Experiment (DoE)

The experimental design was grounded in robust design principles, which aim to enhance process performance by reducing variability and improving reliability under controlled operating conditions. A Taguchi Method L18 orthogonal array was utilized to systematize the study of three printing parameters, i.e., layer height, printing temperature, and printing speed. The Taguchi method was selected due to its structured and efficient approach to evaluating factor sensitivity and identifying optimal parameter settings while minimizing the number of required experiments, making it particularly suitable for manufacturing process optimization. Furthermore, we added two factors of sensor thickness and sensor material. Each factor was tested at three levels (except sensor material, with only 2 factors) and replicated three times, resulting in 54 printing times of 18 combinations. The experimental design is illustrated in Table 1.

The selected factor levels were determined based on a combination of material manufacturer recommendations, commonly adopted ranges reported in prior FDM studies, and preliminary trial prints conducted to ensure stable extrusion and adequate interlayer adhesion. The temperature and printing speed ranges were chosen to balance material flow characteristics with dimensional stability, while the layer height and sensor thickness levels were defined to capture variations in structural flexibility without compromising print integrity.

Table 1: Taguchi's L18 Experimental Design

Experiment Number	Sensor Substrate's Material	Sensor Thickness (mm)	Layer Height (mm)	Printing Temperature (°C)	Printing Speed (mm/s)
1	PLA	0.3	0.06	210	20
2	PLA	0.3	0.10	220	40
3	PLA	0.3	0.15	230	60
4	PLA	0.4	0.06	210	40
5	PLA	0.4	0.10	220	60
6	PLA	0.4	0.15	230	20
7	PLA	0.5	0.06	220	20
8	PLA	0.5	0.10	230	40
9	PLA	0.5	0.15	210	60
10	TPU	0.3	0.06	230	60
11	TPU	0.3	0.10	210	20
12	TPU	0.3	0.15	220	40
13	TPU	0.4	0.06	220	60
14	TPU	0.4	0.10	230	20
15	TPU	0.4	0.15	210	40
16	TPU	0.5	0.06	230	40
17	TPU	0.5	0.10	210	60
18	TPU	0.5	0.15	220	20

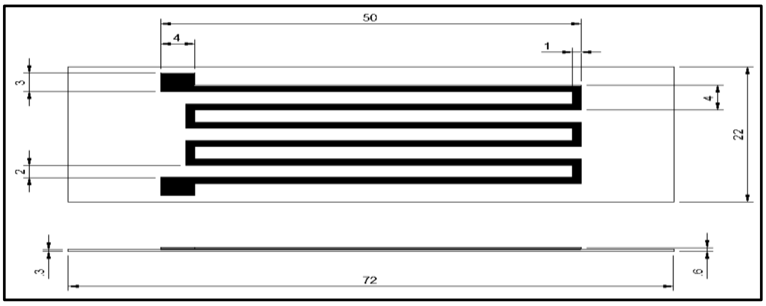

Figure 1: Flexible Strain Sensor Design

3.3. Sensor Fabrication

Sensor design (as shown in Figure 1) was created using Autodesk Fusion 360 and converted into G-code with Ultimaker Cura 3.6.0. Sensors were printed using an FDM 3D printer (Haltech H-01).

3.4. Testing and Analysis

Each printed sensor was subjected to tensile testing using a Universal Testing Machine (UTM), measuring the strain at which each sensor failed. Strain refers to the percentage elongation at failure obtained from tensile testing. This failure point represented the maximum strain level achieved by the sensor. The results were analysed using the Taguchi method's signal-to-noise (S/N) ratio to determine the optimal printing parameters. The S/N ratio approach was selected as it is widely recognized in Taguchi-based robust design for evaluating factor influence and identifying optimal parameter settings while inherently accounting for performance variability. While more comprehensive statistical analyses, such as ANOVA, can provide additional insight into factor significance and interaction effects, the present study focuses on a practical and efficient optimization framework consistent with Taguchi's robust design philosophy, where the primary objective is to identify dominant factors and optimal conditions with minimal experimental complexity. This method provides a practical and efficient basis for process optimization without requiring extensive additional statistical modeling.

This analysis used the "larger is better" approach to identify the optimal conditions. The formula for the larger-is-better S/N ratio using base 10 log is:

$$S/N = -10 \log \left(\frac{1}{n} \sum_{i=1}^{n} \frac{1}{y_i^2} \right) \quad (1)$$

where y = responses for the given factor level combination and n = number of responses in the factor level combination.

