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ENHANCING MECHANICAL PROPERTIES OF FDM-PRINTED NYLON THROUGH ANNEALING HEAT TREATMENT AND PROCESS PARAMETER OPTIMIZATION

This study evaluates the effects of fused deposition modeling (FDM) parameters and annealing on the mechanical properties of 3D-printed nylon. Parameters examined include layer height, wall line count, nozzle temperature, and printing speed. Mechanical tests, tensile, impact, and flexural – were conducted on ASTM-standard specimens using a Taguchi L9 orthogonal array. Layer height had the most influence on tensile and flexural strength, while wall line counts impacted impact strength. The highest tensile strength before annealing was 25.42 MPa, and 25.139 MPa after annealing at 150°C for 91 minutes. Maximum flexural strength (71.91 MPa) and impact strength (16 J) were recorded at optimized parameter settings. Analysis of Variance (ANOVA) showed layer height (51.63%) as the most significant post-annealing, and printing speed (36.63%) before annealing. Scanning electron microscope (SEM) analysis revealed improved layer bonding and reduced voids in annealed samples. Unannealed samples showed brittle fractures and poor fusion. The study confirms the importance of process optimization and thermal treatment in improving nylon part performance.

Keywords: Annealing; ANOVA; Fused Deposition Modelling; Mechanical properties; Nylon

1. Introduction

The Additive Manufacturing (AM), commonly referred to as 3D printing, has become an essential tool in modern fabrication, especially due to its versatility, material efficiency, and ability to translate digital models directly into physical parts. Among the many AM technologies, Fused Deposition Modelling (FDM) stands out for its accessibility and adaptability to a wide range of thermoplastics shown in Fig. 1. FDM creates parts layer by layer by extruding heated filament, which solidifies upon deposition. Despite its advantages – such as rapid prototyping, design flexibility, and minimal waste – FDM parts often fall short in mechanical performance. This is mainly due to weak bonding between layers, anisotropic properties, internal voids, and surface roughness [1,2]. To address these challenges, numerous studies have explored the effects of FDM process parameters on mechanical strength, especially for nylon-based materials. For instance, Ramesh and Panneerselvam [3] found that lower layer heights and higher infill densities significantly boosted tensile and flexural strength, with 100% infill and a 0.1 mm layer height yielding a maximum tensile strength of 43.5 MPa. Their ANOVA results highlighted infill density as the most influential factor.

Vishwas et al. [4] optimized FDM parameters for nylon using a Taguchi L9 array, achieving a peak tensile strength of 25.48 MPa at 0.1 mm layer thickness, 1.2 mm shell thickness, and a 30° orientation – highlighting the role of part orientation in interlayer bonding. Dairabayeva et al. [5] reported a flexural strength of 75.6 MPa using a gyroid infill, 0.1 mm layer thickness, and a 250°C nozzle, with layer thickness contributing 42.73% to performance variation. Terekhina et al. [6] found that infill densities above 60% significantly boosted tensile strength. Mostafa et al. [7] demonstrated a strength-to-cost advantage at 10% infill using optimized shell and contour strategies. Yankin et al. [8] emphasized the role of nozzle diameter and tri-hexagonal infill geometry on fatigue behavior, while Moradi et al. [9] showed that thinner layers and more contours improved strength and elongation, though with longer print times. Kim et al. [10] improved tensile properties in CFRP-nylon by aligning tool paths with stress, and Alzyod et al. [11]

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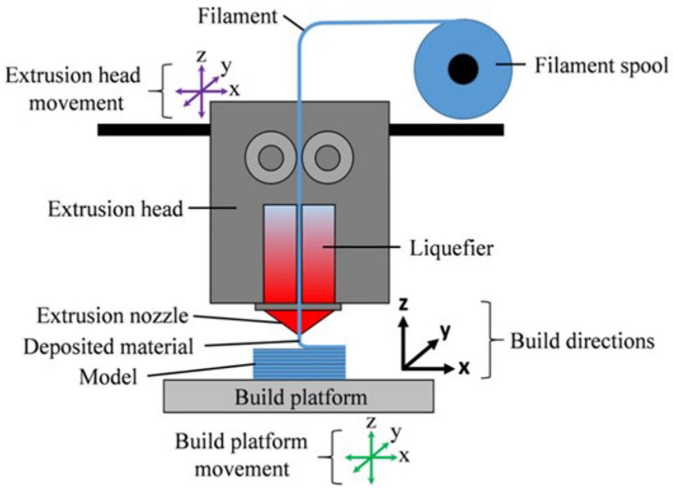

Fig. 1. Key components FDM printer

minimized warpage in PA12 with 0.2 mm layers and a 100°C bed. Engkvist et al. [12] noted that infill pattern and density strongly affect compressive strength, while Yankin et al. [13] achieved 58 MPa tensile strength in PA6 using full infill and octet patterns. Wickramasinghe et al. [14] showed that 5 wt.% carbon fiber reinforcement enhanced both tensile and flexural strength at 0° raster and 0.1 mm layers. Annealing was shown by Babatope and Isaac [15] to improve yield stress (~70 MPa) and modulus (~1.8 GPa) in nylon-6,6 at 150°C, though performance declined at 200°C. Hameed et al. [16] reported ASA samples with 51.86 MPa tensile and 82.56 MPa flexural strength using low layers, high infill, and optimal raster angles.

