UDC 621.798.1:678.744:620.17
DOI: 10.15587/1729-4061.2026.365570

IDENTIFYING OF THE INFLUENCE OF CHAMBER TEMPERATURE ON THE FLEXURAL PROPERTIES OF POLYAMIDE 12 FABRICATED BY FDM/FFF 3D PRINTING

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The thermal environment of the printing chamber is an important factor in determining the quality and mechanical performance of semi-crystalline polymers produced by Fused Deposition Modelling (FDM/FFF), such as Polyamide 12 (PA12). Nevertheless, the impact of temperature in the building chamber on the flexural performance of PA12 parts is not yet clear. The aim of this study is to evaluate the flexural performance of FDM/FFF-printed PA12 as a function of the building chamber temperature and different thermal processing conditions. A Taguchi L25 orthogonal design was employed to investigate the influence of nozzle temperature, bed temperature and building chamber temperature on flexural stress, bending force, elastic modulus and signal-to-noise ratio. The results showed relatively stable mechanical performance under different thermal conditions. Flexural stress ranged from 49.58 to 53.23 MPa, bending force from 173.10 to 185.83 N, and elastic modulus from 1014.26 to 1119.49 MPa. Statistical analysis indicated that building chamber temperature was the most influential, followed by nozzle temperature while bed temperature had the least impact. The optimal processing conditions were obtained at a nozzle temperature of approximately 280°C, a bed temperature of 60–75°C, and a building chamber temperature of 65°C. The improved flexural performance can be ascribed to enhanced interlayer bonding, lower thermal gradients and more stable heat transfer in the entire printing chamber. The results emphasize the important role of chamber temperature at several critical stages during printing in improving structural integrity and mechanical reliability of FDM/FFF-printed PA12 components. The obtained results can be applied to the fabrication and optimization of PA12 engineering components produced under controlled thermal conditions

Keywords: 3D printing, flexural strength, PA12, fused deposition modeling, chamber temperature

Received 25.03.2026
Received in revised form 02.06.2026
Accepted 11.06.2026
Published 30.06.2026

How to Cite: *Nguyen, M. T. P., Pham, T. H. N., Ho, T. M. N. Le, D. (2026). Identifying of the influence of chamber temperature on the flexural properties of polyamide 12 fabricated by FDM/FFF 3D printing. Eastern-European Journal of Enterprise Technologies, 3 (1 (141)), 73–82. https://doi.org/10.15587/1729-4061.2026.365570*

1. Introduction

Additive manufacturing (AM), commonly known as 3D printing, has become an important manufacturing technology for producing complex engineering components with reduced material waste and increased design flexibility. Out of the multiple additive manufacturing technologies, fused deposition modeling (FDM) or commonly referred to as fused filament fabrication (FFF) is widely used due to its simplicity of operation, low cost and ability to print with many thermoplastic materials. Due to these benefits, FDM/FFF technology has been progressively utilized within engineering, automotive, aerospace, biomedical and rapid prototyping applications [1–3]. Nonetheless, despite its advantages, the mechanical performance and dimensional accuracy of FDM-fabricated parts are still critically determined by the processing parameters. Crucial to interlayer bonding quality, cooling behavior and residual stress formation in printed structures are parameters like nozzle temperature, printing speed, layer orientation and thermal environment [4, 5]. During printing, poor thermal control may result in weak interlayer adhesion, internal defects, geometric instabilities and mechanical characteristics that do not meet the necessary standardized requirements for components functionally implicated in load-bearing engineering structures made using FDM. Therefore, improving the understanding of the relationship between thermal processing conditions and mechanical performance remains an important scientific and engineering issue.

Since thermoplastic polymers can be repeatedly melted and solidified during the deposition layer-by-layer in FDM/FFF technology, they are an attractive choice for this technique. Of these materials, polyamide 12 (PA12) has received a great deal of attention for engineering applications due to its high toughness, thermal stability, chemical resistance and fatigue performance. Moreover, PA12 also has better dimensional stability and durability than conventional FDM materials such as PLA and ABS [6–8]. However, the semicrystalline nature of PA12 shows great sensitivity to thermal history during fabrication. The different thermal conditions could play an important role in the crystallization behavior, cooling rate, how much residual stress and how freely polymer chains can diffuse between layers which have a direct influence on mechanical properties and structural integrity of printed parts [9, 10].

Therefore, studies focusing on enhancing the thermal processing conditions and mechanical properties of FDM/FFF-printed PA12 components are still highly relevant for engineering applications demanding improved structural integrity, consistent mechanical behavior and dimensional stability.

2. Literature review and problem statement

Previous studies demonstrated that the mechanical behavior of FDM-printed components is highly dependent on thermal history during fabrication. The most significant effects on flexural strength, stiffness and dimensional stability are caused by changes of processing parameters [11, 12]. As reported in [13], the flexural strength of printed composite parts increased over 20% through the optimization of FDM process parameters, suggesting that optimizing additive manufacturing processes can effectively enhance performance of polymer structures.

Prior studies of PA12 materials focused almost exclusively on nozzle temperature, build orientation, infill density and printing strategy. Optimized FDM conditions were shown to enhance both the strength and toughness of PA12 specimens [9]. In a similar way, the Taguchi method identified nozzle temperature and layer orientation as predominant factors affecting mechanical properties in [10]. It was also shown that the flexural behavior of PA12 specimens is strongly influenced by the build orientation as reported in [14].

