TECHNICAL UNIVERSITY OF CLUJ-NAPOCA

**ACTA TECHNICA NAPOCENSIS**

**Series: Applied Mathematics, Mechanics, and Engineering**
**Vol. 68, Issue IV, November, 2025**

# EXPERIMENTAL INVESTIGATION OF SURFACE QUALITY IN PLA 3D PRINTED COMPONENT USING A DOE APPROACH

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***Abstract:*** *Surface roughness is a critical quality parameter in 3D-printed components, influencing mechanical properties, aesthetic appeal, and functional performance. This study investigates the influence of key process parameters on the surface roughness of Polylactic Acid 3D-printed parts using a Design of Experiments approach. A structured experimental methodology was developed to analyze the effects of the default thickness, number of walls and infill density on surface quality, quantified through Ra measurements. The experiments were designed using a Taguchi orthogonal array to optimize parameter combinations while minimizing experimental runs. An ANOVA analysis and a regression model was performed to determine the significance of each factor. The study provides an optimized parameter set for improving the surface roughness of 3D printed parts.*
***Key words:*** *PLA, 3D printing, surface roughness, Design of Experiments, Taguchi method, ANOVA*

## 1. INTRODUCTION

Additive manufacturing (AM) enables users to create complex structures, with minimal material, time and cost. 3D printed parts require no molds or dies, being accessible to be used in a variety of industries [1]. In this context, quality parameters of 3D printed parts have been optimized to generate consistent and competitive products. Several researchers studied the influence of 3D printing parameters on the average surface roughness of 3D printed parts using Fused Deposition Modelling (FDM). Researchers demonstrated that having a low temperature bed, high printing speed, a medium infill, low layer thickness and a low number of shells are recommended to reduce surface roughness (Ra), when using ABS [2]. Another study demonstrated that when using PLA, the lowest values for Ra were obtained with a low layer height and a high speed [3]. Surface roughness is also influenced by the measuring direction. If a wall has a higher tilt angle, the value of Ra also has higher registered values [4]. To analyze the effects of three printing parameters the current study proposed a Taguchi orthogonal array for 24 PLA samples. The selected printing parameters considered important for the study were infill, default thickness and wall line count. Samples were measured using a digital roughness tester and weighed using a four decimal electronic scale. An Analysis of Variance(ANOVA) was used to determine which factor had the most impact on the measured surface roughness, by comparing the mean values of the three groups.

## 2. METHODS

To determine the surface quality in a PLA 3D printed component an experimental plan based on a Taguchi orthogonal array was used, allowing different parameter combination comparisons while minimizing the number of experimental runs. For mass and roughness, an ANOVA method was applied to determine each of the parameters' significance and their interactions. The Taguchi method was chosen due to its significant advantages in reducing the number of experiments, thus saving time and resources, while identifying critical factors, improving product performance and enabling data-driven optimization. In the implementation of the Design of Experiments (DOE) methodology, the experimental process was

**Received**: 16.05.25; **Similarities**: 23.10.25: **Reviewed**: 04.11./ 28.10.25: **Accepted**:18.11.25.

structured into four distinct and methodologically defined stages.

The ***first stage*** involves defining the factors and establishing the levels. Three factors were defined to be analyzed and optimized, selected from the responses obtained through the systemic analysis, as follows: Infill Density (%); Wall Line Count (number of perimeters/walls of the part); Wall Thickness (the Default Thickness measured in mm).

Each of the three factors will be tested at three levels (Table 1), starting from a Taguchi L9 ($3^3$) orthogonal array to optimize the number of experiments. An extension of the experiment is proposed for a more robust analysis, reducing the risk of statistical errors when applying ANOVA. It was decided to replicate the factors at the intermediate levels, resulting in an L12 matrix (Table 2).

