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Parametric Effect on the Mechanical Property of Extrusion-Based 3D-Printed Parts

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Abstract

Material extrusion-based 3D printing, a prevalent and economical approach for producing complex geometries, heavily relies on acrylonitrile butadiene styrene due to its advantageous mechanical properties and dimensional stability. Nevertheless, the mechanical integrity of 3D-printed components is considerably impacted by process variables. This research investigates the implications of critical parameters – layer height (LH), infill percentage (IP), and infill pattern design (IPD) – on the tensile, compressive, and flexural strength of parts manufactured through material extrusion-based 3D printer. A multi-response Taguchi parametric design matrix was employed, utilizing measured data for compression, flexural, and tensile strength. The objective is to enable reliable design and fabrication of intricate components. Findings reveal that increasing layer thickness from 100 micrometer to 200 micrometer generally diminishes tensile, flexural, and compressive strength, attributed to the formation of larger internal voids and compromised layer adhesion. Conversely, a higher infill percentage enhances material volume and structural integrity, facilitating improved load distribution and reduced stress concentration. Infill pattern designs, such as the honeycomb structure, are often selected for their superior directional strength. To optimize multiple quality characteristics simultaneously, a multivariable approach was employed using grey relational grade (GRG) analysis. Results indicate that parameters including a 0.1 mm layer height, a 25% infill percentage, and a honeycomb infill pattern design collectively yield the highest overall mechanical strength in 3D-printed parts.

Keywords: 3D Printer, ABS, infill pattern design, infill percentage, layer height

INTRODUCTION

This section heavily analyzes how variables affecting the mechanical properties of 3D-printed parts produced through extrusion with specific reference being on the ABS materials. Fused Deposition Modeling (also known as solid free form Fabrication) is a form of rapid additive manufacturing (AM), in which a plastic wire disintegrates, when it gets too heated up within in nozzle system and then released onto the build platform of machine in a series of successive layers in a highly controlled manner to create a 3D object [1]. The effect of printing orientation & additional fixed operational factors on the overall mechanical properties will also be taken into consideration during the review to put the findings into perspective [2]. Previous research has been mainly devoted to experimental characterization of FFF components and according to these results it is concluded that the mechanical characteristics were determined to be more affected by process parameters, e.g., the layer thickness, shell thickness and infill direction than by the printing parameters, e.g., nozzle hot end temperature or primary print speed [3]. Moreover, the material used, which in this case is ABS, which has mechanical strength, significantly influences quality and functionality of the final pieces of the printing [4, 5]. It should be highlighted that the impact of the variables of the operation on

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the physical characteristics of various polymers in 3D printing has been studied extensively. But there still exists a void to define the effect of the operational factors on such properties, especially in the interaction between machine parameters of the constituent polymers [6–8]. However, the low-cost approach of the 3D printer will still be a widely used method of part production by varying fill densities and patterns, as well as other factors such as extrusion temperature and actual printing travel speed [9]. Internal porosities in 3D-printed components necessarily undermine mechanical integrity of 3D-printed components, and a comprehensive study of how this occurs and how to prevent it is required. Such defects – such as inadequate binding between matrix and fibres and texture on the surface – greatly affect mechanical performance of printed elements [10–13]. To be more precise, the material that is actively used in FDM is acrylonitrile butadiene styrene due to its favorable mechanical and thermal characteristics. These have the potential to undergo severe stress and strain, along with great electrical performance, resistance to chemicals, ease of machining, and stability in size, despite the production of an unpleasant odour during printing [14–17]. There are many factors that greatly influence the performance of 3D printer such as environmental conditions, material characteristics, the arrangement of parts, support, and specific machining and working parameters [18–20]. All the above variables determine the quality, rigidity, reliability, and physical integrity of the finally printed part. A careful choice of suitable printing factors is of the essence to make sure that the intended and uniform physical behavior of 3D-printed parts as different characteristics (build orientation) might have a big effect on some of the characteristics (tensile strength, compressive strength, etc.). This research will explore how breaking strength of ABS samples is directly proportional to the changes in layer height (LH), infill percentage (IP) and infill pattern design (IPD). The systematic method of approach will entail important insights into how to best optimize the 3D Printer settings to obtain high-quality mechanical properties in the parts that were 3D printed to be used in different engineering functions. This research work seeks to carefully examine these important parameters, using a quality experimental design to measure the effect of each and combination of the factors on the durability of the manufactured parts.