The optimal settings suggested by the highest S/N ratio were used to print additional sensors to validate the findings. These validation tests were aimed at confirming that the selected parameter settings could reliably reproduce the predicted outcomes.

4. RESULTS AND DISCUSSIONS

4.1. Formability

The printed sensors are shown in Figure 2. The

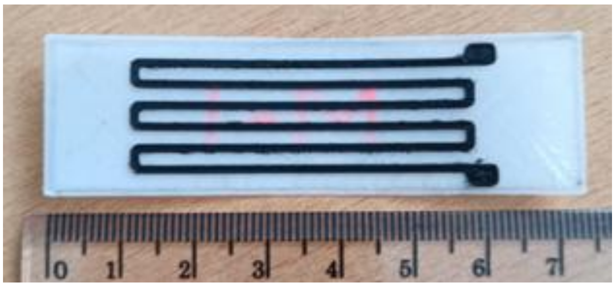

Figure 2: Printed Flexible Strain Sensor on PLA Substrate

Table 2: Tensile Test Results

Experiment Number	Replication 1 (%)	Replication 2 (%)	Replication 3 (%)	Average (%)
1	4.597	3.54	3.394	3.844
2	3.878	2.922	4.416	3.739
3	3.070	3.373	2.822	3.088
4	3.181	3.762	3.759	3.567
5	3.392	3.208	3.057	3.219
6	4.719	4.162	5.413	4.765
7	2.800	2.619	2.459	2.626
8	3.743	3.854	4.608	4.068
9	3.686	3.984	5.138	4.269
10	7.330	8.989	20.276	12.198
11	23.394	16.513	20.216	20.041
12	13.797	6.976	13.17	11.314
13	8.357	5.273	8.127	7.252
14	9.178	7.108	7.322	7.869
15	20.568	12.562	22.697	18.609
16	7.276	6.862	6.357	6.832
17	6.551	4.003	4.613	5.056
18	5.454	6.024	7.059	6.179

sensors' lines are uniformly printed, which is crucial for consistent electrical properties across the sensor. The ABS sensing material was firmly adhered to the PLA substrate and the TPU substrate. Good adhesion ensures there are no gaps or delamination between layers, which could lead to unreliable sensor readings or sensor failure under mechanical stress.

4.2. Strain Analysis

The tensile test results from the experiments are shown in Table 2. The results show distinct performance differences between the two materials used—PLA and TPU. TPU experiments generally demonstrate higher elongation percentages, reflecting the material's inherent flexibility and elasticity. Experiments 10 and 16 with TPU show significantly higher average elongations, peaking at 22.697% in Experiment 16. This substantial increase compared to PLA-based specimens confirms that material selection dominates strain behavior in FDM-printed flexible sensors. On the other hand, PLA experiments yielded lower elongation values, highlighting PLA's stiffer and less elastic characteristics. The highest elongation observed in PLA-based experiments was 4.765% in Experiment 6.

The response table (Table 3) highlights the factors that have the greatest impact on the response. The Delta value is calculated as the difference between the highest and lowest average signal-to-noise (S/N) ratios for each factor and is used to evaluate factor sensitivity. Parameters with larger Delta values exert greater influence on the response and are therefore considered more critical in the optimization process. These values indicate the significance of each factor, with larger values corresponding to greater influence on the research response.

The sensor substrate's material emerges as the most significant factor, which suggests that the choice of substrate material is crucial for the sensor strain performance, as different materials can drastically affect the sensor's flexibility and strength. This finding indicates that substrate selection represents the primary driver of strain variability, suggesting that controlling material properties is essential for achieving consistent mechanical performance in additively manufactured sensors.