Since PA12 is a semi-crystalline polymer, thermal conditions during printing greatly influence its mechanical properties. Temperature plays a vital role in polymer crystallization, cooling rate and interlayer diffusion, which ultimately determine the bonding quality and structural integrity. Studies have shown that higher extrusion temperatures increase interlayer adhesion and mechanical strength by facilitating polymer chain diffusion [15, 16]. Improved thermal management during the deposition process has also been shown to reduce residual stress and enhance bonding quality [16, 17]. In addition, increasing the processing temperature could also lead to better crystallinity and improved mechanical properties of polyamide materials [18].

Despite multiple studies having evaluated the effects of nozzle temperature, infill density, and build orientation on PA12 properties, the influence of building chamber temperature in FDM printing has received limited attention. Another important parameter is the thermal environment in the printing chamber which has a strong influence on heat transfer, cooling rate and even thermal gradients during fabrication [19, 20]. A stable building chamber temperature helps mitigate residual stress, improve interlayer bonding, and enhance the overall mechanical performance of printed parts in general [17, 21]. Nonetheless, few systematic studies investigate the effect of different chamber temperatures on the flexural behavior of parts fabricated through Fused deposition modeling (FDM). This is particularly critical for structural applications necessitating high mechanical reliability.

Although FDM is widely used because of its low cost, the mechanical integrity of printed components remains highly sensitive to process parameters. Among engineering materials, PA12 is particularly valued for its toughness and thermal resistance, although its semi-crystalline nature makes it highly sensitive to thermal history during fabrication. Current research literature has previously fully characterized the influence of nozzle temperature, build orientation and infill density on polymer strength. Notably, the understanding of the building chamber temperature is crucial since it controls how fast the part cools, determining its crystallization behavior throughout. A stable thermal environment is expected to reduce thermal gradients and residual stress in each layer to realize better interlayer bonding by facilitating polymer chain diffusion. This all contributes to the conclusion that it is reasonable to perform a study focused on the effect of building chamber temperature on PA12 flexural properties manufactured via FDM/FFF 3D printing process. This study seeks to fill the identified gap by systematically analyzing how environmental thermal control – rather than just local heating – optimizes the mechanical performance and structural reliability of PA12 for functional engineering applications.

While mechanical properties e.g. extrusion temperature, build orientation and infill density have been studied extensively in previous studies, the effect of building chamber temperature resulting from the printer subsystems on the mechanical behavior of PA12 components is not as much examined. This thermal environment is crucial because it not only controls the cooling rate but also crystallization as well as interlayer fusion of semi-crystalline polymers, such as PA12. This work addresses the issue of stable inter-layer adhesion and lower residual stresses in FDM-printed semi-crystalline polymers by targeting chamber temperature rather than solely nozzle temperature.

3. The aim and objectives of the study

The aim of this study is to investigate the impact of thermal processing conditions, particularly building chamber temperature on flexural characteristics of PA12 components produced using FDM/FFF technology. The obtained results will make it possible to optimize chamber temperature control and improve the structural reliability of PA12 engineering components manufactured by FDM/FFF technology.

This aim is realized by achieving the following objectives:

– to determine the flexural stress, bending force, and elastic modulus of PA12 specimens under different thermal conditions;

– to investigate the effect of nozzle, bed and building chamber temperature using the Taguchi method.

4. Materials and Methods

4. 1. The object and hypothesis of the study

The object of this study is the flexural performance of PA12 components fabricated by FDM/FFF under different thermal processing conditions, with particular emphasis on the influence of building chamber temperature. The main hypothesis is that improving the thermal stability inside the printing chamber enhances interlayer bonding and consequently improves the flexural properties of PA12 specimens. The study assumes that all non-investigated printing parameters remain constant during fabrication and that all specimens are produced under controlled laboratory conditions. To simplify the analysis, only the effects of nozzle temperature, bed temperature, and building chamber temperature are considered, while other factors such as raster angle, layer thickness, and printing speed are kept fixed.

4. 2. Materials

In this study, PA12 filament with a nominal diameter of 1.75 mm and a dimensional tolerance of ±0.05 mm was used as the printing material. The filament was supplied by Shenzhen eSun Industrial Co., Ltd., China, a well-known manufacturer of 3D printing materials. The printing parameters and initial properties of PA12 plastic are listed in Table 1.

Table 1

Properties of PA12

Parameter	Typical value	Unit
Nozzle temperature	240–270	°C
Print bed temperature	80–120	°C
Printing speed	20–50	mm/s
Density	1.12	g/cm^3
Thermal deformation temperature	300	°C/1.2 kg
Drying time	4–6	Hour
Drying temperature	70–80	°C
Melting temperature	178–180	°C
Tensile strength	54.88	MPa
Elongation	50.24	%
Flexibility strength	63.41	MPa
Flexibility modulus	1073	MPa
Impact toughness	13.2	kJ/m^2

The specimens were fabricated as rectangular beams using FDM technology according to ASTM D790, as shown in Fig. 1.