MATERIALS AND EXPERIMENT

This section outlines the experiments and methodology used to explore the complex interactions among layer height, infill percentage and infill pattern on mechanical properties of ABS 3D printer printed parts. It describes the selection of materials, the design and fabrication of test specimens, mechanical characterization procedures of materials such as tensile, compressive and flexural testing. This holistic approach allows for a thorough investigation of the interaction of these important printing parameters and their impact on the structural integrity and performance of the printed products. The Taguchi design of experiments is a powerful technique used to model and analyze the interactions of the parameters of a machine process and the characteristics of the output of a particular objective function. Figure 1(a–c) shows the test sample fabricated using 3D printer for the measurement of mechanical properties. Research indicates that factors – such as Layer height, infill percentage, and infill pattern design – are the most significant factors for material extrusion-based 3D printers. Three process parameters were taken, each at two different levels as given in Table 1. The experimental design uses two levels and three factors, which was designed according to the Taguchi DOE principles described in Table 2 [21, 22] and was carried out using the software Minitab 16.0. The experimental procedure consisted of two main stages, the first being the fabrication of specimens and the second being tensile, compression and flexural tests. These tests were performed under the following ASTM test protocols: tensile (D638), compression (D695) and flexural test (D790) to ensure the comparability and robustness of the results [23–25]. The crosshead speed used for the determination of the testing results was 2 mm/min and the tensile strength, compression and flexural strength test measurements were carried out on a Tinius Olsen testing machine. The material chosen for this study was acrylonitrile Butadiene Styrene, due to its wide use in 3D printing and the desirable properties it possesses of mechanical strength, thermal stability and cost. Its amorphous structure and moderate glass transition temperature make it suitable for a wide range of engineering applications, where moderate strength and rigidity are required. All specimens were fabricated with a material extrusion-based 3D printer which was selected for its accuracy, reliability and widespread

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adoption. The printer is set up to use a 0.4 mm nozzle and 1.75 mm filament diameter to ensure that all the printed samples are uniform. ABS has a glass temperature of ~108°C and a recommended processing window of 215–255°C which are important factors to consider when talking about adhesion of layers and the quality of the printed object. These thermal properties are crucial for ensuring proper inter-layer adhesion, thereby influencing the mechanical strength and dimensional precision of the manufactured parts. To study the effect of each experimental factor and the interaction between the factors on the strength of the parts, Analysis of Variance, as one of the standard statistical methods, is used to interpret the results of the experiments conducted using the Taguchi method. The Taguchi parameter design approach optimizes a single response, which may lead to different optimal parameter settings for each quality trait in 3D printer. To overcome this, a grey relational grade method is used to simultaneously optimize multiple responses and obtain a single set of optimal 3D printer parameter levels for all responses. This process involves initial data processing of experimental results before calculating grey relational coefficients. In this study, the original data sequence was normalized using a "larger-the-better" characteristic approach by using Eq. (1), followed by the calculation of the grey relational coefficient by using Eq. (2), and subsequently the grey relational grade by using Eq. (3). The GRG is computed by equalizing the grey relational coefficients for each criterion response, assigning equal weight to all measured characteristics [26]. The parameter settings corresponding to the maximum GRG are identified as the optimal levels.

$$y_i^*(j) = \frac{y_i(j) - Min.\, y_i(j)}{Max. y_i(j) - Min. y_i(j)};\ i = 1,2,3,4 \dots\dots, n;\ j = 1,2,3,4, \dots\dots, m \tag{1}$$

$$\gamma\ (Y_0(k), Y_i(k)) = \frac{\Delta_{Min} + \zeta\Delta_{Max}}{\Delta_{0i}(k) + \zeta\Delta_{Max}};\ i = 1,2,3,4 \dots\dots, m;\ k = 1,2,3,4, \dots\dots, n \tag{2}$$

$$\gamma\ (Y_0, Y_i) = \sum_{k=1}^{n} W_k\, \gamma\ (Y_0, Y_i);\ i = 1,2,3,4 \dots\dots, m;\ k = 1,2,3,4, \dots\dots, n \tag{3}$$

where $y(j), y_i^*(k), Max.\, y(j)$ and $Min.\, y_i(j)$ represent original dataset, normalized quality characteristics, largest value and smallest value, ζ is distinguishing coefficient, $Y_0(k)$ is ideal normalized response, and W_k is weight percentage of total number of data observed.

Table 1. Factors & level for sample preparation

Factors and their level				
Factors for 3D printer	***Symbol***	***Level***		***Unit***
		1	2	
Layer Height	LH	0.1	0.2	mm
Infill Percentage	IP	15	25	%
Infill Pattern Design	IPD	Triangular	Honeycomb	–

Table 2. Taguchi design for different factors with their level for part fabrication.

S. N.	**Factors**		
	Layer height (LH)	***Infill percentage (IP)***	***Infill pattern design (IPD)***
1	1	1	1
2	2	1	1
3	1	2	1
4	2	2	1
5	1	1	2
6	2	1	2
7	1	2	2
8	2	2	2