Sensor thickness is the second most influential factor, showing that the physical dimensions of the sensor also play influences its ability to withstand strain. However, the delta value is much smaller compared to the substrate material, which suggests that its impact on strain performance may not be as pronounced. Furthermore, the other three factors, i.e., printing temperature, printing speed, and layer height, have comparatively limited influence on the sensor strain performance within the

Table 3: Response Table for Maximum Strain Level

Level	Sensor Substrate's Material	Sensor Thickness	Level Height	Printing Temperature	Printing Speed
1	11.21	16.96	14.46	16.81	15.57
2	19.55	15.88	15.30	14.02	16.31
3		13.29	16.37	15.31	14.26
Delta	8.34	3.67	1.92	2.79	2.05
Rank	1	2	5	3	4

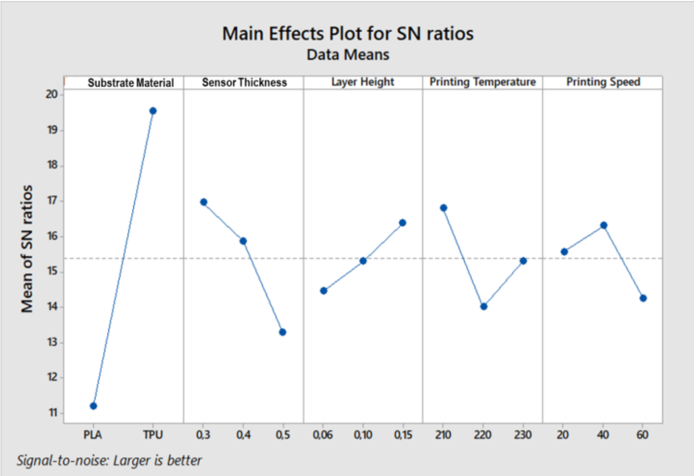

Figure 3: Main Effects Plot for Maximum Strain Level

investigated parameter ranges. This indicates that once material and geometry are appropriately selected, moderate variations in thermal and kinematic settings may not drastically affect maximum strain capacity.

The optimal setting for each factor can be identified by the highest mean S/N ratio. Based on the plot shown in Figure 3, the best maximum strain level is obtained from a combination of TPU substrate materials, sensor thickness of 0.3 mm, layer height of 0.15 mm, printing temperature of 210°C, and printing speed of 40 mm/s.

4.3. Validation of Taguchi Analysis

Validation was conducted to confirm the accuracy of the previous Taguchi analysis. Three FSS were printed using the optimal combination of factors and levels identified in the analysis. These sensors underwent tensile testing to determine their maximum strain levels. The resulting S/N ratios were calculated and compared with the predicted S/N ratios to assess any deviations. The results are shown in Table 4.

Based on the validation test, the results indicated a deviation between the validation S/N ratio and the predicted S/N ratio of 12.16%. This corresponds to an accuracy rate of 87.84%. The relatively small deviation suggests that the analysis conducted is valid. This result confirms the robustness of the experimental design and demonstrates that the Taguchi-based optimization can reliably predict sensor performance under the selected parameter settings. Such predictive capability is particularly valuable in manufacturing environments where consistent product quality is required. The close agreement between predicted and experimental values supports the effectiveness of the orthogonal array design in identifying dominant factors without requiring exhaustive experimentation. Moreover, this particular combination of factors yielded the highest response value in terms of both maximum strain level and S/N ratio compared to other combinations.

4.4. Discussion on The Influencing Factors

Substantial differences in the average maximum strain levels between sensors using PLA and TPU substrates. Sensors with a PLA substrate typically exhibit a maximum stretch level ranging from 2.6 to 4.7 percent, while those with a TPU substrate show a higher range of 5 to 20 percent. This indicates that TPU significantly enhances the sensor's strain capabilities compared to PLA. The pronounced difference between the two materials further highlights the importance of parameter sensitivity analysis in supporting informed manufacturing decisions, particularly when balancing flexibility requirements with structural reliability. TPU's elasticity provides stronger and more durable adhesion between layers, with characteristics akin to rubber in terms of elasticity, durability, and toughness, as noted in (Rodríguez-Parada et al., 2021; Sorimpuk et al., 2022).

For sensor thickness, optimal performance is observed at 0.3 mm, suggesting that thinner sensors, which offer greater flexibility, are better suited for strain applications. This flexibility allows the sensor to elongate more under tensile stress, evenly distributing stress across its cross-sectional area and reducing the likelihood of material failure. On the other hand, the optimal printing temperature was found at the lowest temperature 210°C. This could indicate higher temperatures causing some degradation of material properties or adversely affecting

Table 4. Taguchi Analysis Validation Test Results

No.	Maximum Strain (%)	Validation S/N Ratio	Predicted S/N Ratio	S/N Ratio Deviation
1	24.411			
2	23.773	27.8752	24.4868	12.16%
3	26.300			

the adhesion between layers, as previously observed in (Hadi et al., 2023; Nurgesang et al., 2022). However, this research does not show a significant trend between the difference in printing temperature and the maximum strain level produced.

