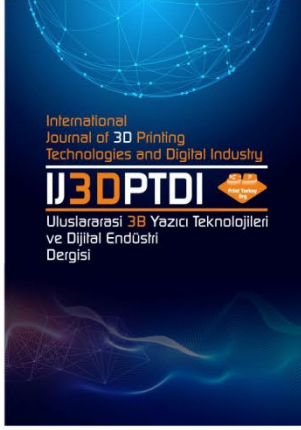




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EXPERIMENTAL AND STATISTICAL ANALYSIS OF THE EFFECT OF 3D PRINTING PARAMETERS ON MECHANICAL PERFORMANCE

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ABSTRACT

This study examines the influence of material type, layer height, and fill rate on the surface hardness, bending strength, and printing duration of specimens produced via Fused Deposition Modeling (FDM). Specimens made from PLA+ and ABS were fabricated using two distinct layer thicknesses (0.10 mm and 0.20 mm) and four varying fill rates (40%, 60%, 80%, and 100%). The mechanical properties of these specimens were assessed through three-point bending tests and Shore D hardness evaluations. The Taguchi optimization method was employed to identify optimal printing parameters that maximize bending strength and surface hardness while minimizing printing time. The findings revealed that PLA+ displayed superior bending strength compared to ABS, particularly at elevated infill densities. Furthermore, the fill rate predominantly affected the surface hardness, with higher densities correlating with improved hardness values. Statistical analysis conducted through ANOVA indicated that the material type significantly impacts bending strength, while the fill rate primarily influences surface hardness. In addition, the findings indicate that the print time is significantly affected by both material selection and filler density. The results obtained have been verified by producing control samples. According to the verification tests, the model was able to perform predictions with deviations changing between %3-16. This study highlights the essential trade-off between mechanical performance and production efficiency in 3D printing applications and suggests a different approach to optimizing manufacturing process parameters in order to improve part quality while reducing production costs.

Keywords: Fused Deposition Modeling, Bending Strength, Hardness, Taguchi Analysis.

1. INTRODUCTION

Additive Manufacturing (AM) is a manufacturing technique that, unlike traditional manufacturing methods, is based on the principle of layer-by-layer deposition of materials and allows complex three-dimensional (3D) structures to be produced with high precision and minimal material waste [1]. This technology has received a great deal of attention in recent years, especially due to its design flexibility, rapid prototyping and personalized production [2]. It is widely used in various industries such as aerospace, automotive, robotic systems, healthcare, consumer products and even architecture to produce lightweight and high-performance components [3-4].

Among additive manufacturing techniques, Fused Deposition Modeling (FDM) is one of the most widely preferred methods due to its low cost, ease of use and wide range of materials [5-6]. FDM is particularly suitable for thermoplastic materials such as polylactic acid (PLA) and acrylonitrile butadiene styrene (ABS) [7]. These materials are frequently preferred in industrial and academic studies due to their environmentally friendly properties and mechanical performance [8].

The FDM process is based on the principle of extruding a thermoplastic filament through a heated nozzle and depositing it layer by layer according to a predetermined pattern [9]. However, the mechanical performance of

components produced by this method is significantly affected by various parameters such as layer thickness, fill rate, build-up rate, print orientation, material composition and nozzle temperature [10-11]. Optimizing these parameters plays a critical role in improving the durability, surface quality and dimensional accuracy of the produced parts [12]. In the comparative optimization of the production parameters of ABS and PLA specimens, it was found that material type, fill rate and printing speed were effective on tensile strength and printing times [13]. In another study, it was reported that the bending and tensile strength of polyethylene terephthalate (PET) reinforced with PLA and thermoplastic polyurethane (TPU) decreased slightly compared to standard PET, but the impact strength increased significantly [14].

Popescu et al. [9] investigated the FDM process parameters that affect the mechanical properties through a literature review and reported that layer thickness, build-up rate and print orientation are critical factors. It was found that thin layer thickness and appropriate print orientation increased tensile and bending strength. Similarly, Sood et al. [15] performed ANOVA analysis on the experimental data by examining five basic process parameters (layer thickness, orientation, printing angle, printing width and air gap) and showed that layer thickness and printing angle are significant factors on tensile, bending and impact strength. Camargo et al. [16] found that layer thickness improves mechanical properties, but the fill parameter showed different results in different tests. It was observed that as the layer thickness increased, tensile and bending strength increased while impact energy decreased. Letcher et al. [17] Afrose et al. [18] investigated the effects of print orientation on fatigue strength and tensile strength, results showed that 45° orientation gave the best fatigue strength and tensile strength.