*Table 1*

**Levels of the three factors selected for analysis**

| No. | Parame□er | Minimum | □verage | Maximum |
|---|---|---|---|---|
| 1 | Infill | 15% | 40% | 100% |
| 2 | Wall Line Count | 1 | 2 | 3 |
| 3 | Default Thickness | 0.45 mm | 0.67 mm | 1 mm |

*Table 2*

**Taguchi L12 array structure**

| No. | Variables | | | Variable Codes | | |
|---|---|---|---|---|---|---|
| | Infill | Wall Line Count | Default Thickness | A | B | C |
| E1 | 40% | 2 | 0.67 mm | 0 | 0 | 0 |
| E2 | 15% | 1 | 0.45 mm | -1 | -1 | -1 |
| E3 | 15% | 1 | 1 mm | -1 | -1 | +1 |
| E4 | 15% | 3 | 0.45 mm | -1 | +1 | -1 |
| E5 | 15% | 3 | 1 mm | -1 | +1 | +1 |
| E6 | 40% | 2 | 0.67 mm | 0 | 0 | 0 |
| E7 | 100% | 3 | 1 mm | +1 | +1 | +1 |
| E8 | 100% | 3 | 0.45 mm | +1 | +1 | -1 |
| E9 | 100% | 1 | 1 mm | +1 | -1 | +1 |
| E10 | 100% | 1 | 0.45 mm | +1 | -1 | -1 |
| E11 | 40% | 2 | 0.67 mm | 0 | 0 | 0 |
| E12 | 40% | 2 | 0.67 mm | 0 | 0 | 0 |

This array will make sure that each factor will be equally tested.

In the ***second phase*** of the experimental procedure, a selection of 24 samples, in accordance with the Taguchi array, was additively manufactured using FDM. The material chosen for fabrication was Winkle PLA filament, utilized in two color variants (Glacier White and Jet Black) sourced from the same manufacturer. This approach allows for the investigation of whether the color pigment present in the filament has any measurable influence on the experimental outcomes, while maintaining consistency in material composition and production origin. Each of the 24 specimens was individually fabricated on the 3D printer's build platform (Fig.1) to eliminate potential sources of variability associated with part positioning, such as non-uniform thermal distribution, localized cooling rates, or bed-leveling inconsistencies. This controlled printing strategy was employed to ensure the repeatability and reliability of the experimental results by minimizing process-induced deviations.

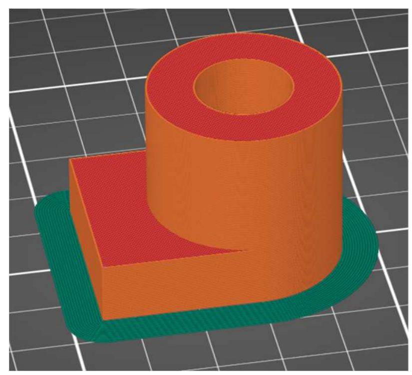

**Fig. 1.** The position of the sample on the printer bed

For the fabrication of the 3D printed samples a Prusa MK4S was used loaded with PLA material. The printing parameters for part fabrication were set as given in Table 2, for every combination. An outer brim was also added and lower the first layer speed to 5 mm/s in order to ensure printing adhesion.

In the ***third phase*** of the experimental protocol, quantitative assessments were conducted to determine the mass and surface roughness of the fabricated specimens. Each of the 24 samples, comprising 12 white PLA and 12 black PLA specimens, was weighed using a Pioneer Plus PA323 precision electronic scale to ensure accurate mass measurements. Surface roughness evaluations were performed employing a contact INSIZE roughness tester to measure the arithmetic average roughness (Ra) parameter. This dual-measurement approach facilitated a comparative analysis of the influence exerted by color pigmentation on both the mass and surface texture characteristics of PLA-based 3D-printed components.

The ***fourth stage*** involves applying ANOVA to examine the statistical influence of each studied parameter.

## 3. RESULTS AND DISCUSSIONS

### 3.1 Mass measurement and analysis

The mass of each specimen was measured using a Pioneer Plus precision electronic scale with a resolution of four decimal places, ensuring accurate and repeatable readings for subsequent statistical analysis. The complete dataset for the white and black PLA samples is presented in Table 3 and Table 4, respectively. Each sample corresponds to a unique combination of three key printing parameters: infill density, wall line count, and default wall thickness.