The optimal printing speed is determined to be 40 mm/s. Both increasing and decreasing this speed result in a lower S/N ratio. At 40 mm/s, the extruder has adequate time to accurately deposit each layer of material, ensuring strong adherence between layers. Printing too rapidly can cause insufficient bonding as the material may not melt and fuse properly with the underlying layer. On the other hand, printing too slowly can lead to overheating of the material, which may degrade its properties and result in warping or other deformations. The speed of 40 mm/s likely strikes a balance, providing a cooling rate that allows each layer to adequately cool before the next is applied, without causing the rapid cooling that can induce brittleness. Previous studies have shown an inverse relationship with tensile strength; higher printing speeds typically result in lower tensile strength (Nurgesang et al., 2022). However, different findings by Ansari & Kamil (2021) suggest that higher speeds can actually enhance tensile strength due to a faster bonding process between layers.

While layer height has the smallest contribution to the overall performance in this study, its impact on the mechanical properties of printed objects is still noteworthy. Several studies have explored the relationship between layer height and the strength of the printed object. Typically, a larger layer height is associated with better Young's modulus results, suggesting enhanced tensile strength due to more substantial bonding between thicker layers (Mazlan et al., 2023). Conversely, another study indicates that a smaller layer height can actually increase tensile strength, possibly due to tighter packing and increased layer adhesion (Stojković et al., 2023).

Despite these findings, the current research does not establish a clear trend linking layer height variations to the maximum strain level achieved in the sensors. This absence of a significant correlation suggests that while layer height can affect material strength, its impact on the sensor's ability to handle maximum strain is not as pronounced. This could be due to the interplay of multiple factors in the printing process that might overshadow the subtle effects of layer height changes. This implies that for flexible strain sensor applications, geometric and material factors outweigh micro-layer structural adjustments in determining ultimate strain capacity. As a result, altering layer height alone does not consistently result in predictable changes in the maximum strain capacity of the printed sensors.

4.5. Practical and Industrial Implications

The findings of this study provide practical guidance for manufacturing process optimization in additive manufacturing environments. The identification of substrate material as the dominant factor influencing strain performance indicates that material selection should be prioritized during early-stage process planning. This prioritization can be interpreted as a parameter hierarchy for decision-making, where material selection serves as a primary control variable, while other parameters function as secondary tuning variables. In production settings where consistent sensor performance is required, controlling material variability may yield greater performance stability than fine-tuning secondary parameters such as layer height or printing temperature. Such an approach aligns with quality engineering principles, where controlling high-impact factors leads to more stable process outcomes.

The demonstrated effectiveness of the Taguchi-based optimization approach also highlights its applicability as a structured decision-support tool for parameter setting in functional 3D printing. By reducing experimental effort while identifying critical factor sensitivities, the method supports efficient process development and quality control strategies. From a process capability perspective, the relatively low sensitivity of certain parameters (e.g., layer height and printing speed within the tested range) suggests the existence of a wider feasible operating window, which can facilitate more robust and stable production without requiring overly tight process control. From an industrial engineering perspective, the results contribute to improving process reliability, reducing trial-and-error experimentation, and enhancing repeatability in the fabrication of functional printed components. The findings can be further interpreted as supporting the development of standardized operating procedures (SOPs) for FDM-based sensor fabrication, where optimal parameter combinations serve as baseline settings for consistent production. These insights may support the development of standardized parameter-setting guidelines for flexible electronic devices produced using FDM technology. In addition, the parameter sensitivity information generated in this study can inform process control strategies, enabling practitioners to focus monitoring efforts on critical variables while allowing flexibility in less sensitive parameters, thereby improving overall manufacturing efficiency and decision-making.

5. CONCLUSIONS

This study has successfully optimized printing parameters for FSS to achieve maximum strain level analysis. The results reveal that TPU is the superior substrate material, offering significantly higher strain capabilities compared to PLA due to its enhanced elasticity and durability. The sensor thickness is best found at 0.3 mm, indicating that thinner sensors exhibit greater flexibility and better strain distribution. The optimum printing temperature at 210°C shows lower temperature might be better as it can mitigate material degradation. For printing speed, 40 mm/s proves to be the most effective as this can balance cooling rates and material deposition for strong layer adhesion. Additionally, we found that layer height demonstrates the least influence on the overall performance.

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