This study is aimed to optimize FDM process parameters and annealing to enhance the mechanical properties of Ultimaker Transparent Nylon, valued for its crystallinity, durability, and resistance to wear and chemicals. A Taguchi L9 orthogonal array was used to vary print speed, nozzle temperature, wall line count, and layer height. All samples were annealed at 150°C for 91 minutes and tested for tensile, flexural, and impact strength. SEM analysis was performed to assess micro structural changes. The results highlight the importance of both printing and thermal treatment in improving nylon's mechanical performance.

2. Materials and methodology

The material used in this study was Ultimaker Transparent Nylon, known for its extended shelf life, and high durability. It exhibits a low coefficient of friction along with excellent impact, abrasion, and chemical resistance against organic compounds and alkalis. With a filament diameter of 2.85 mm, this material is widely used for industrial modelling, tooling, functional prototypes, and final products. Its strong mechanical properties make it ideal for engineering applications requiring high strength and wear resistance.

2.1. Experimental procedure

This study was carried out in many phases, as seen Fig. 2 in Methodology steps first, modelling the specimens and chosen the material and equipment selection and select the printing parameters. Taguchi's L9 orthogonal array was selected for the experiment's design. Using Solid Works 2021, a computer-aided design (CAD) program, the testing specimen was created. Its surface geometry was then defined by converting it into a stereolithography (STL) format file. Using the Ultimaker Cura 5.4.0 program, the model was sliced and converted to G-Code format. The Ultimaker S3 FDM printer was used to create the

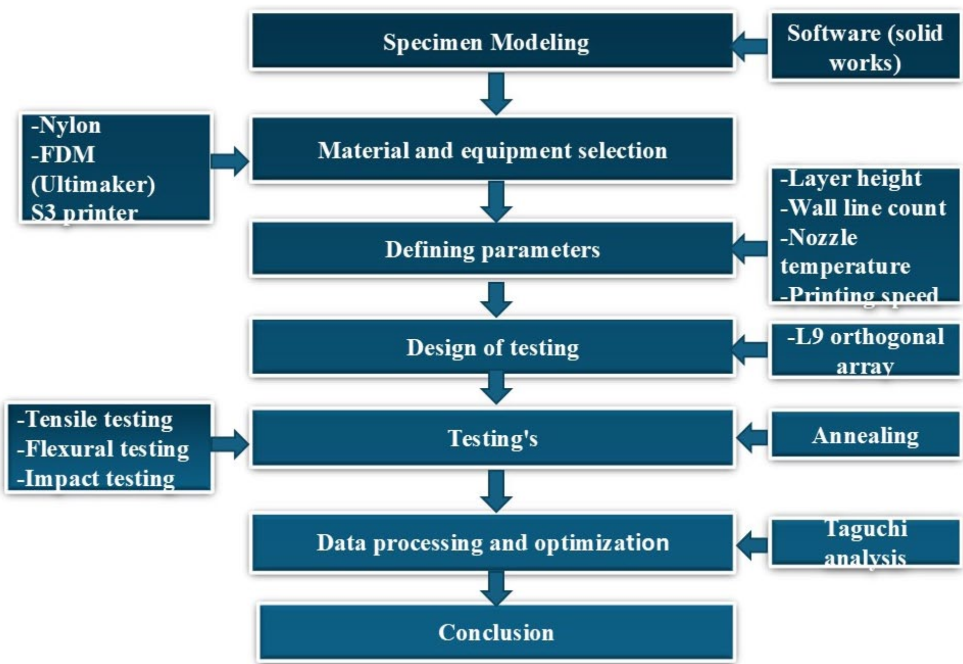

Fig. 2. Methodology steps

specimens. The models were fabricated in Solid Works software (2021), and exported as a STL file.

2.2. Process parameters

This study is focused type of thermoplastics for FDM printing such as (Nylon). According to the literature review, four parameters and at three levels was chosen are shown in TABLE 1. The specimens were printed using Ultimaker S3, the desktop printer capable of dual extrusion. Ultimaker Cura 4.11.0 software was used to set each experimental run based on the Taguchi array. To study the tensile, flexural and impact behaviour of the FDM printed parts: Layer height, wall line count, nozzle temperature and printing speed.