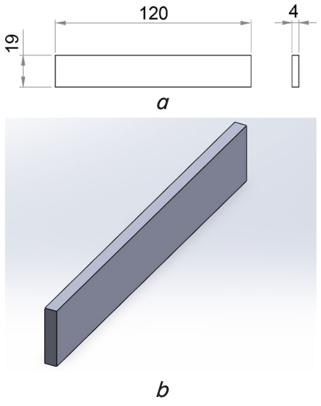

Fig. 1. Flexural testing: *a* – dimensions of flexural specimen; *b* – 3D model of flexural specimen

Five samples were produced for each experimental condition, and the average flexural strength and standard deviation were calculated to evaluate result repeatability and reliability of the experimental results.

4. 3. 3D printing machine

The specimens were fabricated using a modified FDM 3D printer equipped with a temperature-controlled chamber (Fig. 2).

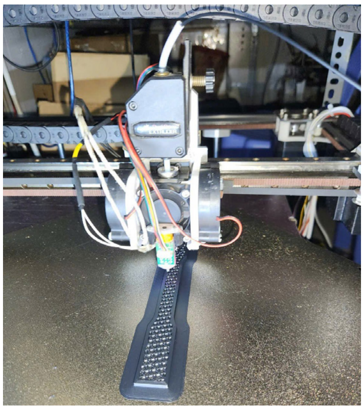

Fig. 2. Klipper 3D printer firmware and the test sample is being printed

The printer uses a 0.4 mm nozzle and has a build volume of 400 × 400 × 350 mm. Printing parameters were configured in Ultimaker Cura, while the building chamber temperature was maintained at up to 60°C with a stability of ±1°C to ensure uniform thermal conditions during printing. After fabrication, all specimens were stored at room temperature before mechanical testing.

4. 4. Printing setting and analysis method

This study investigated the effects of nozzle temperature (240–290°C), bed temperature (55–85°C), and building chamber temperature (35–65°C) on the flexural properties of PA12 specimens, as listed in Table 2.

The parameter ranges were selected based on PA12 material characteristics and previous studies, while other printing settings were kept constant. All experiments were conducted under controlled laboratory conditions at 23 ± 2°C and 50 ± 5% relative humidity. The 3D model of the specimen is presented in Fig. 1.

Table 2

Printing parameters

Parameters	Levels				
	1	2	3	4	5
A – Nozzle temperature (°C)	240	260	270	280	290
B – Print bed temperature (°C)	55	60	65	75	85
C – Building chamber temperature (°C)	35	40	45	55	65

4. 5. Taguchi method

The Taguchi method was applied to evaluate the effects of printing parameters on the flexural performance of PA12 specimens while reducing the number of experiments and experimental cost. The data obtained were further analyzed using ANOVA to determine the significance of each parameter [22]. The overall procedure of the Taguchi method is illustrated in Fig. 3 [23].

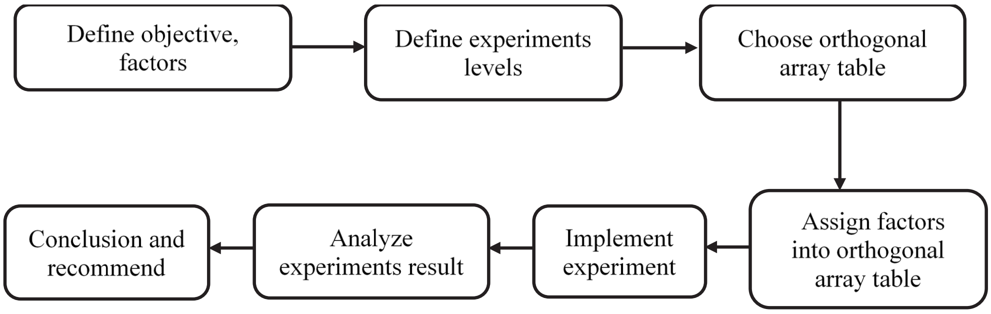

Fig. 3. Taguchi process diagram

Three process parameters, including nozzle temperature, bed temperature, and building chamber temperature, were investigated using a Taguchi L25 orthogonal array in Minitab, as shown in Table 3. Five specimens were fabricated for each experimental condition, resulting in a total of 125 samples. The repeated measurements were used to calculate average values and standard deviations, improving the reliability of the flexural test results for subsequent S/N ratio and ANOVA analyses.

Table 3

Orthogonal array

No.	Orthogonal array			Factors		
	A	B	C	Nozzle temperature (°C)	Print bed temperature (°C)	Building chamber temperature (°C)
1	1	1	1	240	55	35
2	1	2	2	240	60	40
3	1	3	3	240	65	45
4	1	4	4	240	75	55
5	1	5	5	240	85	65
6	2	1	2	260	55	40
7	2	2	3	260	60	45
8	2	3	4	260	65	55
9	2	4	5	260	75	65
10	2	5	1	260	85	35
11	3	1	3	270	55	45
12	3	2	4	270	60	55
13	3	3	5	270	65	65
14	3	4	1	270	75	35
15	3	5	2	270	85	40
16	4	1	4	280	55	55
17	4	2	5	280	60	65
18	4	3	1	280	65	35
19	4	4	2	280	75	40
20	4	5	3	280	85	45
21	5	1	5	290	55	65
22	5	2	1	290	60	35
23	5	3	2	290	65	40
24	5	4	3	290	75	45
25	5	5	4	290	85	55

The Taguchi method uses the signal-to-noise ratio (S/N) to simultaneously represent the quality characteristics' mean and variability. It is an effective evaluation tool that helps determine the influence of input factors on the desired output. Within the framework of this method, three different types of objective functions are used to determine the signal-to-noise characteristics [23, 24]:

– a larger value is optimal

$$SN = -10\log\left[\frac{1}{n}\sum_{i=1}^{n}\frac{1}{y_i^2}\right]; \tag{1}$$

– a smaller value is optimal

$$SN = -10\log\left[\frac{1}{n}\sum_{i=1}^{n}y_i^2\right]; \tag{2}$$

– nominal value is optimal

$$SN = -10\log\left[\frac{1}{n}\sum_{i=1}^{n}\left(y_i - y_n\right)^2\right]. \tag{3}$$

There i – the experimental number, y_i – the mean value of the characteristic given by the experiment, n – the number of experiments, y_n – the target value.