*Table 3*

**White PLA samples mass**

| No. | Sample code | Variables | | | Mass [g] |
|---|---|---|---|---|---|
| | | Infill | Wall Line Count | Default Thickness | |
| 1 | E1_A | 40% | 2 | 0.67 mm | 15.1899 |
| 2 | E2_A | 15% | 1 | 0.45 mm | 7.7154 |
| 3 | E3_A | 15% | 1 | 1 mm | 10.5110 |
| 4 | E4_A | 15% | 3 | 0.45 mm | 11.0470 |
| 5 | E5_A | 15% | 3 | 1 mm | 18.5983 |
| 6 | E6_A | 40% | 2 | 0.67 mm | 15.2743 |
| 7 | E7_A | 100% | 3 | 1 mm | 23.9801 |
| 8 | E8_A | 100% | 3 | 0.45 mm | 23.6209 |
| 9 | E9_A | 100% | 1 | 1 mm | 23.7957 |
| 10 | E10_A | 100% | 1 | 0.45 mm | 23.6798 |
| 11 | E11_A | 40% | 2 | 0.67 mm | 15.1818 |
| 12 | E12_A | 40% | 2 | 0.67 mm | 15.2156 |

To evaluate the influence of the selected process parameters on sample weight, a one-way single factor ANOVA was performed separately for white and black PLA specimens.

The three independent variables (Infill, Wall Line Count, and Default Wall Thickness) were treated as categorical factors, while sample weight was considered the dependent variable. The ANOVA results are summarized in Table 5.

*Table 4*

**Black PLA samples mass**

| No. | Sample code | Variabiles | | | Mass [g] |
|---|---|---|---|---|---|
| | | Infill | Wall Line Count | Default Thickness | |
| **1** | E1_N | 40% | 2 | 0.67 | 15.5496 |
| **2** | E2_ N | 15% | 1 | 0.45 mm | 7.8454 |
| **3** | E3_ N | 15% | 1 | 1 mm | 10.7222 |
| **4** | E4_ N | 15% | 3 | 0.45 mm | 11.3403 |
| **5** | E5_ N | 15% | 3 | 1 mm | 19.0465 |
| **6** | E6_ N | 40% | 2 | 0.67 mm | 15.5266 |
| **7** | E7_ N | 100% | 3 | 1 mm | 24.3688 |
| **8** | E8_ N | 100% | 3 | 0.45 mm | 24.0156 |
| **9** | E9_ N | 100% | 1 | 1 mm | 24.2803 |
| **10** | E10_N | 100% | 1 | 0.45 mm | 24.0848 |
| **11** | E11_N | 40% | 2 | 0.67 mm | 15.5397 |
| **12** | E12_N | 40% | 2 | 0.67 mm | 15.5332 |

*Table 5*

**ANOVA for mass measurements**

| Parameters | Infill | Wall Line Count | Default Thickness |
|---|---|---|---|
| **F-stat White** | 20.552 | 0.487 | 0.456 |
| **p-value White** | 0.0004 | 0.629 | 0.647 |
| **Interpretation White** | ☑ Significant | ⚠ Almost significant | ⚠ Almost significant |
| **F-stat Black** | 19.915 | 0.489 | 0.459 |
| **p-value Black** | 0.0004 | 0.628 | 0.645 |
| **Interpretation Black** | ☑ Significant | ⚠ Almost significant | ⚠ Almost significant |

The statistical analysis reveals that, for both white and black PLA materials, the Infill parameter exhibits a statistically significant influence on the final weight of the printed samples (p-value < 0.001), as indicated by the high F-statistic values. Conversely, the Wall Line Count and Default Wall Thickness parameters show no statistically significant effect, with p-values well above the commonly accepted threshold of 0.05. These results are consistent across both color variants, suggesting that infill percentage predominantly governs the mass of FDM-printed parts, while modifications in wall count or thickness have a comparatively negligible impact under the conditions tested.

The consistency between the two datasets confirms that the influence of filament color (i.e., pigment variation) does not introduce any systematic bias in weight outcomes, provided that all other printing parameters are held constant.

### 3.2. Roughness measurement and analysis

Surface roughness measurements were performed using an INSIZE surface roughness tester. For each specimen, measurements were taken at seven distinct locations to ensure a representative assessment of the overall surface quality. This distribution of measurement points was designed to provide a comprehensive representation of the surface texture, accounting for possible anisotropies introduced during the layer-by-layer deposition process. The seven selected points were:

- ✓ On the outer cylindrical surface along two diametrically opposed generators: *GS1* – left generator in the lower area of the specimen; *GS2* – left generator in the upper area of the specimen; *GD1* – right generator in the lower area of the specimen; *GD2* – right generator in the upper area of the specimen.
- ✓ On the inner cylindrical surface, along three generators positioned at 0°, 60°, and -60°: IS0 – generator at 0°; IS60 – generator at 60°; IS-60 – generator at -60°.