TABLE 1

Printing parameters

Parameters	Units	Symbols	Level 1	Level 2	Level 3
Layer height	33	A	0.1	0.2	0.3
Wall line count	—	B	2	3	4
Nozzle temperature	°C	C	240	250	260
Printing speed	mm/s	D	35	45	65

2.3. The design of experiments

The Taguchi L9 Orthogonal Array was selected for this study to optimize the mechanical properties of 3D-printed Nylon specimens while minimizing the number of experimental runs. With four parameters – layer height, wall line count, printing speed, and nozzle temperature each at three levels, the L9 design ensures a balanced distribution of factor levels, allowing for an independent evaluation of their effects on the response variables. This approach significantly reduces experimental time and cost, requiring only 9 runs (27 specimens) instead of 81 runs (243 specimens) for a full factorial design. The Taguchi analysis was performed using Minitab Statistical Software Version 21.1.0. Tensile samples were printed to compare for annealing and without annealing tensile results as per The L9 orthogonal array table are shown in TABLE 2.

2.4. Annealing behavior and condition

Nine tensile specimens were annealed using a Rapid infrared annealing (RIA) Instruments hot air oven with precise Proportional-Integral-Derivative (PID) temperature control and uniform air circulation. The process began with heating the specimens from 30°C to 150°C over 30 minutes. They were then held at 150°C for 91 minutes to allow the semi-crystalline nylon to restructure into a more crystalline form. This enhanced tensile strength, stiffness, and dimensional stability. After the holding stage, gradual cooling to room temperature ensured uniform stress relief. This controlled annealing process improved interlayer bonding and overall mechanical performance.

TABLE 2

L9 Orthogonal Array with parameters

Exp. No	Layer height (mm)	Wall line count	Nozzle temperature (°C)	Printing speed (mm/s)
1	0.1	2	240	35
2	0.1	3	250	45
3	0.1	4	260	65
4	0.2	2	250	65
5	0.2	3	260	35
6	0.2	4	240	45
7	0.3	2	260	45
8	0.3	3	240	65
9	0.3	4	250	35

2.5. Specimens design and evaluation nethod

For evaluating the mechanical properties of 3D-printed Nylon, the specimens for the tensile test, flexural test, and impact test were prepared in accordance with ASTM standards.

2.5.1. Tensile tests

Tensile testing was conducted on 3D-printed nylon specimens prepared as per ASTM D638 Type-1 shown in Fig. 3, using a universal testing machine (Model M-50) with a 5 mm/min crosshead speed and 50 kN. load capacity. A total of 18 samples were tested under ambient conditions until fracture.

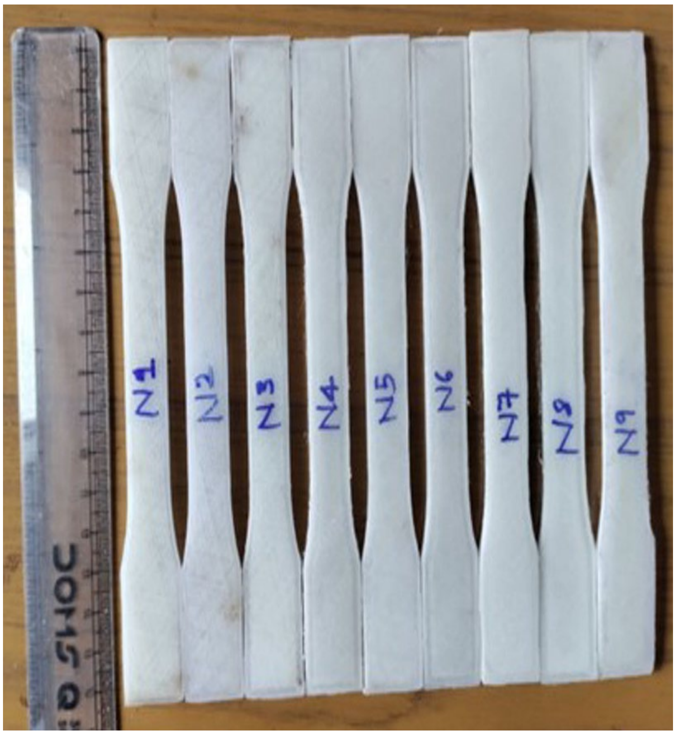

Fig. 3. Printed specimens for tensile test as per the experimental design

2.5.2. Impact test

Impact testing was performed as per ASTM D6110 using specimens with a 110×10×10 mm size and a 45° notch, tested on an IT-30 Charpy machine with 300 J capacity presented in Fig. 4. The striker was first released without a specimen to verify zero error, and then used to fracture the notched sample. The absorbed energy was recorded, and impact strength was calculated using the standard formula in Eq. (1).

$$Impact\ Strength = \frac{Energy\ Absorbed\ (\text{Joules})}{Cross\ sectional\ Area\ (\text{mm}^2)} \tag{1}$$

Fig. 4. Printed specimens for Charpy impact test as per the experimental design

2.5.3. Flexural test

Flexural testing was conducted as per ASTM D790 shown in Fig. 5, using specimens measuring 130×12.7×3 mm on a TUE-C-200 Tensile/Universal Testing Equipment – Computerized universal testing machine. A three-point bending setup was used with a crosshead speed of 1.5 mm/min. The test continued until a 5% deflection was reached, applying load at the midpoint to calculate flexural strength as shown in Eq. (2).