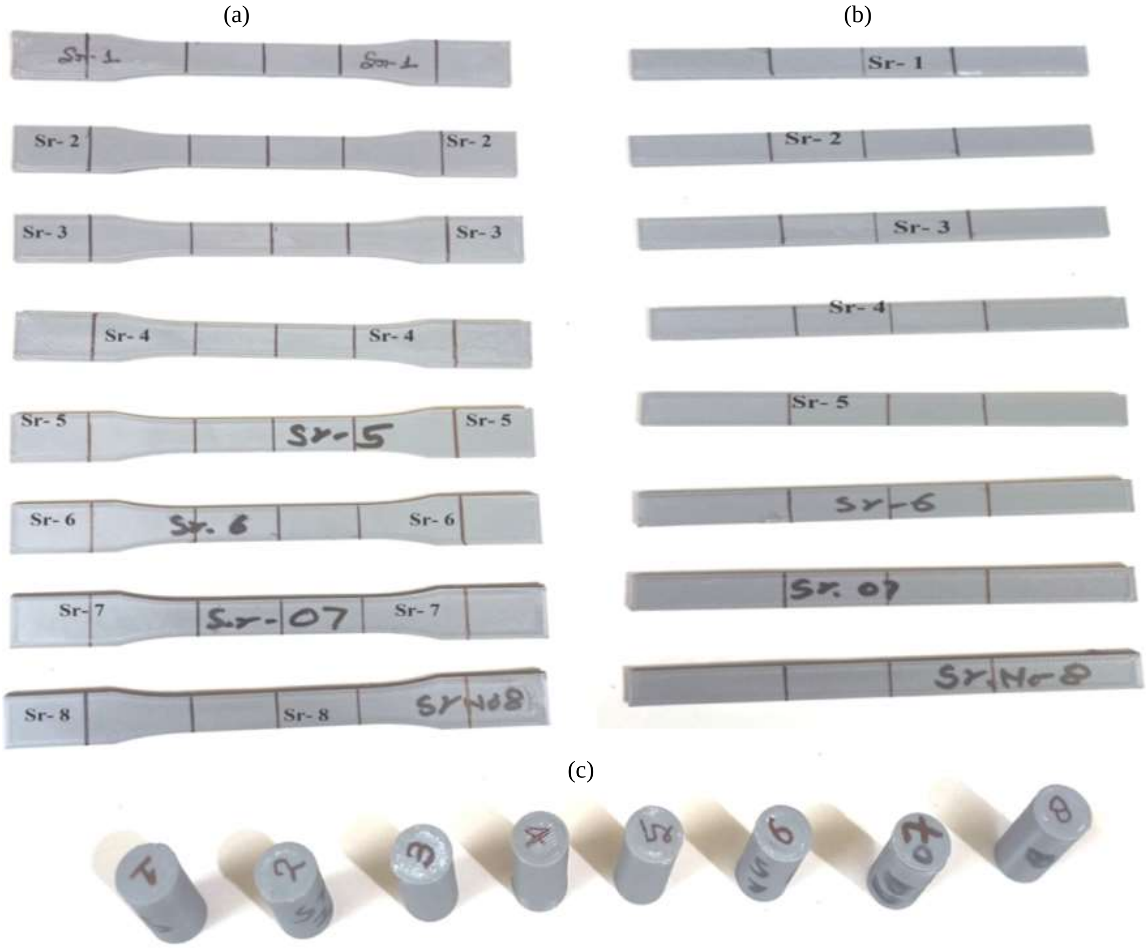

Figure 1. Sample for (a) Tensile, (b) Flexural, and (c) Compressive strength test fabricated using 3d printer.

RESULT & DISCUSSION

This section presents the findings from a comprehensive experimental investigation, analyzing the effects of varying layer height, infill percentage, and infill pattern design on the tensile, compression, and flexural strengths of printed ABS specimens. A key focus is placed on how alterations in layer height impact inter-layer bonding and the overall density and mechanical characteristics of ABS material printed components. Further, subsequent subsections will provide results for each mechanical test, supported by graphical representations and statistical analyses to highlight significant trends and observations. The mechanical properties of an object processed using an extrusion-based 3D printer are investigated through experimental analysis. A multi-response Taguchi parametric design decision matrix, incorporating measured data for compression, flexural, and tensile strength, is presented in Table 3. The Analysis of variance, results for tensile strength, compression strength, and flexural strength are detailed in Tables 4–6, respectively, and it is employed to identify significant process parameters and their interactions influencing the object's mechanical strength. Main effect graphs of the S/N ratio for the three mechanical properties are illustrated in Figure 2, and Table 7 outlines the optimal factor level settings for these properties. Non-uniform temperature gradients can lead to variations in object size, deformation, and inner-layer delaminating, ultimately impacting the object's mechanical properties. Careful selection of deposition time, print speed, and non-deposition time can mitigate uneven heating and cooling cycles that induce thermal gradients, thereby influencing the overall mechanical integrity. The rate of neck formation between adjacent layers tends to be greater in lower sections compared to upper ones. As specimen height increases, neck growth effectively closes inter-layer gaps in the lower regions, enhancing the mechanical performance of fabricated objects. Objects manufactured in a specific build platform region consistently