Signal-to-noise (S/N) ratio analysis by Taguchi method and analysis of variance (ANOVA) are widely used statistical techniques for optimization of experimental parameters and determination of their effects on mechanical

performance [19]. Travieso-Rodriguez et al. [20] investigated the effect of six different printing parameters (layer height, layer width, fill rate, layer orientation, print speed and fill pattern) on bending strength of PLA specimens using Taguchi and ANOVA and found that layer orientation is the most critical parameter. Zisopol et al. [21] performed experimental analyses to compare the mechanical performance of PLA and ABS materials and showed that PLA offers higher bending strength compared to ABS.

This study aims to investigate the effect on bending strength, surface hardness and printing time of PLA+ and ABS specimens printed by FDM for two different layer thicknesses and three different fill rates. In addition, using Taguchi optimization method, it is also aimed to determine the best parameters for the bending strength performance and surface hardness of ABS and PLA. In addition, printing time was added to the analysis to determine the optimum conditions for production costs.

2. MATERIALS AND METHODS

The specimens, investigated for bending strength and surface hardnesses within this study, were produced in additive manufacturing processes using a 3D printer (Creality K1) with Fused Deposition Modeling (FDM) method. The filament diameters are 1.75 mm and were produced with ESUN's PLA+ and ABS filaments. The infill pattern for all specimens is grid. The specimens were fabricated with four different fill rates (40%, 60%, 80% and 100%), two different layer thicknesses (0.10 mm and 0.20 mm) and two different materials (ABS, PLA). Specimen dimensions were selected according to ASTM D790 standard [22]. The dimensions of the specimen are presented in Figure 1. The CAD model of the specimen was created with the academic version of SOLIDWORKS software. Then, the model was saved in STL format, sliced with Creality Print Software and G-codes were generated. For fabrication, the printing parameters recommended by ESUN for Creality K1 were utilized [23]. The mechanical properties and printing parameters of the filament are given in Table 1.

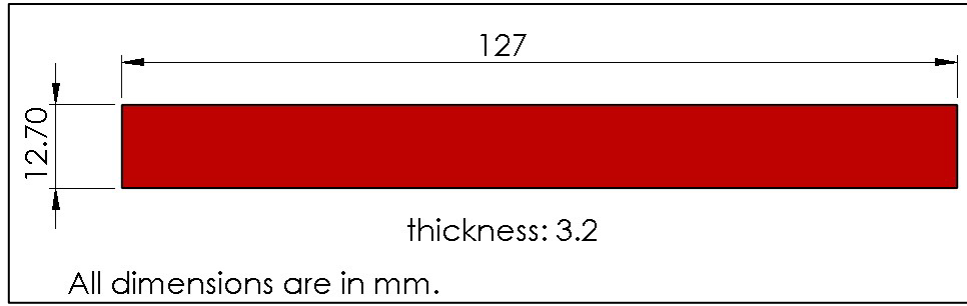


Figure 1. Bending specimen dimension according to ASTM 790 [22].

Table 1. Mechanical properties [24-25] and printing parameters [23] of ABS and PLA.

Material Type	Mechanical Properties		Printing Parameters	
ABS	Density	:1.04 g/cm ³	Printing Temperature	:240 °C
	Flexural Modulus	:1177 MPA	Heating Table Temperature	:105 °C
	Tensile Strength	:43 MPa	Printing Speed	:50 mm/s
	Bending Strength	:66 MPa		
	Elongation	:22 %		
PLA	Density	:1.23 g/cm ³	Printing Temperature	:220 °C
	Flexural Modulus	:1973 MPA	Heating Table Temperature	:60 °C
	Tensile Strength	:60 MPa	Printing Speed	:300 mm/s
	Bending Strength	:74 MPa		
	Elongation	:20 %		

In accordance with the aim of the study, Taguchi method was used for optimization of material type, layer thickness and fill rate according to bending strength, surface hardness and printing time. The Taguchi experimental design was performed according to L8 Taguchi's orthogonal array with Minitab software. The effect rates of input parameters on output parameters and the statistical significance of output parameters for the optimization model were determined by ANOVA. Taguchi L8 orthogonal array design given in Table 2. Where the input parameters are fill rate, layer height and material type. The output parameters are bending strength, surface hardness and printing time. The criteria used for Taguchi optimization are signal/noise (S/N) ratios [26]. The bending strength and surface hardness, which are the output parameters investigated in the study, were desired to be high and optimizations were made with the “larger is better” method. The related equation is given in Equation (1). The printing time is desired to be low to reduce production costs. For this, the optimization was done with the “smaller is better” method and the related equation is given in Equation (2).

$$S / N = -10 \log \left[\frac{1}{n} \left(\sum \frac{1}{y^2} \right) \right] \quad (1)$$

$$S / N = -10 \log \left[\frac{1}{n} \left(\sum Y^2 \right) \right] \quad (2)$$

Table 2. Taguchi L8 orthogonal array design.