$$\sigma^f = \frac{3pl}{2bd^2} \tag{2}$$

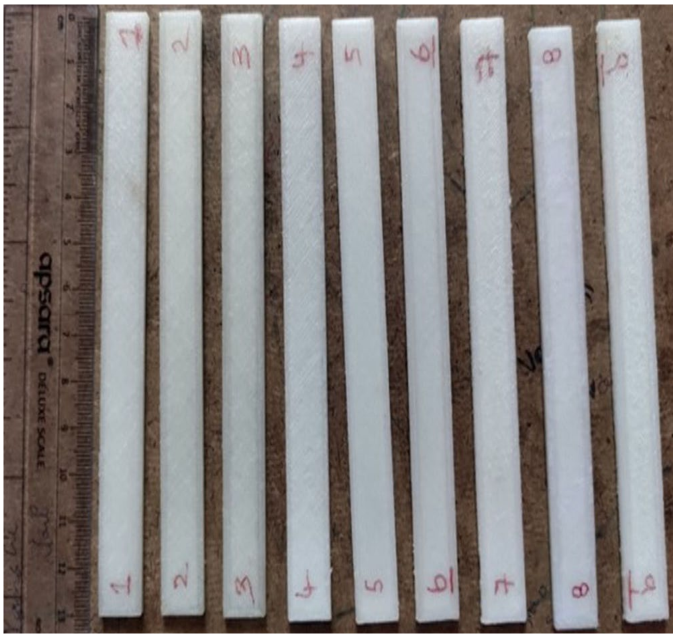

Fig. 5. Printed specimens for Flexural test as per the experimental design

3. Results and discussions

3.1. Micro structure analyses (SEM)

Following established protocols, scanning electron microscope (SEM) imaging was performed on the fracture surfaces of 3D-printed Nylon specimens after tensile testing. The analysis focused on specimens with the highest tensile strength and the lowest tensile strength with comparisons made between annealed and non-annealed samples. The SEM images were captured in a cross-sectional view of the fracture surfaces to study micro structural differences and damage mechanisms resulting from tensile loading. The specimens were coated with a thin layer of gold-palladium (Au-Pd) to enhance conductivity, ensuring high-quality imaging by minimizing charging effects during SEM observation. Carbon sheets were used to securely hold the specimens in place during the imaging process. A sufficient drying period was allowed post-coating to ensure coating stability.

The SEM analysis of tensile fracture surfaces reveals a clear improvement in interlayer bonding and fracture behaviour of 3D-printed Nylon specimens after annealing at 150°C shown in Fig. 6. When unannealed, the specimens show a brittle fracture mode characterized by voids, poor fusion zones, and layer delimitation, which causes them to fail too soon under tensile loads. The fracture surfaces become more ductile when annealing, exhibiting smoother crack propagation patterns, plastic deformation zones, and a significantly reduced void content. Stronger filament interfaces and improved mechanical performance are made possible by the thermal post-processing, which permits molecular chain relaxation and inter-diffusion.

Fig. 6 showed ductile fractures with smoother, more cohesive structures and reduced voids, indicating enhanced interlayer bonding. In contrast, unannealed samples (Fig. 7) exhibited brittle fractures, frequent voids, and poor layer adhesion.

3.2. Tensile strength results without annealing

In unannealed conditions, the highest tensile strength achieved was 25.42 MPa, at 0.1 mm layer height, 3 wall lines,

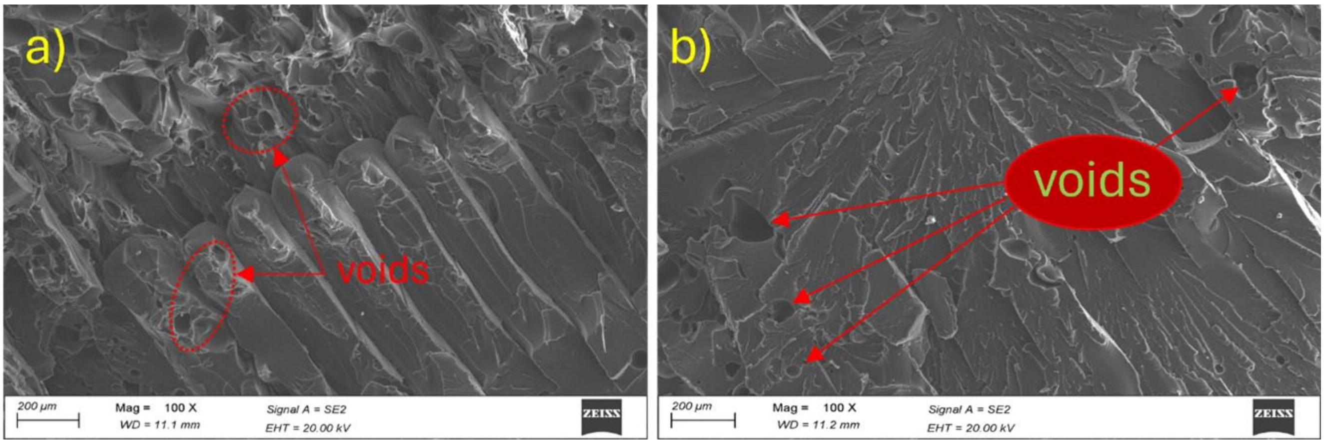

Fig. 6. SEM image of tensile fracture morphology of the specimen with annealing (a) exp-3 (b) exp-5