5. Research results of the influence of chamber temperature on the flexural properties of FDM/FFF-printed PA12

5. 1. Results of PA12 mechanical property testing for flexural strength

The experimental results for the flexural properties of PA12 specimens are presented in Table 4.

From the data in Table 4, the comparison of the flexural stress, bending force, and elastic modulus values obtained from the experimental tests of PA12 specimens is presented in Fig. 4.

Table 4 and Fig. 4 summarize the flexural properties of FDM-printed PA12 specimens, including maximum stress, bending force, and elastic modulus. Overall, the results demonstrate relatively stable mechanical behavior across all 25 experimental conditions. The flexural stress ranges from 49.58 to 53.23 MPa, with an average value of 51.62 ± 0.99 MPa, while the maximum bending force varies from 173.10 to 185.83 N (average 180.27 ± 3.5 N). Similarly, the elastic modulus ranges from 1014.26 to 1119.49 MPa, with an average of 1067.71 ± 23.09 MPa. The low standard deviations (%SD below ~2.2%) confirm the good repeatability and reliability of the experimental system. Among all samples, specimen No. 3 consistently achieved the best performance, with values of 53.23 MPa, 185.83 N, and 1119.49 MPa, respectively. Other samples, such as No. 13, 15, 16, 17, and 19, also exhibited relatively high and stable mechanical properties, indicating a favorable processing window. In general, the obtained results indicate that thermal processing conditions significantly influenced the flexural behavior of the printed PA12 specimens. The relatively narrow variation observed among the experimental conditions indicates that PA12 exhibits stable flexural behavior within the investigated processing window. This finding suggests that the material can maintain reliable mechanical performance under practical manufacturing conditions, making it suitable for engineering components, functional prototypes, fixtures, and lightweight load-bearing structures produced by FDM/FFF technology.

Table 4

Flexural properties of PA12 specimens (mean ± SD)

No.	A	B	C	Stress (MPa)	Force (N)	Elastic modulus (MPa)
1	1	1	1	51.6 ± 1.44	180.15 ± 5.02	1041.19 ± 27.4
2	1	2	2	52.33 ± 1.12	183.13 ± 4.22	1089.91 ± 52.46
3	1	3	3	53.23 ± 1.2	185.83 ± 4.2	1119.49 ± 29.86
4	1	4	4	49.58 ± 0.8	173.1 ± 2.78	1014.26 ± 18.66
5	1	5	5	51.73 ± 0.57	181.86 ± 2.44	1069.73 ± 18.64
6	2	1	2	49.9 ± 0.76	174.22 ± 2.64	1022.77 ± 15.74
7	2	2	3	50.28 ± 0.73	175.55 ± 2.56	1042.05 ± 30.03
8	2	3	4	52.04 ± 0.85	181.68 ± 2.97	1090.99 ± 18.92
9	2	4	5	51.87 ± 0.48	181.11 ± 1.69	1060.61 ± 19.82
10	2	5	1	51.83 ± 0.99	180.97 ± 3.44	1027.16 ± 27.66
11	3	1	3	50.75 ± 1.5	177.19 ± 5.24	1056.62 ± 27.28
12	3	2	4	51.06 ± 0.87	178.26 ± 3.03	1071.51 ± 21.52
13	3	3	5	53.08 ± 1.18	185.31 ± 4.13	1103.68 ± 17.13
14	3	4	1	52.37 ± 0.92	182.84 ± 3.2	1069.48 ± 16.45
15	3	5	2	52.69 ± 0.93	183.94 ± 3.24	1077.21 ± 21.06
16	4	1	4	52.8 ± 1	184.33 ± 3.49	1110.74 ± 21.33
17	4	2	5	52.65 ± 1.72	183.8 ± 6	1084.16 ± 39.84
18	4	3	1	50.22 ± 0.85	175.33 ± 2.97	1044.73 ± 18
19	4	4	2	52.71 ± 0.58	184.03 ± 2.02	1088.1 ± 8.48
20	4	5	3	52.45 ± 0.49	183.12 ± 1.69	1095.61 ± 17.83
21	5	1	5	52.49 ± 2.76	183.24 ± 9.63	1092.66 ± 49.53
22	5	2	1	50.59 ± 0.68	176.61 ± 2.36	1046.86 ± 16.11
23	5	3	2	51.04 ± 0.67	178.19 ± 2.35	1062.88 ± 12.19
24	5	4	3	50.77 ± 0.59	177.26 ± 2.07	1054.99 ± 10.96
25	5	5	4	50.36 ± 1.18	175.81 ± 4.13	1055.34 ± 20.29
Average				51.62 ± 0.99	180.27 ± 3.5	1067.71 ± 23.09