Figure 2 illustrates a representative measurement area selected on each specimen's surface for Ra evaluation, emphasizing the consistent methodology applied across all samples to minimize spatial variability in surface texture data. The measurement results for the Ra surface roughness parameter [$\mu m$] are presented in Tables 6 and 7 below. The INSIZE roughness tester generates a comprehensive analysis report, capturing values for 19 distinct surface texture parameters, among which Ra was selected as the primary indicator for comparative evaluation in this study.

To statistically evaluate the influence of the selected process parameters on the surface roughness (Ra) values obtained from the seven measurement zones, a one-way Analysis of Variance (ANOVA) was conducted using the Anova: Single Factor tool available in Microsoft Excel. The analysis was performed independently for each of the three variables (Infill, Wall Line Count, and Default Thickness) with separate evaluations for the white and black PLA samples.

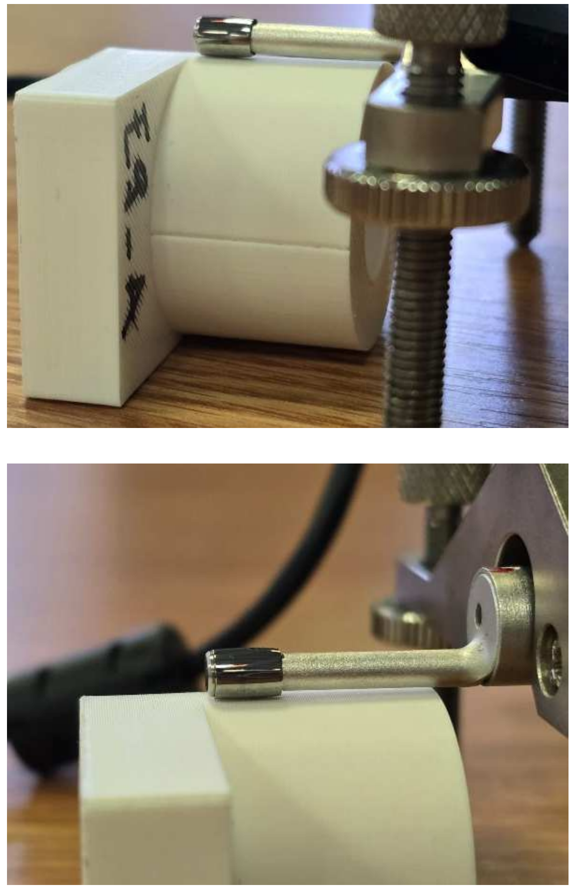

**Fig. 2.** One of the areas of sample measurement

*Table 6*

**Roughness values for white samples**

| | | Ra [µm] | | | | | | |
|---|---|---|---|---|---|---|---|---|
| **No.** | **Sample code** | **GS1** | **GS2** | **GD1** | **GD2** | **IS0** | **IS60** | **IS-60** |
| **1** | E1_A | 12.197 | 11.835 | 11.556 | 11.375 | 13.023 | 11.978 | 12.96 |
| **2** | E2_A | 11.524 | 11.914 | 10.786 | 11.413 | 11.834 | 12.773 | 13.292 |
| **3** | E3_A | 12.561 | 12.874 | 12.803 | 12.550 | 13.120 | 13.092 | 12.999 |
| **4** | E4_A | 10.785 | 11.463 | 10.978 | 12.094 | 12.576 | 12.644 | 13.113 |
| **5** | E5_A | 13.017 | 12.132 | 11.452 | 11.811 | 12.559 | 12.609 | 12.658 |
| **6** | E6_A | 12.157 | 11.854 | 13.681 | 11.919 | 12.162 | 12.71 | 11.299 |
| **7** | E7_A | 13.367 | 12.114 | 12.515 | 12.61 | 13.505 | 13.271 | 13.751 |
| **8** | E8_A | 12.547 | 11.315 | 12.483 | 12.479 | 12.612 | 13.228 | 13.251 |
| **9** | E9_A | 12.318 | 11.621 | 12.732 | 12.835 | 13.329 | 13.362 | 13.726 |
| **10** | E10_A | 11.2 | 11.709 | 11.487 | 11.819 | 13.186 | 12.598 | 13.923 |
| **11** | E11_A | 12.199 | 11.821 | 12.663 | 13.745 | 13.037 | 12.117 | 11.602 |
| **12** | E12_A | 11.841 | 13.632 | 12.423 | 12.503 | 12.404 | 13.676 | 13.413 |