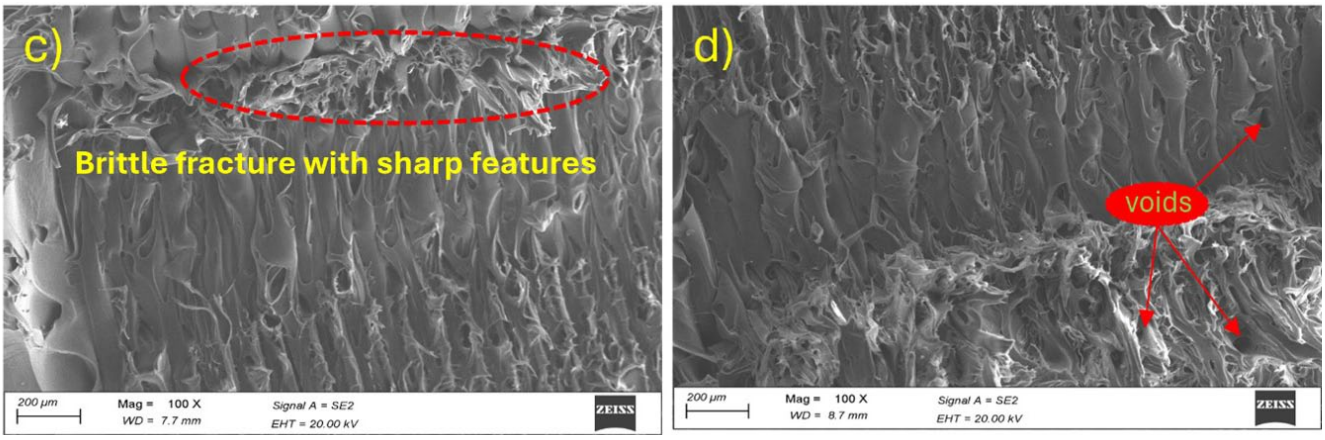

Fig. 7. SEM image of tensile fracture morphology of the specimen without annealing (a) exp-2 (b) exp-4

250°C, and 45 mm/s speed, indicating that finer layers and moderate printing speed greatly contribute to mechanical performance. However, samples with high speed and thick layers (e.g., Exp-4 with 0.2 mm LH, 2 walls, 65 mm/s) showed a drastic drop to 10.306 MPa due to weak interlayer adhesion and increased voids. The ANOVA results show that printing speed (36.63%) and layer height (8.12%) had the largest influence before annealing shown in Fig. 8. This finding is supported by M. Vishwas et al. [4], who found that using a 0.1 mm layer height and optimal shell thickness significantly improved tensile strength in FDM-printed nylon, with measured values reaching ~23 MPa. Furthermore, A. Yankin et al. [13] demonstrated that orientation angle and process speed significantly affect tensile properties in nylon and ABS, particularly under unannealed conditions, where residual stresses often contribute to temporary stiffness. Although my results match or exceed those of similar unannealed nylon studies, the mechanical behavior lacks the ductility and structural stability observed in annealed samples. Thus, while optimal printing parameters can yield high tensile strength without post-processing, their reliability may be limited by internal stress concentrations and imperfect bonding between layers.