RUNs	Material Type	Fill Rate (%)	Layer Height (mm)
RUN 1	ABS	40	0.10
RUN 2	PLA	40	0.20
RUN 3	ABS	60	0.10
RUN 4	PLA	60	0.20
RUN 5	ABS	80	0.20
RUN 6	PLA	80	0.10
RUN 7	ABS	100	0.20
RUN 8	PLA	100	0.10

Three specimens were produced from each specimen type. The production process is illustrated in Figure 2 (a) and the specimens are illustrated in Figure 2 (b). Hardness measurements were performed with a Shore D hardness gauge (Zwick R5LB041) by averaging the hardness values taken from five different points on the surface for each specimen. The hardness measuring gauge is presented in Figure 2 (c). The bending tests were then carried out in accordance with ASTM 790 using a UTEST UTM-0100AE model three-point bending machine at a speed of 5 mm/min [22]. The three-point bending machine and the test process are given in Figure 2 (d).



Figure 2. 3D printer used for specimen production (a), specimen fabrication (b), test specimens (c), shore D hardness gauge and measurement operation (d) and three-point bending test device and bending operation (e).

3. RESULTS AND DISCUSSION

3.1. Hardness

Figure 3 illustrates the Shore D hardness values achieved under varying production parameters. The results indicate the significant effects of infill density, material type, and layer thickness on hardness. The experimental data suggest that hardness values increase with elevated infill densities. The lowest recorded hardness value was 31.50 Shore D in RUN 2, while the highest was 85.50 Shore D in RUN 8. This trend indicates that the relationship between fill density and internal structural homogeneity directly reflects material hardness. Higher fill densities contribute to a more homogeneous and compact internal structure, thereby increasing the hardness of the material [27-28]. Similarly, in a study investigating the surface hardness of PLA samples produced at different fill rates, it

was found that an increase in the fill rate also increased the surface hardness [29]. In specimens with infill densities up to 60%, ABS exhibited superior hardness values compared to PLA. For example, RUN 3 demonstrated an ABS hardness of 52.81 Shore D, while RUN 4 showed a PLA hardness of 44.43 Shore D at the same infill density. However, when infill density surpassed 60%, PLA specimens exhibited higher hardness values. In RUN 6, the PLA specimen achieved a hardness of 77.57 Shore D. In contrast, the ABS specimen in RUN 5, featuring a similar infill density, recorded a hardness of 69.10 Shore D. This observation suggests that the inherent rigidity of PLA becomes increasingly pronounced at higher infill densities. Due to its superior molecular bonding characteristics, PLA typically exhibits a harder structure than ABS [30-31]. Portoacă

et al. [32] in their study comparing the wear performance of ABS and PLA, stated that PLA samples had higher surface hardness than ABS samples for the same filling ratios. This was explained by better surface quality and more homogeneous material accumulation. Additionally, specimens with reduced layer thickness displayed higher hardness values. Specifically, when comparing RUN 7 and RUN 8, the specimen with the thinner layer thickness (RUN 8) achieved a higher hardness value. Thinner layers facilitate uniform material deposition, enhancing hardness by minimizing internal voids and improving mechanical properties [33-34]. RUN 8, exhibiting the highest hardness value, underscores that a combination of 100% infill density and a layer thickness of 0.1 mm represents the optimal configuration for surface hardness.

Although these findings are consistent with some studies in literature, there are also some conflicting results. For example, some studies have reported a decrease in hardness when the filling ratio exceeds 75%. This can be explained by internal stresses caused by excessive pressure and micro voids that develop during cooling [35]. In the current study, all specimens were left on the printing plate until they reached room temperature. This prevented the formation of internal stress caused by heat changes.