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exhibit superior surface finish and mechanical properties compared to those produced elsewhere. Based on the analysis presented in Table 7, the most significant factors influencing the tensile strength of the fabricated objects are layer height, infill percentage, and the interplay between layer height and infill percentage. Regarding compression strength, infill pattern design, layer height, and infill percentage emerge as the primary determinants. Furthermore, for flexural strength, layer height, infill density percentage, and infill pattern design exhibit the most substantial impact. To optimize multiple quality characteristics simultaneously, a multivariable approach was employed using Grey Relational Grade analysis. The grey relational grade for each targeted quality characteristic across various experimental runs was computed and is presented in Table 8. Subsequently, Table 9 displays the Analysis of Variance results for the grey relational grade of different characteristics. The analysis indicates that the influencing process parameters, in ascending order of their impact, are infill percentage, infill pattern design, and layer height. Main effect graph of means of mean for gray relational grade is shown in Figure 3. Figure 4 shows the SEM Image of 3D-printed test sample. SEM analysis shows that the interlayer bonding and formation of the voids are the main factors affecting the mechanical behavior of the fabricated specimens. These openings serve as main starting points of cracks, and hence they dictate failure characteristic of the material. Findings suggest that decreasing layer height in 3D printing generally correlates with improved tensile strength. This enhancement is attributed to better adhesion between layers and a reduction in voids within the deposited material. Studies on ABS samples indicate that increasing layer thickness from lower value of 100 micrometer to higher value of 200 micrometer can negatively impact tensile, flexural, and compressive strength. Conversely, thinner layers may yield higher material strength, potentially by minimizing inter-layer distortion. Ultimately, layer heights that surpass an optimal threshold tend to diminish mechanical performance by fostering larger internal voids and weakening layer adhesion. The infill percentage is a critical determinant of mechanical properties; higher infill densities generally correlate with superior tensile, flexural, and compressive strength because of a greater internal material volume. This increased material volume fosters a more robust internal structure, which aids in effective load distribution and reduces localized stress concentrations. Empirical evidence suggests that increasing the infill percentage creates a more continuous load path, thereby enhancing the strength and stability of 3D-printed components.

Moreover, a higher infill percentage improves a part's resistance to deformation under load, leading to enhanced dimensional stability and overall structural integrity. The mechanical characteristics of printed characteristics of components fabricated via additive manufacturing are notably affected by their internal design of infill patterns, such as honeycomb or triangular designs, which create distinct anisotropic characteristics. This influence stems from the alteration of load distribution pathways and the overall structural integrity of the printed object. Consequently, the selection of an infill pattern directly impacts tensile, flexural, and compressive strength by determining the internal material arrangement and bonding. Infill Patterns design – like the honeycomb – is often favored for their enhanced directional strength. The optimal settings for machine parameters that enhance multiple quality characteristics are those that yield the highest average gray relational grade.

Table 3. Measured data for tensile, compression and flexural strength test method.

S. N.	Machine process parameter					
	Layer thickness (LH)	***Infill percentage (IP)***	***Infill pattern design (IPD)***	***Tensile strength of 3D-printed ABS parts***	***Compression strength of 3D-printed ABS parts***	***Flexural strength of 3D-printed ABS parts***
1	1	1	1	22.21	35.26	24.642
2	2	1	1	14.41	27.93	17.217
3	1	2	1	21.71	40.75	28.559
4	2	2	1	18.98	32.48	22.936
5	1	1	2	22.91	36.79	41.465
6	2	1	2	16.23	30.71	34.080
7	1	2	2	22.52	41.93	48.573
8	2	2	2	21.97	36.2	40.161

Table 4. Measured ANOVA for tensile strength.

Source	DF	Seq SS	Adj SS	Adj MS	F	P	% of Contribution
LH	1	8.279	8.279	8.279	1951.1	0.014	51.54
IP	1	2.740	2.740	2.740	645.7	0.025	17.06
IPD	1	1.047	1.047	1.047	246.7	0.040	6.51
LH*IP	1	3.612	3.612	3.612	851.2	0.022	22.48
LH*IPD	1	0.367	0.367	0.367	86.6	0.068	2.28
IP*IPD	1	0.010	0.010	0.010	2.47	0.361	0.065
Residual Error	1	0.004	0.004	0.004			
Total	7	16.06					

Table 5. Measured ANOVA for compression strength.

Source	DF	Seq SS	Adj SS	Adj MS	F	P	% of Contribution
LH	1	8.766	8.766	8.766	52.3	0.087	13.56
IP	1	5.400	5.400	5.400	32.2	0.111	8.35
IPD	1	49.64	49.649	49.64	296.1	0.037	76.80
LH*IP	1	0.199	0.199	0.199	1.1	0.473	0.307
LH*IPD	1	0.345	0.345	0.345	2.0	0.387	0.535
IP*IPD	1	0.118	0.118	0.118	0.7	0.555	0.182
Residual Error	1	0.167	0.167	0.167			
Total	7	64.64					

Table 6. Measured ANOVA for flexural strength.