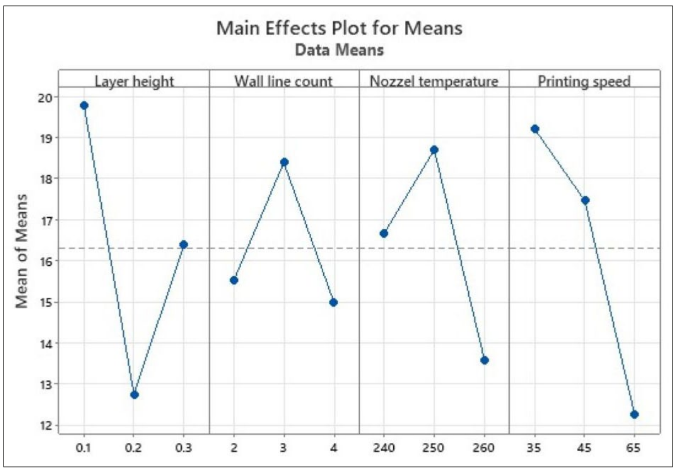

Fig. 8. Mean effects of the plot for tensile

3.3. Tensile strength results with annealing

The maximum tensile strength of 25.139 MPa was achieved for nylon specimens annealed at 150°C for 91 minutes, under optimized settings: 0.2 mm layer height, 3 wall lines, 260°C nozzle temperature, and 35 mm/s printing speed. This increase from pre-annealed values is due to enhanced interlayer fusion and crystallinity induced by the annealing process. The marginal improvements on the tensile strength (25.42 → 25.139) is attributed to the relief of residual stress during annealing, which initially elevated the unannealed strength .While peak values did not increase significantly, annealing improved crystallinity and interlayer bonding .SEM confirmed reduce voids, smoother fracture surfaces, and increase ductility. Thus the primary benefit of annealing lies in improved fracture behavior, dimensional stability, and a long-term reliability rather than a large rise in peak strength. The ANOVA analysis revealed layer height (51.63%) as the most significant contributor, with printing speed (27.87%) also playing a substantial role shown in Fig. 9. These results are in strong agreement with the study by F. Kartal and A. Kaptan [17], who observed a significant rise in tensile modulus of PLA samples annealed at 150°C for 90 minutes, due to thermal relaxation and molecular chain alignment. Similarly, E. de Avila et al. [18] noted that annealing FDM nylon at elevated temperatures led to notable improvements in tensile strength, particularly by reducing residual stresses and promoting crystalline realignment. Additionally, R.T. Mushtaq et al. [19] reported that post-annealed nylon-6 displayed superior tensile properties and reduced void content when subjected to optimized layer height and print temperature combinations.

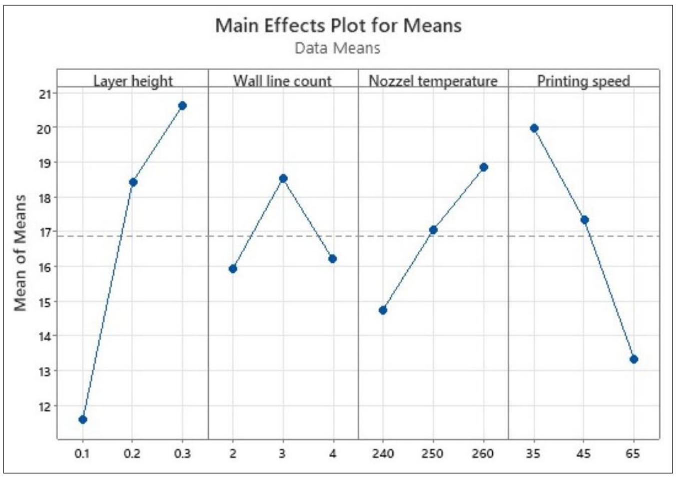

Fig. 9. Mean effects of the plot for tensile with annealing

Annealing at 150°C for 91 minutes generally improved tensile strength when appropriate parameters – such as 0.2-0.3 mm layer height, 3-4 wall lines, and moderate speeds – were used. The highest tensile strength after annealing (25.139 MPa) was observed in Experiment 5, where optimal fusion and crystallinity were achieved. In contrast, experiments 1-3 showed a drop in strength after annealing, mainly due to insufficient heat diffusion, high print speeds, or poor initial bonding. Unannealed samples sometimes exhibited higher strength due to residual stresses, but this often came at the cost of long-term mechanical reliability. Experiments 4, 6, 7, and 9 demonstrated significant improvements after annealing, aided by better heat penetration and structural support from increased wall lines. Thick layers and slower speeds favoured improved interlayer bonding during heat treatment. SEM analysis further supports that annealing reduces voids and improves ductility. Overall, annealing is most effective when paired with carefully chosen printing parameters. This highlights the importance of thermal post-processing in enhancing FDM-printed nylon's structural performance.

3.4. Impact strength

Our maximum impact strength was 16 J, achieved at 0.2 mm layer height, 4 wall lines, 240°C, and 45 mm/s, indicating that higher wall line count plays a key role in energy absorption under impact loading. The ANOVA analysis indicated wall lines count (33.33%) and layer height (18.78%) as the most significant factors shown in Fig. 10. These results align with the findings of S. Hartomacioğlu [20], demonstrated that 3D-printed nylon reinforced with carbon/glass fibers achieved higher impact strength (up to 18 J) when printed with optimized wall orientation and contour counts in ZX orientation. Likewise, S. Terekhina et al. [6] concluded that increasing infill density and wall lines positively affects the toughness of printed nylon components, particularly when the infill exceeds 60%. While our experiments used pure nylon without annealing, the 16 J result compares favorably with reinforced or structurally optimized counterparts, demonstrating that proper control of wall structures and print speed alone can significantly improve impact performance. However, to further enhance energy absorption, applying thermal post-processing or using specialized infill patterns may yield even better results in future work.