The response values of the analyzed factors were divided into three groups (according to the variation levels – Table 1), each with 4 observations (according to the Taguchi L12 matrix – Table 2): *For Infill*: Group 1 – 15%, Group 2 – 40%, Group 3 – 100%; *For Wall Line Count*: Group 1 – 1, Group 2 – 2, Group 3 – 3; *For Default Thickness*: Group 1 – 0.45 mm, Group 2 – 0.67 mm, Group 3 – 1 mm.

*Table 7*

**Roughness values for black samples**

| No. | Sample code | GS1 | GS2 | GD1 | GD2 | IS0 | IS60 | IS-60 |
|---|---|---|---|---|---|---|---|---|
| | | Ra µm] | | | | | | |
| 1 | E1_N | 11.35 | 12.217 | 11.637 | 11.493 | 11.282 | 13.136 | 12.061 |
| 2 | E2_N | 11.002 | 11.257 | 11.98 | 12.138 | 12.992 | 12.746 | 13.615 |
| 3 | E3_N | 11.973 | 12.329 | 12.019 | 12.014 | 12.986 | 12.316 | 13.713 |
| 4 | E4_N | 11.513 | 11.267 | 11.57 | 12.141 | 12.808 | 12.405 | 12.162 |
| 5 | E5_N | 13.746 | 11.471 | 11.136 | 10.473 | 12.244 | 12.739 | 12.617 |
| 6 | E6_N | 12.379 | 12.229 | 11.612 | 12.822 | 12.686 | 11.525 | 12.399 |
| 7 | E7_N | 13.013 | 11.889 | 11.835 | 11.679 | 12.737 | 12.681 | 12.042 |
| 8 | E8_N | 12.109 | 11.596 | 11.791 | 11.423 | 12.492 | 13.064 | 12.63 |
| 9 | E9_N | 11.771 | 12.347 | 11.813 | 11.349 | 12.714 | 13.344 | 13.420 |
| 10 | E10_N | 11.215 | 10.842 | 11.954 | 11.955 | 12.236 | 12.736 | 13.785 |
| 11 | E11_N | 11.541 | 11.502 | 11.637 | 12.061 | 12.381 | 12.75 | 11.981 |
| 12 | E12_N | 11.701 | 11.331 | 11.391 | 12.178 | 11.634 | 11.967 | 12.687 |

The resulting *F*-statistics and *p*-values for each surface measurement zone are presented in Tables 8, 9, and 10. These tables provide a comparative view of the statistical significance for each parameter across all sample groups and measurement zones. Statistical significance was determined based on a conventional threshold of $p < 0.05$. Values below this threshold are marked as significant, those between 0.05 and 0.10 as almost significant, and values above 0.10 as not significant.

*Table 8*

**ANOVA results for infill**

| Measure zone | F-stat White | p-value White | Interpretation | F-stat Black | p-value Black | Interpretation |
|---|---|---|---|---|---|---|
| GS1 | 0.252 | 0.782 | ✕ Not significant | 0.165 | 0.849 | ✕ Not significant |
| GS2 | 0.881 | 0.447 | ✕ Not significant | 0.199 | 0.822 | ✕ Not significant |
| GD1 | 1.971 | 0.194 | ✕ Not significant | 1.247 | 0.332 | ✕ Not significant |
| GD2 | 0.546 | 0.596 | ✕ Not significant | 0.958 | 0.419 | ✕ Not significant |
| IS0 | 2.160 | 0.171 | ✕ Not significant | 3.085 | 0.095 | ⚠ Almost significant |
| IS60 | 0.997 | 0.406 | ✕ Not significant | 1.707 | 0.235 | ✕ Not significant |
| IS-60 | 4.488 | 0.044 | ☑ Significant | 1.587 | 0.256 | ✕ Not significant |

Based on the obtained ANOVA results, *Infill density* appears to have a limited global impact on *Ra* values. *Wall Line Count* and *Default Thickness* exhibit localized, material-dependent effects on surface roughness, particularly in angled or top-layer measurement zones. These findings highlight the importance of parameter tuning not only for mechanical performance but also for surface quality optimization.