Source	DF	Seq SS	Adj SS	Adj MS	F	P	% of Contribution
LH	1	5.847	5.847	5.847	821.2	0.022	58.26
IP	1	3.292	3.292	3.292	462.3	0.030	32.80
IPD	1	0.709	0.709	0.709	99.6	0.064	7.07
LH*IP	1	0.015	0.015	0.015	2.1	0.384	0.149
LH*IPD	1	0.165	0.165	0.165	23.1	0.130	1.644
IP*IPD	1	0.001	0.009	0.009	0.00	0.991	0.009
Residual Error	1	0.007	0.007	0.007			
Total	7	10.03					

Table 7. Optimum level and significant parameter for mechanical properties.

Parameter	Levels			Significant parameter
	LH	*IP*	*IPD*	
Tensile strength	1	2	2	LH, LH*IPD, IP
Compressive strength	1	2	2	IPD, LH, IP
Flexural strength	1	2	2	LH, IP, IPD

Table 8. Grey relational coefficient for mechanical parameters & their integrated Grey relational grade (GRG).

S. N.	Layer height (LH)	Infill percentage (IP)	Infill pattern design (IPD)	Grey relational coefficient for compressive strength	Grey relational coefficient for flexural strength	Grey relational coefficient for tensile strength	Grey relational grade
1	1	1	1	0.396	0.512	0.859	0.589
2	2	1	1	0.333	0.333	0.333	0.333
3	1	2	1	0.439	0.855	0.779	0.691
4	2	2	1	0.379	0.425	0.519	0.441
5	1	1	2	0.688	0.576	1	0.754
6	2	1	2	0.519	0.384	0.388	0.430
7	1	2	2	1	1	0.917	0.972
8	2	2	2	0.650	0.549	0.819	0.673

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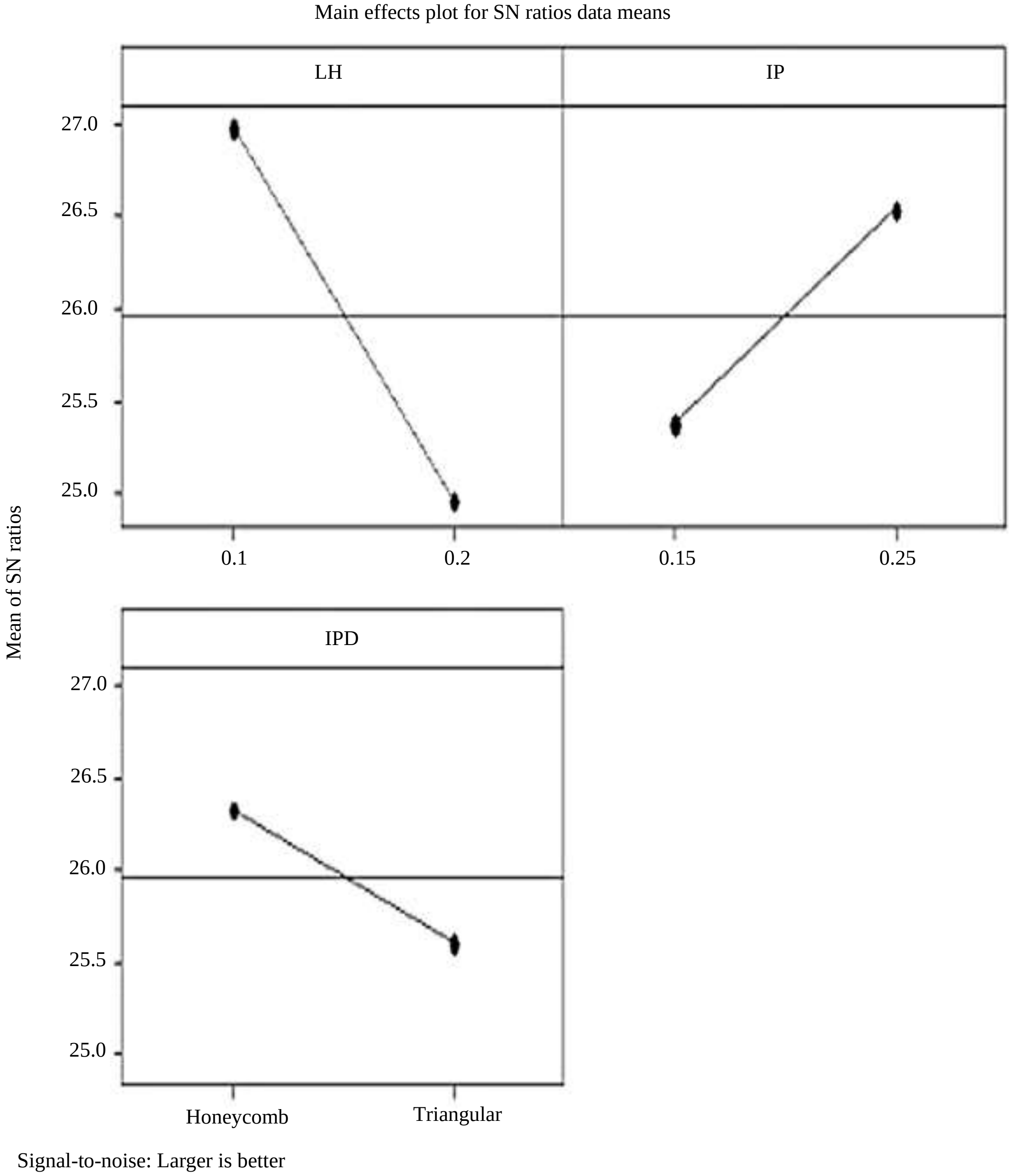
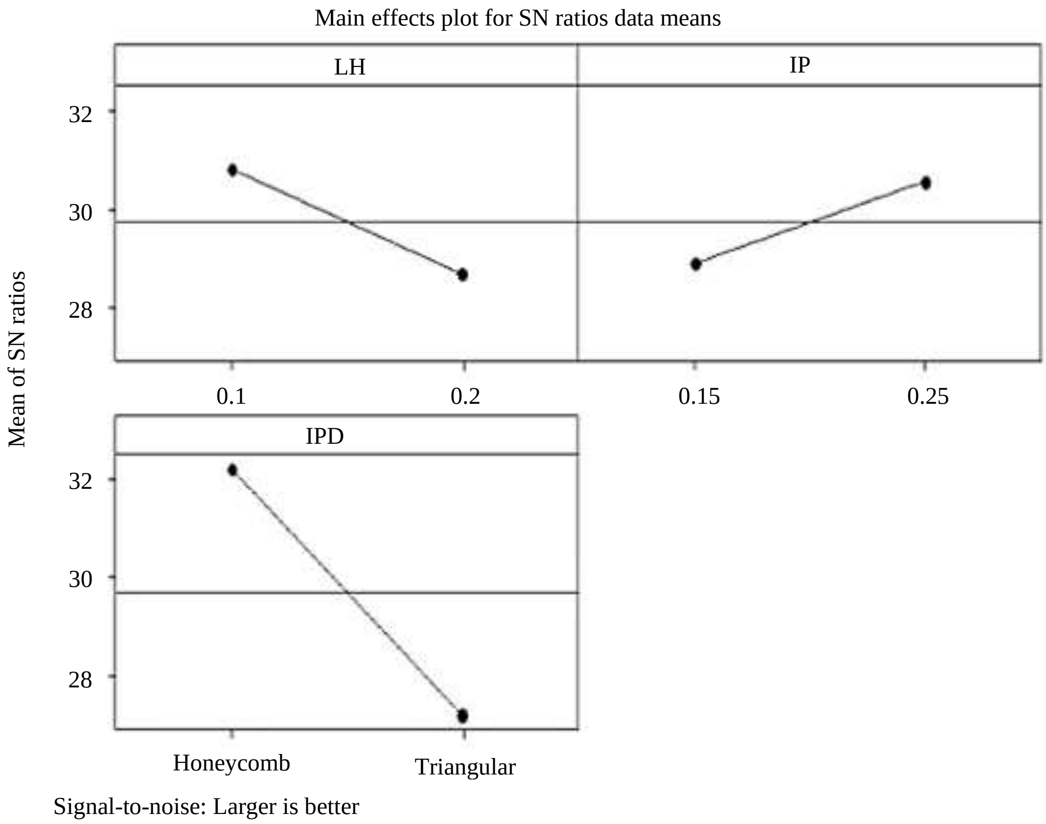
Table 9. ANOVA for grey relational grade.