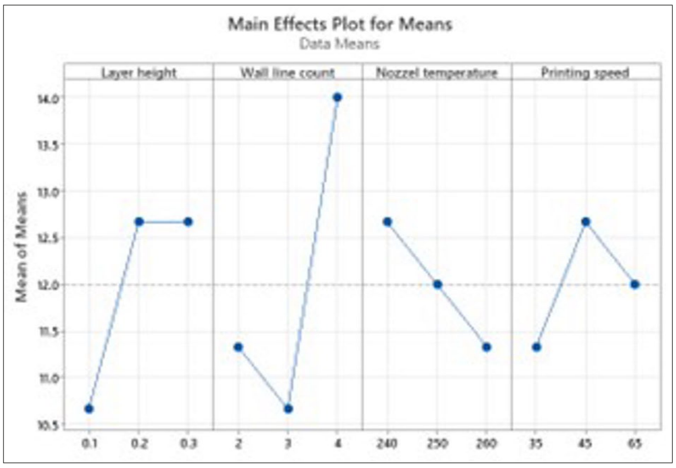

Fig. 10. Mean effects of the plot for impact strength

3.5. Flexural strength

The maximum flexural strength in our experiments was 71.91 MPa, achieved with 0.1 mm layer height, 3 wall lines, 250°C, and 45 mm/s printing speed. This result illustrates how finer layer thickness and optimal wall configuration promote better load distribution and resistance to bending. The ANOVA analysis confirmed that layer height (55.19%) was the most impactful parameter, followed by printing speed (7.97%). This outcome agrees with the findings of D. Dairabayeva et al. [9], reported flexural strength improvements up to 70 MPa for nylon when printed with reduced layer thickness and gyroid infill pattern. They attributed this enhancement to improved geometric consistency and better interlayer fusion. Similarly, K.G. Mostafa et al. [7] emphasized that the combination of reduced infill density and optimized contours could increase flexural strength while keeping material cost low, with recorded values ranging from 55 to 68 MPa. Our highest value of 71.91 MPa surpasses many reported benchmarks and demonstrates that even without annealing; careful parameter optimization can result in structurally robust nylon prints. These results highlight the critical role of print resolution and speed in achieving superior flexural performance shown in Fig. 11.

Final the Tensile strength, Impact strength and flexural strength are represented in TABLE 3.

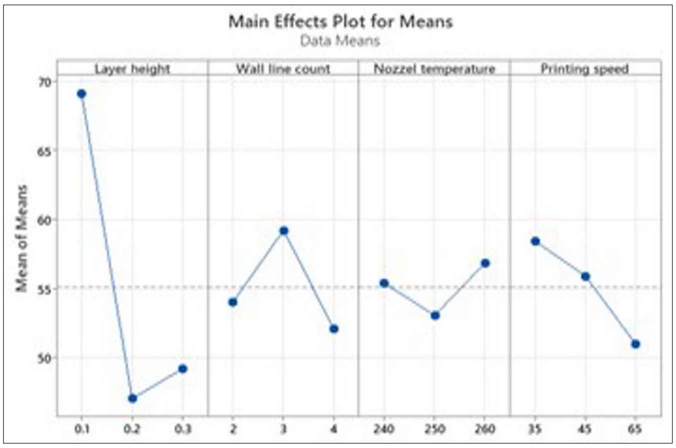

Fig. 11. Mean effects of the plot for flexural strength

3.6. ANOVA Results for tensile (with annealing & without annealing), impact, flexural strengths

Analysis of Variance (ANOVA) based on regression was used to assess how 3D printing parameters settings and annealing condition affected the mechanical performance of nylon specimens. The results for each mechanical property are listed below, along with the F-values, p-values, and % contributions. TABLES 4-7 display the results of the ANOVA tests conducted on tensile test (with annealing without annealing), impact, flexural.

TABLE 4 relives According to the ANOVA results, printing speed had the largest contribution (36.63%) to the tensile strength without annealing, followed by nozzle temperature (6.69%) and layer height (8.12%). The impact of wall line count was negligible (0.19%). Printing speed had a marginal impact ($F = 3.03$, $p = 0.157$), but none of the other parameters were statistically significant at the 95% Confidence level ($p > 0.05$).

TABLE 5 relives According to the ANOVA results showed that layer height had the greatest significant effect on tensile strength (51.63%), followed by nozzle temperature (10.53%) and printing speed (27.87%). The number of wall line count had a negligible influence very small impact (0.05%). The major influence of layer height ($F = 20.86$, $p = 0.010$) and printing speed ($F = 11.26$, $p = 0.028$) was confirmed by their statistical significance.

TABLE 3

L9 design and outcome results of the experiments

Ex/No	Layer height (MM)	Wall line count (-)	Nozzle temperature (°C)	Printing speed (mm/S)	Tensile strength MPa		Impact Strength (J)	Flexural strength (MPa)
					With annealing	Without annealing		
1	0.1	2	240	35	11.561±0.05	22.245 ±0.03	10	71.56
2	0.1	3	250	45	13.860 ±0.05	25.42 ±0.03	10	71.91
3	0.1	4	260	65	9.318 ±0.05	11.682±0.03	12	63.7
4	0.2	2	250	65	14.105 ±0.05	10.306 ±0.03	12	39.83
5	0.2	3	260	35	25.139 ±0.05	14.993 ±0.03	10	56.21
6	0.2	4	240	45	16.096 ±0.05	12.951 ±0.03	16	45.14
7	0.3	2	260	45	22.091 ±0.05	14.029 ±0.03	12	50.68
8	0.3	3	240	65	16.613 ±0.05	14.758 ±0.03	12	49.47
9	0.3	4	250	35	23.216 ±0.05	20.375 ±0.03	14	47.48