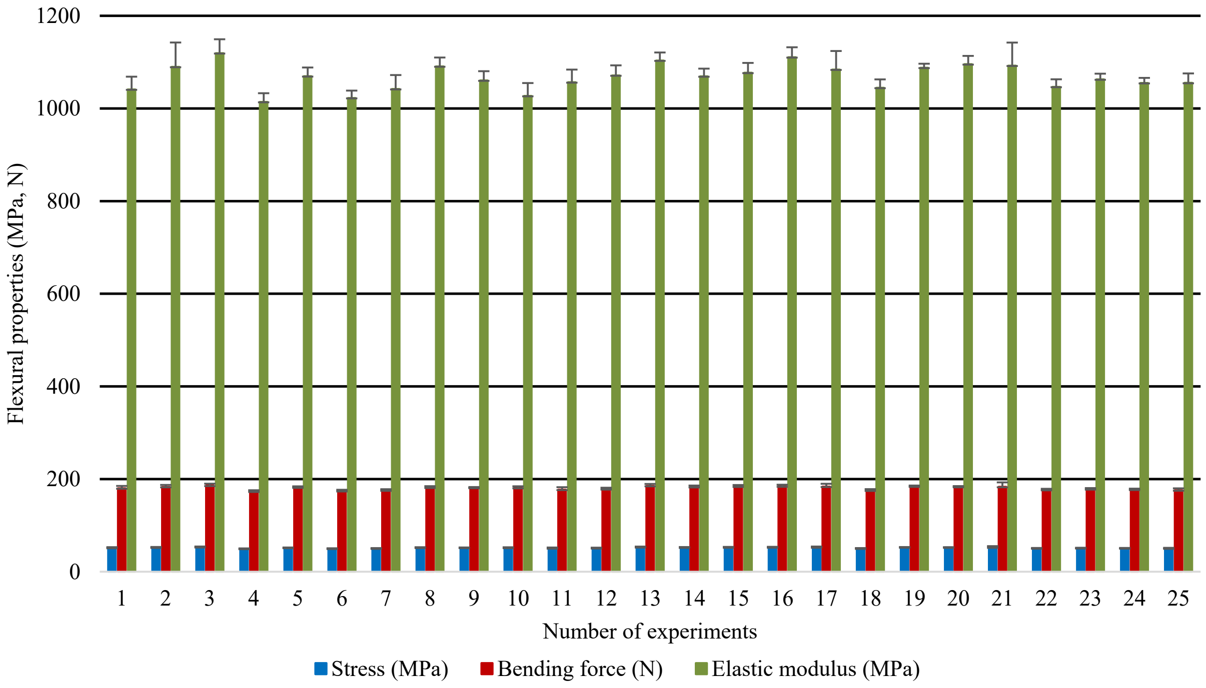

Fig. 4. Comparison of flexural stress, bending force, and elastic modulus of PA12 specimens (mean ± SD)

5. 2. Taguchi analysis of the influence of printing parameters on the flexural properties of PA12

The Taguchi experimental results were analyzed using the signal-to-noise (S/N) ratio to evaluate the influence of nozzle temperature, bed temperature, and building chamber temperature on the flexural performance of PA12. The signal-to-noise (S/N) ratios obtained from the Taguchi analysis for the flexural properties of PA12 specimens are presented in Table 5.

In addition to the signal-to-noise ratios, the response table for the means of the flexural properties of PA12 specimens under different processing conditions is presented in Table 6.

Table 5

Signal-to-noise (S/N) ratios for flexural properties of PA12

Factor	Level	Stress (dB)	Bending force (dB)	Elastic modulus (dB)
Nozzle temperature (°C)	1	34.27	45.14	60.56
	2	34.18	45.04	60.41
	3	34.32	45.18	60.63
	4	34.35	45.21	60.70
	5	34.16	45.02	60.53
Delta		0.19	0.19	0.29
Rank		2	2	2
Bed temperature (°C)	1	34.24	45.10	60.54
	2	34.21	45.08	60.56
	3	34.30	45.16	60.70
	4	34.23	45.09	60.48
	5	34.29	45.16	60.55
Delta		0.09	0.09	0.22
Rank		3	3	3
Building chamber temperature (°C)	1	34.21	45.06	60.39
	2	34.27	45.14	60.57
	3	34.23	45.09	60.61
	4	34.18	45.04	60.57
	5	34.38	45.25	60.69
Delta		0.20	0.21	0.3
Rank		1	1	1

Table 6

Response table for means of flexural properties

Factor	Level	Stress (MPa)	Bending force (N)	Elastic modulus (MPa)
Nozzle temperature (°C)	1	51.69	180.8	1067
	2	51.19	178.7	1049
	3	51.99	181.5	1076
	4	52.17	182.1	1085
	5	51.05	178.2	1063
Delta		1.12	3.9	36
Rank		2	2	2
Bed temperature (°C)	1	51.51	179.8	1065
	2	51.38	179.5	1067
	3	51.92	181.3	1084
	4	51.46	179.7	1057
	5	51.81	181.1	1065
Delta		0.54	1.8	27
Rank		3	3	3
Building chamber temperature (°C)	1	51.32	179.2	1046
	2	51.73	180.7	1068
	3	51.50	179.8	1074
	4	51.17	178.6	1069
	5	52.36	183.1	1082
Delta		1.20	4.4	36
Rank		1	1	1