Source	DF	Seq SS	Adj SS	Adj MS	F	P	% of Contribution
LH	1	0.15922	0.15922	0.15922	3436.5	0.011	53.0
IP	1	0.05623	0.05623	0.05623	1213.6	0.018	18.7
IPD	1	0.07526	0.07526	0.07526	1624.5	0.016	25.0
LH*IP	1	0.00012	0.00012	0.00012	2.5	0.356	0.039
LH*IPD	1	0.00172	0.00172	0.00172	37.1	0.103	0.573
IP*IPD	1	0.00775	0.00775	0.00775	167.4	0.049	2.5
Residual Error	1	0.00004	0.00004	0.00004			
Total	7	0.30036					



(a)



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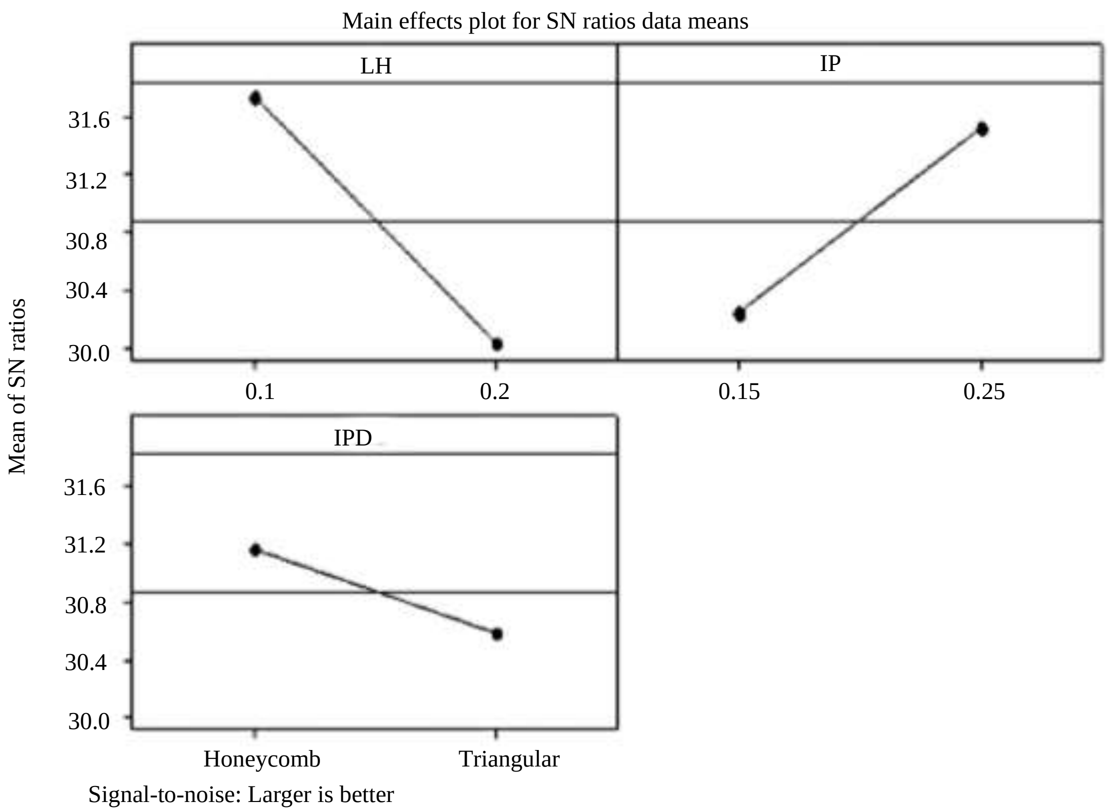

(c)

Figure 2. Main effect plot: (a) Tensile, (b) Compressive, and (c) Flexural strength test sample.

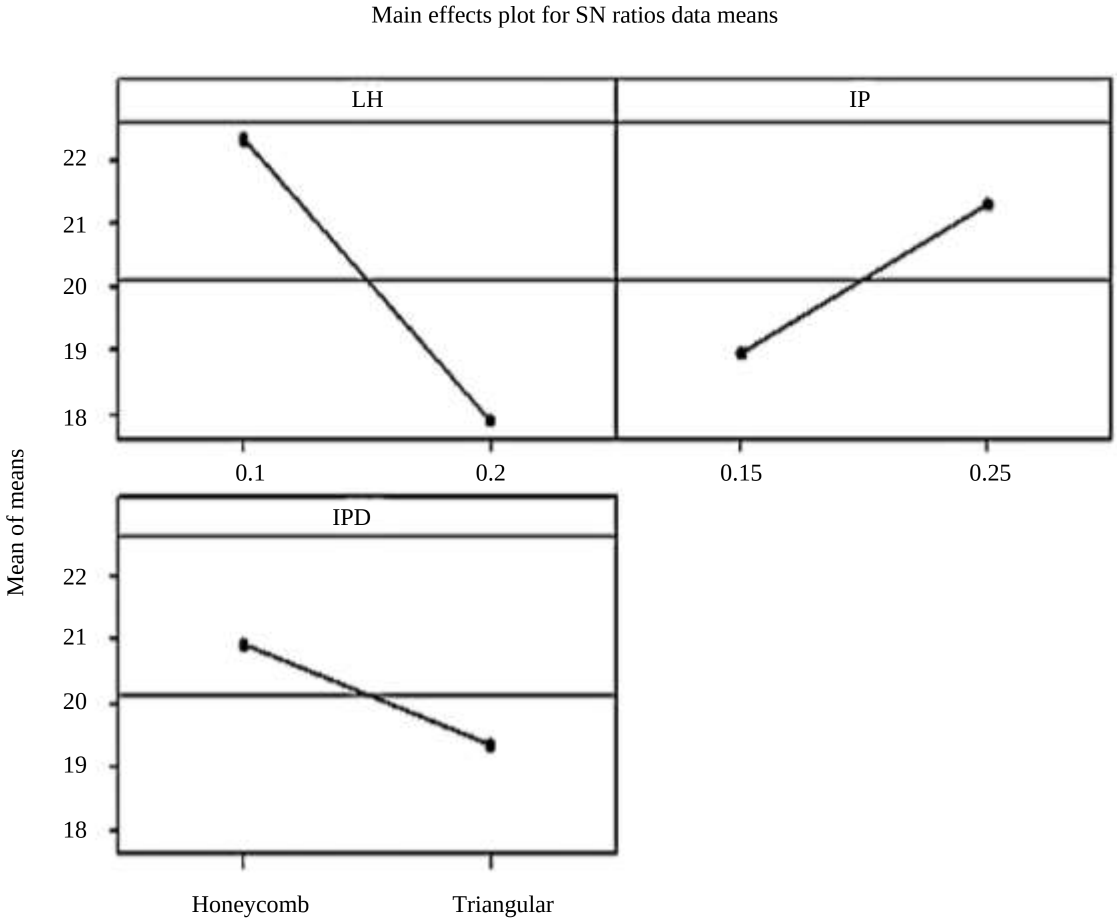

Figure 3. Main effect graph for grey relational grade (GRG).