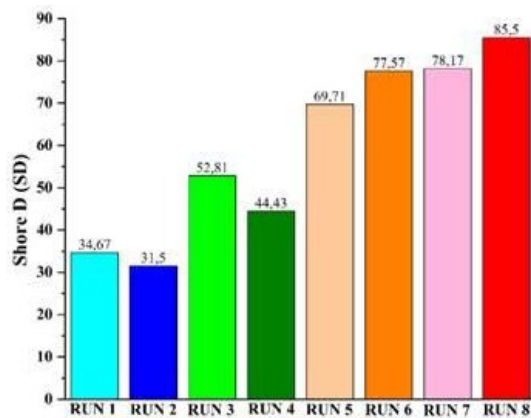


Figure 3. Shore D Hardness results for PLA and ABS materials considering different printing parameters.

3.2. Three-Point Bending Test

Force-displacement curves of bending specimens are given in Figure 4. ABS curves (Figure 4(a)) revealed that as the fill rate increased, the specimens were able to withstand larger forces and exhibited larger displacements. Notably, the bending strength of

ABS significantly increases with higher fill rates. The specimen with a 40% fill rate demonstrated the lowest performance, achieving a maximum force of 6 N, whereas the specimen with a 100% fill rate reached a maximum force of 27 N. This improvement can be attributed to the enhanced homogeneity of the internal structure, which allows for more uniform stress distribution as the fill rate escalates [36-37]. Figure 4 (b) displays the force-displacement curves for PLA specimens. PLA consistently exhibited a substantially higher bending strength compared to ABS. The PLA specimen with a 40% fill rate recorded a maximum force of 13 N, while the 100% fill rate specimen attained a maximum force of 57 N. This superior performance of PLA is largely due to its rigid molecular structure and enhanced interlayer bond strength [38]. Additionally, PLA's lower thermal shrinkage relative to ABS improves interlayer adhesion, thereby augmenting mechanical strength.

Current research supports these results. Zisopol et al. [21] noted that PLA exhibits higher bending strength than ABS, and that this difference is particularly pronounced at high filler ratios. In addition, Sudin et al. [39] reported that PLA has higher strength and stiffness values than ABS and nylon. These findings indicate that PLA is more resistant to bending loads due to its rigid structure, interlayer bond quality, and low internal void ratio. Azadi et al. [40] showed that PLA specimens outperformed ABS in high cycle bending fatigue tests, with PLA specimens exhibiting up to 11 times longer fatigue lifetimes at comparable stress levels. This was attributed to PLA's semi-crystalline structure and reduced interlayer voids, which also support our findings on its superior interlayer adhesion and rigidity. Similarly, Abeykoon et al., [41] demonstrated that optimized FDM parameters (100% infill density, 90 mm/s print speed, and 215°C nozzle temperature) maximized PLA's mechanical performance, with pure PLA achieving a flexural modulus 68% higher than ABS under identical printing conditions. Their SEM analysis further confirmed that PLA's superior interlayer adhesion and minimal porosity, linked to its linear infill pattern and optimal melt viscosity, contributed to its enhanced rigidity.

The advantages of PLA over ABS are particularly pronounced at higher fill rates for instance, whereas ABS reached 27 N at a 100% fill rate, PLA achieved 57 N, nearly double the strength of ABS.

Figure 4 (c) provides a comparative analysis of the bending strengths of both ABS and PLA specimens. PLA consistently exhibited higher bending strength at identical fill rates and layer thicknesses than ABS. For example, at a 40% fill rate, ABS recorded a maximum force of 6 N, while PLA reached 13 N. Similarly, at a 60% fill rate, ABS displayed 10 N, compared to PLA's 24 N. This disparity in performance can be attributed to the superior rigidity of PLA and its stronger interlayer bond strength [38]. The study's findings underscore that bending strength is significantly influenced by both the fill rate and the material type: higher fill rates yield increased strength for both ABS and PLA, with PLA outperforming ABS at every filling level. These results suggest that PLA is more suitable than ABS for applications necessitating high mechanical strength, highlighting the criticality of optimizing fill rates to attain maximum bending strength.

The analysis of printing times (Table 3) reveals that production duration increases with higher fill rates and layer thickness, particularly at elevated fill rates. For instance, a PLA specimen with a 40% fill rate (RUN 2) was produced in 4.5 minutes, while a 100% filled PLA specimen (RUN 8) required 12 minutes. In contrast, for ABS specimens, the RUN 1 specimen at a 40% fill rate took 21.5 minutes, compared to the RUN 7 specimen at a 100% fill rate, which was completed in 20.5 minutes. These findings indicate that while augmenting fill rates and layer thicknesses enhances the mechanical strength of the materials, it significantly extends production time. As such, finding a balance between mechanical performance and production efficiency is crucial. Although PLA and high fill rates offer benefits for applications demanding high strength, careful consideration must also be given to production time and cost, particularly in mass production or time-sensitive scenarios, where strategic selection of parameters such as fill rate and layer thickness is essential for optimizing both mechanical performance and production efficiency.