The Taguchi analysis results presented in Tables 5, 6 consistently indicate that building chamber temperature is the dominant factor influencing the flexural properties of FDM-printed PA12. Based on the S/N ratio analysis using the "larger-is-better" criterion, building chamber temperature exhibits the highest *Δ* values across all responses, including maximum stress (*Δ* = 0.20), maximum bending force (*Δ* = 0.21), and elastic modulus (*Δ* = 0.30), ranking first in all cases. Nozzle temperature shows the second strongest influence (*Δ* = 0.19, 0.19, and 0.29, respectively), while bed temperature has the lowest effect (*Δ* = 0.09, 0.09, and 0.22). These results demonstrate that environmental thermal control plays a more critical role than local heating conditions in determining both the magnitude and stability of mechanical performance.

The main effects of the printing parameters on the flexural properties of PA12 are presented in Fig. 5.

For all investigated responses, the values increased from 240°C to 280°C and decreased at 290°C. The maximum values obtained at 280°C indicate improved interlayer diffusion, whereas excessive nozzle temperature may lead to thermal degradation and reduced mechanical performance of the printed specimens.

The signal-to-noise (S/N) ratio plots of the printing parameters under the "larger is better" criterion are presented in Fig. 6.

The obtained S/N ratio trends are consistent with the mean response analysis, confirming the reliability of the Taguchi design. For all investigated flexural properties, the optimal parameter combination was identified at a nozzle temperature of 280°C, a bed temperature of 65–75°C, and a building chamber temperature of 65°C, where the maximum S/N ratio values were obtained. It should be noted that these results apply to PA12 filament processed under the investigated parameter ranges (240–290°C nozzle temperature, 55–85°C bed temperature, and 35–65°C building chamber temperature) using an enclosed FDM/FFF printing system. Within this processing window, building chamber temperature was consistently identified as the most influential factor affecting flexural stress, bending force, and elastic modulus. From a practical perspective, maintaining the chamber temperature near 65°C can contribute to more stable thermal conditions, improved interlayer bonding, enhanced process repeatability, and greater reliability of PA12 components intended for structural and functional applications.

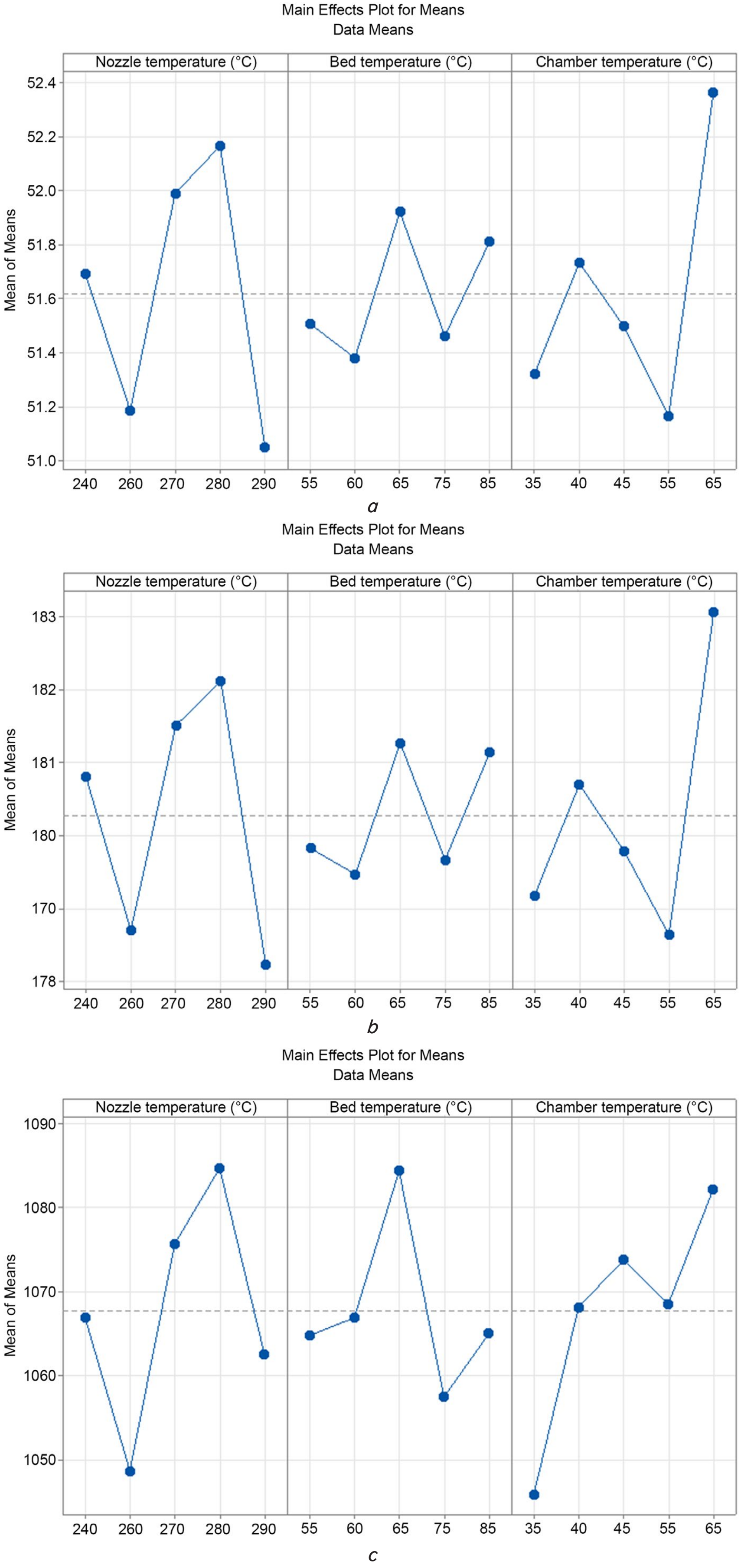

Fig. 5. Main effects plots of printing parameters: *a* — maximum stress; *b* — maximum bending force; *c* — elastic modulus of PA12