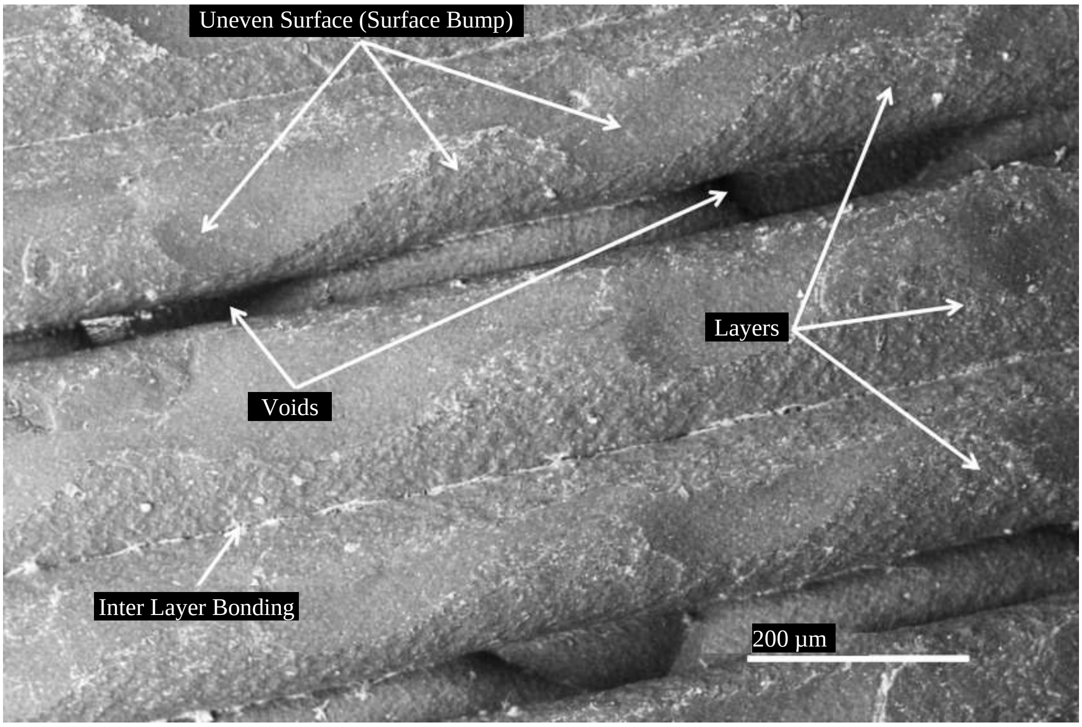

Figure 4. Scan electron microscopy image of 3D-printed test sample.

CONCLUSION

The mechanical characteristics of components fabricated via extrusion-based 3D printing were assessed through experimental investigation. A multi-response Taguchi parametric design matrix and analysis of variance were employed, utilizing measured data for compression, flexural, and tensile strength. The ANOVA revealed that for tensile strength, the most significant factors were layer height, infill percentage, and their interaction, with layer height contributing approximately 51%. For compression strength, infill pattern design, layer thickness, and infill percentage were the primary determinants, with infill pattern design accounting for roughly 76%. Regarding flexural strength, layer thickness (LH), infill percentage (IP), and infill pattern design (IPD) demonstrated the most substantial impact, with layer height and infill percentage contributing approximately 58% and 32%, respectively. To optimize multiple quality characteristics concurrently, a multivariable approach using Grey Relational Grade analysis was implemented. The GRG computed for each targeted quality characteristic across various experimental runs indicates that the influencing process parameters, in ascending order of impact, are infill percentage, infill pattern design, and layer height. The analysis suggests that optimizing factors – such as a 0.1 mm layer height, 25% infill percentage, and a honeycomb infill pattern design – will enhance the general mechanical capabilities of fabricated components.

Authors' Contribution

Shweta Mishra conceived and designed the study, analyzed the data, and wrote the manuscript. Dr. Mohd Anas supervised the research, provided guidance throughout the study, and critically reviewed the manuscript. All authors reviewed and approved the final version of the manuscript.

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Conflicts of Interests

There are no financial or non-financial conflicts of interest that could influence the interpretation of the research findings or bias the content of this manuscript.

Data Availability Statement

The data used in this study were obtained from various sources. The primary sources of data included Google Scholar for accessing academic literature, books related to additive manufacturing, and journals, and the college library for reference materials.

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