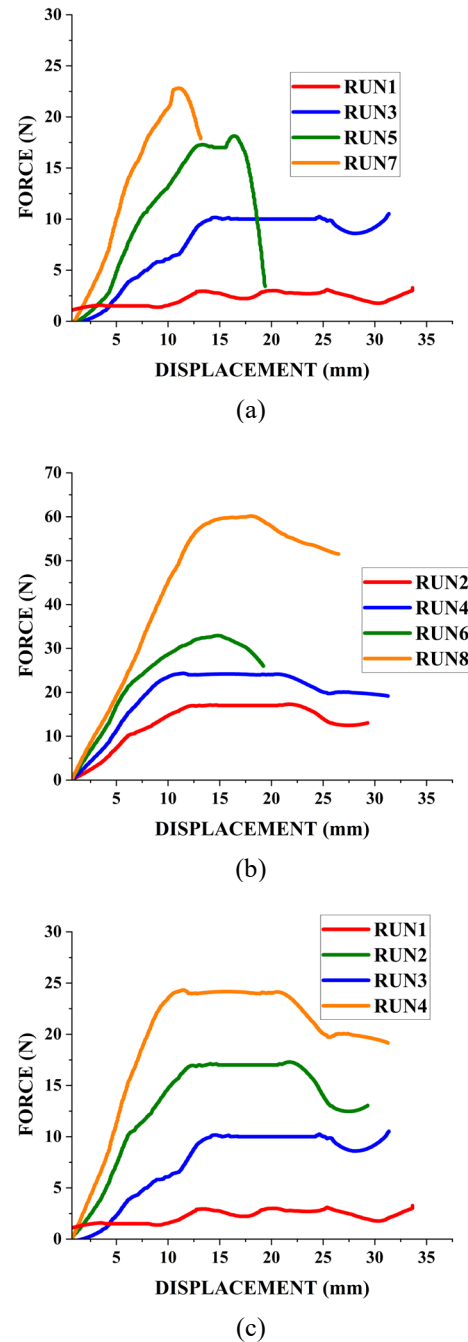


Figure 4. Force-Displacement Curves for ABS (a), PLA (b), and ABS vs. PLA (c) under Three-Point Bending Test

3.3. Statistical Results and Optimization with Taguchi

In this section, the results obtained by analyzing the experimental data with Taguchi and ANOVA were evaluated. All statistical analyses were performed for 95% confidence interval ($p < 0.05$). Table 3 shows the experimental results. The model data and ANOVA results generated as a consequence of the analyses are presented in Table 4.

Accordingly, the R^2 of the model has values above 96%. This is an indication that the model could explain the results with great accuracy. The ANOVA results revealed that material type was found to be significant ($p < 0.05$) for maximum force change. The effect of material type on the maximum force change was calculated as 43.05%. Similarly, Prajapati et al. reported that material type has an effect on bending strength [42]. The effects of fill rate and layer height on maximum force were found to be insignificant ($p > 0.05$). Although the effect of fill rate on maximum force was found to be insignificant, the experimental results demonstrate that fill rate has an effect on

maximum force. The regression equation expressing the change in maximum force is given in equation (3).

$$\begin{aligned} \text{Max Force} = & 24.84 - \\ & 14.75 \times (\%40 \text{ Fill Rate}) - \\ & 6.09 \times (\%60 \text{ Fill Rate}) + \\ & 2.49 \times (\%80 \text{ Fill Rate}) + \\ & 18.34 \times (\%100 \text{ Fill Rate}) - \\ & 11.40 \times (\text{ABS Material Type}) + \\ & 11.40 \times (\text{PLA Material Type}) + \\ & 3.50 \times (0.1 \text{ mm Layer Height}) - \\ & 3.50 \times (0.2 \text{ mm Layer Height}) \end{aligned} \quad (3)$$

Table 3. Experimental results.