TABLE 4

ANOVA for tensile strength without annealing

Source	DF	Adj SS	Adj MS	F-Value	P-Value	% Contribution
Regression	4	109.939	27.4847	1.07	0.475	51.65%
Layer height	1	17.289	17.2890	0.67	0.458	8.12%
Wall line count	1	0.412	0.4119	0.02	0.905	0.19%
Nozzle temperature	1	14.260	14.2604	0.55	0.498	6.69%
Printing speed	1	77.978	77.9775	3.03	0.157	36.63%
Error	4	102.897	25.7243			48.34%
Total	8	212.836				100%

TABLE 5

ANOVA for tensile strength with annealing at 150°C at 91 min time

Source	DF	Adj SS	Adj MS	F-Value	P-Value	% contribution
Regression	4	214.878	53.719	9.10	0.027	90.09%
Layer height	1	123.134	123.134	20.86	0.010	51.63%
Wall line count	1	0.127	0.127	0.02	0.890	0.05%
Nozzle temperature	1	25.125	25.125	4.26	0.108	10.53%
Printing speed	1	66.491	66.491	11.26	0.028	27.87%
Error	4	23.615	5.904			9.90%
Total	8	238.492				100%

TABLE 6

ANOVA for impact strength

Source	DF	Adj SS	Adj MS	F-Value	P-Value	%Contribution
Regression	4	19.6190	4.9048	1.58	0.333	61.30%
Layer height	1	6.0000	6.0000	1.94	0.236	18.78%
Wall line count	1	10.6667	10.6667	3.45	0.137	33.33%
Nozzle temperature	1	2.6667	2.6667	0.86	0.406	8.33%
Printing speed	1	0.2857	0.2857	0.09	0.776	0.89%
Error	4	12.3810	3.0952			38.69%
Total	8	32.0000				100%

TABLE 7

ANOVA for flexural strength

Source	DF	Adj SS	Adj MS	F-Value	P-Value	% Contribution
Regression	4	685.00	171.249	1.78	0.296	63.99%
Layer height	1	590.84	590.835	6.13	0.068	55.19%
Wall line count	1	5.51	5.510	0.06	0.823	0.514%
Nozzle temperature	1	3.26	3.256	0.03	0.863	0.30%
Printing speed	1	85.40	85.396	0.89	0.400	7.97%
Error	4	385.37	96.343			36.00%
Total	8	1070.37				100%

TABLE 6 relives According to the ANOVA results showed Impact strength was most significantly affected by wall line count was the largest contributor to impact strength (33.33%), followed by layer height (18.78%) and nozzle temperature (8.33%). Less than 1% was caused by printing speed. Wall line count had a considerable impact ($F = 3.45, p = 0.137$), but none of the other characteristics were statistically significant ($p > 0.05$).

TABLE 7 relives According to the ANOVA results showed The largest factor influencing flexural strength was layer height had the highest contribution (55.19%), which was followed by printing speed (7.97%). wall line count (0.514%) and nozzle temperature (0.30%) were negligible. Although none of the parameters were statistically significant, layer height displayed a trend that was almost significant ($F = 6.13, p = 0.068$), indicating that it might have an impact.

5. Conclusions

This study comprehensively investigated the mechanical behaviour of FDM 3D-printed nylon specimens under varying process parameters, with and without annealing. Using an L9 orthogonal array, the influence of layer height, wall line count, nozzle temperature, and printing speed was systematically examined on tensile, impact, and flexural strengths.

The results that layer height were the most significant factor influencing tensile and flexural strengths, while wall line count most significantly affected impact strength.

- The highest tensile strength without annealing (25.42 MPa) was obtained with a fine layer height of 0.1 mm, moderate wall line count (3), 250°C nozzle temperature, and 45 mm/s speed. After annealing, the optimal tensile strength (25.139 MPa) was achieved with a moderate layer height of 0.2 mm, 3 wall lines, 260°C, and slower speed of 35 mm/s,
- Indicating that annealing enhanced interlayer bonding and crystallinity, leading to improved mechanical performance in certain parameter combinations.
- For impact strength, wall line count had the greatest influence, with the maximum value of 16 J obtained at 0.2 mm layer height, 4 wall lines, 240°C, and 45 mm/s.
- In the flexural test, the highest flexural strength of 71.91 MPa was recorded with 0.1 mm layer height, 3 wall

lines, 250°C, and 45 mm/s, highlighting that fine layers and moderate printing speeds promote superior structural integrity.

- SEM analysis of fractured tensile specimens, revealing that annealed samples exhibited smoother, more fused interlayer regions, indicating enhanced bonding and reduced voids. In contrast, non-annealed and poorly printed samples showed layer separation, voids, and brittle fracture features, confirming weaker interfacial adhesion.

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