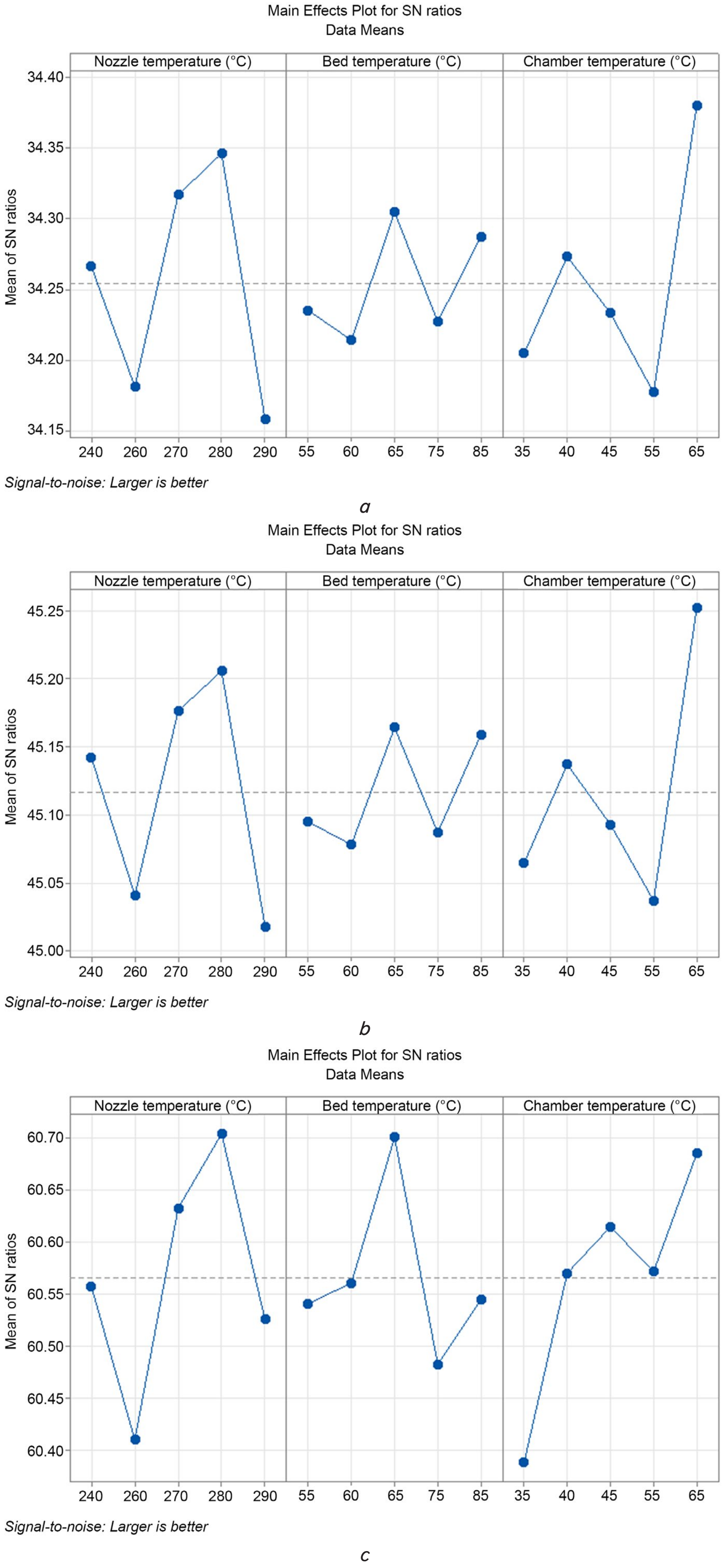

Fig. 6. Signal-to-noise (S/N) ratio plots: *a* – maximum stress; *b* – maximum bending force; *c* – elastic modulus under the "larger is better" criterion

6. Discussion of studying the influence of building chamber temperature on the flexural properties of FDM-printed PA12 Material

The experimental results shown in Table 4 and Fig. 4 demonstrate that the thermal processing conditions significantly influenced the flexural behavior of FDM-printed PA12 specimens. The flexural stress was between 49.58 and 53.23 MPa (Mean ± SD = 51.62 ± 0.99 MPa) with bending force ranging from 173.10 to 185.83 N, while the elastic modulus varied in a range of 1014.26–1119.49 MPa. The low standard deviation observed in all responses further confirms the high repeatability and reliability of the experimental method.

Considering the found flexural properties, they are similar or even slightly improved compared to the results derived from earlier works. Paper [21] reported flexural stress values of approximately 45–52 MPa. The improved mechanical performance in this work is due to the increased interlayer adhesion associated with optimized thermal conditions that improve polymer chain mobility and stress-transfer efficiency [15, 16].