Specimen No	Fill Rate (%)	Material Type	Layer Height (mm)	Maximum Force (N)	SEM	Hardness (SD)	SEM	Printing Time (min)
RUN 1	40	ABS	0.1	3.08±0.17	0.09	37.67±2.17	1.25	21.5
RUN 2	40	PLA	0.2	17.11±2.11	1.22	31.50±2.14	1.24	4.5
RUN 3	60	ABS	0.1	9.98±0.98	0.57	52.81±4.42	2.55	28.5
RUN 4	60	PLA	0.2	27.53±3.57	2.06	44.43±3.32	1.92	5.5
RUN 5	80	ABS	0.2	16.89±2.78	1.61	69.10±4.69	2.71	18
RUN 6	80	PLA	0.1	37.78±4.11	2.37	77.57±5.98	2.95	10.5
RUN 7	100	ABS	0.2	23.82±3.56	2.06	78.17±5.73	3.31	20.5
RUN 8	100	PLA	0.1	62.54±5.78	3.34	85.50±6.24	3.60	12

The effective parameters on hardness were found to be fill rate and layer height. The effect of fill rate on hardness was calculated as 96.70% and the effect of layer height as 3%. Here, the great effect of fill rate on hardness change was remarkable. Material type was found to have no effect on the hardness change. The regression equation for hardness is given in equation (4). In support of the results, Varma et al. found that fill rate and layer height have an effect on hardness change [43]. Printing time is affected by the material type. The recommended production speed of ABS is considerably lower than PLA. This is the reason for this difference. The related regression equation is given in equation (5).

$$\begin{aligned} \text{Hardness} = & 59.22 - \\ & 26.13 \times (\%40 \text{ Fill Rate}) - \\ & 10.60 \times (\%60 \text{ Fill Rate}) + \\ & 14.12 \times (\%80 \text{ Fill Rate}) + \\ & 22.62 \times (\%100 \text{ Fill Rate}) - \\ & 0.53 \times (\text{ABS Material Type}) + \\ & 0.53 \times (\text{PLA Material Type}) + \\ & 3.42 \times (0.1 \text{ mm Layer Height}) - \\ & 3.42 \times (0.2 \text{ mm Layer Height}) \end{aligned} \quad (4)$$

$$\begin{aligned} \text{Printing Time} = & 15.13 - \\ & 2.12 \times (\%40 \text{ Fill Rate}) + \\ & 1.88 \times (\%60 \text{ Fill Rate}) - \\ & 0.88 \times (\%80 \text{ Fill Rate}) + \\ & 1.12 \times (\%100 \text{ Fill Rate}) + \\ & 7 \times (\text{ABS Material Type}) - \\ & 7 \times (\text{PLA Material Type}) + \\ & 3 \times (0.1 \text{ mm Layer Height}) - \\ & 3 \times (0.2 \text{ mm Layer Height}) \end{aligned} \quad (5)$$

Table 4. Model summary and ANOVA results.

Model Summary					
	S	R ²	Adj. R ²		
Maximum Force (N)	6.43	96.58%	88.03%		
Hardness (SD)	1.89	99.77%	99.20%		
Printing Time (min)	2.15	98.13%	93.44%		
ANOVA Results					
	Source	DF	Contribution	F-Value	P-Value
Maximum Force (N)	Fill Rate	3	49.46%	9.64	0.095
	Material Type	1	43.05%	25.18	0.038
	Layer Height	1	4.07%	2.38	0.263
	Error	2	3.42%		
	Total	7	100%		
Hardness (SD)	Fill Rate	3	96.70%	282.40	0.004
	Material Type	1	0.07%	0.64	0.509
	Layer Height	1	3.00%	26.30	0.036
	Error	2	0.23%		
	Total	7	100%		
Printing Time (min)	Fill Rate	3	4.08%	1.45	0.433
	Material Type	1	79.45%	84.76	0.012
	Layer Height	1	14.59%	15.57	0.059
	Error	2	1.87%		
	Total	7	100%		

Figure 5 presents the SN ratios of the output parameters. According to the maximum force results (Figure 5 (a)), the maximum force increases with an increase in fill rate. With the increase in fill rate, the gaps between the layers of the specimens are filled and the material could exhibit properties closer to homogeneous [44]. Similarly, in the study where bending tests were applied to PLA specimens with different fill rates, it was found that the fill rate was the most effective parameter in bending strength [45]. In addition, PLA specimens have higher maximum force values than ABS specimens. Prajapati et al. reported that PLA was superior to ABS in terms of bending strength [38]. Layer height changes are not effective in the maximum force change, supporting the ANOVA results. When Figure 5 (b) is examined, again as in maximum force, there is an increase in surface hardness with an increase in fill rate. Şirin et al. also indicated in their study on PLA specimens that an increase in fill