*Table 9*

**ANOVA results for Wall Line Count**

| Measure zone | F-stat White | p-value White | Interpretation | F-stat Black | p-value Black | Interpretation |
|---|---|---|---|---|---|---|
| GS1 | 0.486 | 0.630 | ✕ Not significant | 2.919 | 0.105 | ✕ Not significant |
| GS2 | 0.636 | 0.551 | ✕ Not significant | 0.240 | 0.791 | ✕ Not significant |
| GD1 | 0.799 | 0.478 | ✕ Not significant | 4.291 | 0.049 | ☑ Significant |
| GD2 | 0.101 | 0.904 | ✕ Not significant | 1.678 | 0.240 | ✕ Not significant |
| IS0 | 0.161 | 0.853 | ✕ Not significant | 2.928 | 0.104 | ✕ Not significant |
| IS60 | 0.509 | 0.617 | ✕ Not significant | 0.867 | 0.452 | ✕ Not significant |
| IS-60 | 3.090 | 0.095 | ⚠ Almost significant | 30.791 | 0 | ☑ Significant |

*Table 10*

**ANOVA results for Default Thickness**

| Measure Zone | F-stat White | p-value White | Interpretation White | F-stat Black | p-value Black | Interpretation Black |
|---|---|---|---|---|---|---|
| GS1 | 6.262 | 0.019 | ☑ Significant | 3.452 | 0.077 | ⚠ Almost significant |
| GS2 | 1.438 | 0.287 | ✕ Not significant | 3.921 | 0.059 | ⚠ Almost significant |
| GD1 | 2.588 | 0.129 | ✕ Not significant | 0.971 | 0.415 | ✕ Not significant |
| GD2 | 0.618 | 0.560 | ✕ Not significant | 2.150 | 0.172 | ✕ Not significant |
| IS0 | 1.683 | 0.239 | ✕ Not significant | 2.734 | 0.118 | ✕ Not significant |
| IS60 | 0.821 | 0.470 | ✕ Not significant | 0.853 | 0.457 | ✕ Not significant |
| IS-60 | 2.841 | 0.110 | ✕ Not significant | 1.608 | 0.252 | ✕ Not significant |

## 4. CONCLUSION

This study has demonstrated that among the key FDM process parameters investigated *Infill density* had the most consistent and statistically significant impact on sample weight, while its influence on *Ra* was generally limited and localized. Surface roughness analysis showed that *Wall line count* and *Default thickness* exhibited zone-specific effects, particularly in internal and angled areas, with notable variation between white and black PLA samples. These findings emphasize the importance of a localized and material-sensitive approach. By employing a structured DOE methodology and ANOVA, the study provides evidence-based insights into the complex interaction of FDM process parameters. The localized influence of surface-related parameters such as wall line count and default thickness, particularly in internal and angled zones, highlights the directional sensitivity of surface finish in FDM-printed parts. The consistency of results across both filament colors confirms that pigment differences have minimal impact under controlled conditions. These findings support the need for zone-specific process calibration and encourage future investigations that integrate multi-criteria optimization and post-processing strategies for improved surface quality. The results contribute to the formulation of optimized parameter sets for enhancing the surface finish of PLA components.

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## Investigație experimentală a calității suprafeței la componente imprimate 3D din PLA utilizând DoE


Rugozitatea suprafeței reprezintă un parametru de calitate în cazul componentelor realizate prin imprimare 3D, influențând proprietățile mecanice, aspectul estetic și performanța funcțională. Acest studiu investighează influența principalilor parametri de proces asupra rugozității suprafeței pieselor imprimate 3D din PLA, utilizând o abordare bazată pe DOE. S-a dezvoltat o metodologie experimentală pentru a analiza efectele celor trei parametri analizați asupra calității suprafeței, cuantificată prin măsurători Ra. Experimentele au fost proiectate utilizând o matrice ortogonală Taguchi, cu scopul de a optimiza combinațiile de parametri și de a reduce numărul total de teste. Analiza datelor a fost realizată prin ANOVA și modelare de regresie, pentru a determina semnificația fiecărui factor și a interacțiunilor dintre aceștia. Studiul propune un set de parametri optimizați pentru îmbunătățirea rugozității, oferind informații pentru producători și cercetători interesați de creșterea calității suprafețelor pieselor realizate prin FDM.



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