From the process-structure-property point of view, a strong correlation exists between flexural strength, bending force and stiffness as all investigated mechanical responses displayed similar trends. Most values fell within small ranges of 50–53 MPa, 178–185 N and 1040–1100 MPa where the processing windows are relatively stable. Nevertheless, the lower values of the samples No. 4 and No. 6 indicate that poor thermal control could accelerate cooling and reduce interlayer diffusion leading to increased residual stresses and decreased performance [5, 17].

One of the main contributions of this study is the systematic analysis of chamber temperature effects in bending behavior for PA12 produced by FDM/FFF technology. Through experimental analysis of the correlation between thermal environment and mechanical performance, this study offers a clearer explanation of how chamber temperature can impact levels of interlayer bonding, structural integrity, and flexural reliability of semi-crystalline polymer based additive manufacturing parts. Maintaining a constant temperature within the building chamber of 35–60°C (±1°C) reduced thermal gradients between deposited layers, resulting in more consistent structures and enhanced flexural properties. The best flexural stress (53.23 MPa), bending force (185.83 N), and elastic modulus (1119.49 MPa) were observed in sample No. 3 with a nozzle temperature of 240°C, bed temperature of 65°C, and building chamber temperature of 45°C, indicating the optimal parameter combination. The results correlate with previous studies [16, 25] in which controlling the thermal environment had a direct effect on interlayer bonding and the mechanical properties of printed products made with FDM polymers.

The Taguchi analysis reiterated that flexural performance was primarily affected by building chamber temperature. The response analysis showed that flexural stress and bending force ($\Delta = 1.20$ and $\Delta = 4.40$ respectively) were primarily influenced by chamber temperature while bed temperature had a smaller influence on these responses [10]. As the building chamber temperature increased, all the analyzed responses had their gradual increase until a maximum point at around 65°C, suggesting that improved interlayer diffusion and reduced thermal gradients in printed structures are effective at this temperature. Moreover, the predominant effect of building chamber temperature on S/N ratio indicates improved process stability and lower variability in mechanical properties under controlled thermal conditions [25, 26]. From a mechanistic perspective, improved process stability and reduced variability were observed across the fabrication process for functional components, fixtures, housings, and lightweight load-bearing structures that require consistent mechanical performance to ensure reliable service behavior. Hence, it is believed that a more optimum chamber temperature can assist in lowering manufacturing defects, increasing product quality and confidence in the practical application of FDM/FFF-printed PA12 components in professional applications.

The results obtained are limited to PA12 parts processed via the FDM/FFF technique, within the parameter windows examined in this study. Moreover, the valid regions are limited to nozzle temperatures of 240–290°C, bed temperatures of 55–85°C and chamber temperatures of 35–65°C with chamber temperature being the most influential parameter governing flexural performance as well as process stability. The results offer a realistic way to select thermal processing conditions to produce PA12 components with good stiffness, strength and dimensional reliability. This study is mainly limited because the experiments were carried out at a laboratory scale with standard test specimens. The general applicability of the results would be further confirmed by validations on industrial-scale printing systems and/or more complicated geometries. In addition, future investigations should include tensile, impact, and fatigue evaluations to provide a comprehensive mechanical characterization of the FDM-printed PA12 and other semi-crystalline polymers over both short-term and long-term durability evaluations.

7. Conclusions

1. The experimental results showed that the thermal processing conditions significantly affected the flexural behavior of FDM-printed PA12 specimens. The obtained flexural stress, bending force, and elastic modulus ranged from 49.58 to 53.23 MPa, 173.10 to 185.83 N, and 1014.26 to 1119.49 MPa, respectively, demonstrating stable mechanical performance and good experimental repeatability.

2. Taguchi analysis confirmed that building chamber temperature was the most influential parameter affecting flexural performance. The optimal conditions were approximately 280°C nozzle temperature, 60–75°C bed temperature, and 65°C building chamber temperature, resulting in improved interlayer bonding and enhanced structural stability of the printed PA12 specimens. Within the investigated processing range, these findings provide practical guidance for optimizing the thermal conditions of FDM/FFF-printed PA12 components. They may contribute to improved process consistency, structural reliability, and the performance of engineering applications that require stable flexural properties.

Conflict of interest

The authors declare that they have no conflict of interest about this study, whether financial, personal, authorship, or otherwise, that could affect the study and its results presented in this paper.

Financing

This study was conducted entirely with the authors' own resources and received no grants or financial support from public or private entities.

Data availability

Data will be made available on reasonable request.

Use of artificial intelligence

The authors confirm that they did not use artificial intelligence technologies when creating the current work.

Acknowledgements

We acknowledge Ho Chi Minh City University of Technology and Engineering, and Material Testing Laboratory (HCMUTE). They allowed me to join their team and access the laboratory and research machines. With their appreciated support, it is possible to conduct this study.

Authors' contributions

Mai Tran Phong Nguyen: Conceptualization, Methodology, Software, Formal analysis, Data curation, Writing – original draft, Project administration; **Thi Hong Nga Pham**: Validation, Resources, Data curation, Writing – review & editing; **Thi My Nu Ho**: Supervision, Methodology, Formal analysis; **Duong Le**: Methodology, Formal analysis, Data curation, Writing – review & editing.

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