rate leads to an increase in surface hardness [28]. The hardness increase is linearly increasing up to 80% fill rate. At 100% fill rates, there is a decrease in the amount of increase. Considering that increases in fill rates are accompanied by increases in production costs, it may indicate that 80% fill rate may provide sufficient surface hardnesses in applications produced with 3D manufacturing methods and where high surface hardness is required. The results indicated that material type had no significant effect on hardness change. It was found that the surface hardness decreased slightly with increasing layer height. As the layer height decreases, the number of layers increases and the micro gaps between the layers decrease and harder structures could be obtained [43]. According to Figure 5(c), decreasing the fill rate and increasing the layer height have the effect of decreasing the printing time. In addition, preferring PLA as material type also decreases the printing time.

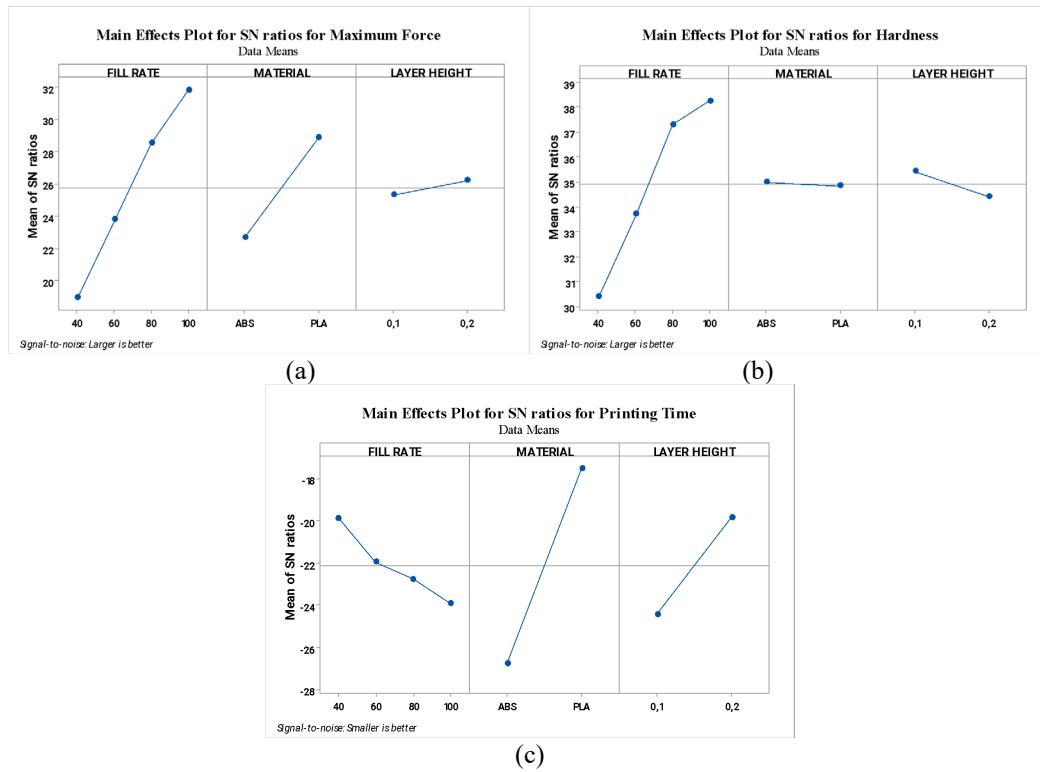


Figure 5. SN ratios of maximum force (a), hardness (b) and printing time (c)

Table 5. Regression and experimental results for control specimens.

Specimen Name	Control 1			Control 2		
	Regression Equation Results	Experimental Results	Error Rate (%)	Regression Equation Results	Experimental Results	Error Rate (%)
Max. Force (N)	51.08	59.13±3.42	13.61	35.48	34.45±1.63	-2.99
Hardness (SD)	78.95	75.67±1.31	-4.33	84.73	73.21±0.55	-15.74
Printing Time (min)	6.25	7	10.71	26.25	29	9.48

Control samples were fabricated to validate the established model. Three Control 1 specimens with 100% fill ratio and 0.2 mm layer thickness were fabricated for PLA. The purpose of selecting this specimen configuration is to compare it with the RUN 8 specimen, which yielded the best results, in order to reveal the effect of layer thickness changes on the results. For ABS, three specimens were produced from the Control 2 specimen with a layer thickness of 0.1 mm at 100% fill rate. The purpose of selecting this sample configuration for the verification tests is to obtain the best performance for ABS based on statistical analysis results. Hardness measurements were taken from at least five different points for each sample type, and bending tests were performed. In addition, estimated results were calculated using regression equations. The experimental data obtained and the values calculated using the regression equation are given in Table 5. According to this, the maximum force for

sample Control 1 was calculated as 51.08 N, while the experimental results were found to be 59.13 N. The hardness value was 78.95 SD according to the statistical model and 75.67 SD according to the experimental results. The error rate for maximum force was approximately 13.61%, while for hardness it was 4.33%. The model was able to predict the printing time with an error of 10.71% at 6.25 minutes. Additionally, the Control 1 specimens exhibited lower maximum force and hardness compared to RUN 8. These results confirm that a decrease in layer thickness increases maximum force and hardness.

For Control 2 specimens, the maximum force results were calculated as 35.48 N. In experimental tests, this value was found to be 34.45 N. The performance of the statistical model for maximum force was quite good, with an error rate of approximately 2.99%. Similarly, the model estimated the hardness of the Control 2 sample with an error rate of 15.74% and the

printing time with an error rate of 9.48%. Consistent with the Taguchi analysis, the highest maximum force and hardness values were obtained with these specimens.

According to Taguchi analyses, for applications where high strength and high surface hardness are required, parts made of PLA with a fill rate of 80% and above are preferable. However, the low deformation onset temperatures [13] limit the use of PLA, especially in applications with operating temperatures above 60 °C. ABS could be preferred for applications at higher temperatures. Although an increase in fill rate and decrease in layer height increases bending strength and surface hardness, it also increases production times and costs. For applications where strength and surface hardness are not important, lower fill rates and thicker layer heights may be preferred. Additionally, a positive correlation was observed between surface hardness and bending strength, particularly at higher infill densities. Specimens with increased hardness values generally exhibited enhanced bending resistance, suggesting that a denser internal structure and improved interlayer bonding not only enhance surface properties but also contribute significantly to overall mechanical performance. There are studies that confirm the results obtained. Turaka et al. [46] compared the mechanical properties of ABS and composite-reinforced ABS samples produced at different fill rates and optimized them with Taguchi. According to the results obtained, the best bending strengths were observed in samples with fill rates of 60% and above. Another study stated that changes in layer height affect bending strength and that a decrease in layer height increases bending strength [47].

4. CONCLUSION

This study examined the effects of material type, layer height, and fill rate on surface hardness, bending strength, and printing time for FDM-printed PLA+ and ABS specimens. The Taguchi optimization method was utilized to ascertain the optimal parameters that enhance mechanical performance and production efficiency. Based on the experimental results and subsequent statistical analyses, the following conclusions were drawn:

- Surface hardness for both PLA and ABS specimens significantly increased with elevated fill rates. The maximum hardness value of 85.50 Shore D was attained with PLA at a 100% fill rate and a layer thickness of 0.10 mm.
- In bending strength, PLA demonstrated superior performance to ABS across all fill rates and layer thicknesses. For instance, at a 100% fill rate, PLA achieved a maximum force of 57 N, nearly double that of ABS, recorded at 27 N.
- Layer thickness significantly influenced surface hardness, with thinner layers (0.10 mm) correlating with higher hardness values.
- The fill rate emerged as the most potent parameter affecting bending strength, with increased fill rates resulting in heightened strength for both materials.
- It was observed that printing time increased with higher fill rates and reduced layer heights. For example, a PLA specimen with a 100% fill rate and a layer height of 0.10 mm required 12 minutes to print, in contrast to 4.5 minutes for a specimen with a 40% fill rate and a layer height of 0.20 mm.
- Statistical analysis employing ANOVA revealed that material type exerted the most substantial effect on bending strength, contributing 43.05%, while fill rate had the greatest influence on surface hardness, contributing 96.70%. Although less impactful, layer height still had a notable effect on hardness, contributing 3%.
- The results from the Taguchi optimization suggest that for applications necessitating high strength and surface hardness, PLA with a fill rate of 80% or higher and a layer thickness of 0.10 mm is deemed optimal.
- Validation tests demonstrated that the optimization model could generate estimates with deviations of between 3% and 16%.

Future research could expand on this study by exploring the influence of alternative infill patterns, such as honeycomb or gyroid, to yield valuable insights into strength, surface hardness, and printing efficiency. Finally, assessing high-temperature behavior and impact resistance would provide a more comprehensive understanding of the industrial applicability of PLA and ABS materials.

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