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OPTIMIZATION FDM PROCESS PARAMETERS FOR FLEXURAL STRENGTH IMPROVEMENT OF CARBON FIBRES REINFORCED POLYAMIDE PARTS

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Abstract

The FDM process was primarily developed only for certain types of polymer materials. Due to limited mechanical, thermal and electrical properties, these materials can't be used in industrial applications. By adding different nanoparticles and fibers to pure polymers, the aforementioned properties of pure polymers can be improved. However, optimization of process parameters is crucial to produce parts with optimal properties, such as mechanical strength. In this paper was presented the use of Taguchi method for optimization FDM process parameters (layer thickness, raster angle, wall thickness, printing speed, printing temperature and build plate temperature) to improve flexural strength of carbon fiber reinforced polyamide parts. The ranking of the most influential parameters was carried out using Taguchi analysis, and the statistical significance of the analyzed parameters was checked using ANOVA analysis. Based on the results of the Taguchi analysis and ANOVA analysis, it was concluded that the raster angle has a dominant influence on the flexural strength. Maximum flexural stress increases with the increase of the raster angle and maximum value is at a raster angle of 90º. Taguchi analysis showed that increasing build plate temperature and printing temperature are also important for improving the flexural strength.

Keywords: FDM; polymer composite; Taguchi method; flexural strength; optimization.

1. Introduction

The ISO/ASTM 52900 standard defines Additive Manufacturing (AM) as the the process of joining materials to make objects from three-dimensional (3D) model data, usually layer by layer, as opposed to subtractive manufacturing methodologies. According to the type of material used and the process physics, several of the most significant additive manufacturing procedures can be distinguished, such as fused deposition modeling (FDM), stereolithography (SLA), selective laser sintering (SLS), Ink jet modeling, etc.

The FDM process is one of the most commonly used additive manufacturing processes, which is used for modeling, prototyping, but also for the production of fully functional products in various engineering applications. The base material which is in the form of thermoplastic filament wound on a reel is delivered to the extruder of the device where it is heated and melted and then extruded to the build platform. Thermoplastic filament material such as polylactic acid (PLA), acrylonitrile butadiene styrene (ABS), poly carbonate (PC), polyamide (PA), polyethylene terephthalate (PET) and thermoplastic polyurethane (TPU) are used commonly in the FDM process [1][2][3]. However, the application of these materials, due to inadequate mechanical and physical properties, is limited only to conceptual modelling and prototyping due to the limited functionality of the manufactured parts. For this reason, in recent times, the application of various types of polymer composites for the FDM process is becoming more and more common. Different ways of reinforcement can be used for polymers, such as metal and ceramic particles, as well as continuous and short fibres of carbon, glass and Kevlar. Parts made using these composite materials have better mechanical, thermal and electrical properties, compared to the unreinforced polymer printed parts [4][5].

Ning et al. [6] presented influence of adding carbon fibres, with different content and length, on the mechanical properties of ABS printed parts including tensile properties (tensile strength, Young's modulus, toughness, yield strength, and ductility) and flexural properties (flexural stress, flexural modulus, flexural toughness, and flexural yield strength). It was concluded that the content and length of carbon fibres have a great influence on the mechanical properties of the material. Compared with the pure plastic specimen, CFRP composite specimen with 5 wt.% carbon fibre content had larger flexural strength, flexural modulus, and flexural toughness with an increase of 11.82%, 16.82%, and 21.86%, respectively. Also, by increasing the content of carbon fibres, the porosity of the material increases, which affected the deterioration of the mechanical properties for samples made with 10% carbon fibre. The effect of printing orientation on the mechanical behaviour of 3D printed carbon fibre reinforced polyamide composites was investigated in [7]. Dynamic mechanical analysis, flexural and tensile tests are performed to evaluate the mechanical behaviour of test specimens. The dynamic mechanical analysis test reveals higher storage and loss modulus in horizontal orientation as compared with angular and vertical orientation, mainly credited with better mechanical restraints imposed by carbon fibres on the matrix movement. Flexural properties of horizontally printed specimens are better as compared with the other configurations attributed to good stress transferability between the constituents. Influence of the percentage content of short carbon fibres in polyamide on the mechanical and thermal properties of PA/CF composite parts made by the FDM process was investigated in Liao et al. [8]. Compared to parts made of pure PA12, adding 10% carbon fibre to the PA12 matrix can achieve an increase in tensile strength, tensile modulus and flexural strength without significantly reducing the impact toughness of the material. The results showed that the tensile strength and flexural strength of polyamide (PA12) reinforced with 10% carbon fibre improved by 102.2% and 251.1%, respectively. Also, Spoerk et al. [9] were observed that the addition of short carbon fibres improves the flexural strength and modulus, compared to pure PP. The percentage content of fibres up to 10% enables a good material flow through the nozzle, printability, good surface quality and strong adhesion between the matrix and the fibres, compared to the fibre content of 20% and 30%.

Wang et al. [10] investigated the influence of the percentage content of short carbon fibres (CF) and glass fibres (GF) in the PEEK matrix on the mechanical properties, microstructure, surface quality and porosity of the printed samples. Test samples were made with three different fibre percentages (5%, 10% and 15%). The results show that the addition of CF/GF to PEEK can significantly increase the tensile and flexural strength at the expense of reducing the ductility. A lower percentage fibre content of 5% results in an increase in all analysed mechanical properties, improving surface quality and reducing porosity. It was observed that with GF/PEEK, a stronger adhesion between the fibres and the matrix is enabled than with CF/PEEK composites.

The aim of this paper was to determine the effect and optimization of process parameters (layer thickness, raster angle, wall thickness, printing speed, printing temperature and built plate temperature) to improve flexural strength of FDM printed carbon fibre reinforced polyamide parts using Taguchi method. In this research, a large number of input parameters were included, some of which have not been analysed in previous research when analysing the impact on flexural strength. Hence, this research provides a complete picture of the influence of all important FDM process parameters on the flexural strength of the carbon fibres reinforced polyamide parts.

2. Experimental procedure

Appropriate equipment and devices for the production of test samples, as well as appropriate equipment for testing mechanical properties, were used for the realization of experimental research. All test samples with process parameters defined by the experiment plan were produced on one material extrusion device (FDM device), Ultimaker S3 (Fig. 1.). The Ultimaker S3 3D printer enables the heating of the extruder up to 280 °C, and the use of special nozzles (CC nozzles) for the extrusion of composite polymer materials (Fig. 1a.). These nozzles have a diamond tip that has a high resistance to abrasion, which is very important when using composite materials. Another important feature of this device is the heated build plate (Fig. 1b.). The build plate of this device can be heated up to 140 °C, which is especially important when using certain materials that have weak adhesion to the surface and are sensitive to high temperature gradients, which can lead to deformations of parts as well as delamination due to insufficient cohesion between individual layers. This problem is even more pronounced when using polymer composite materials reinforced with short fibres where, in addition to the adhesion of the first layer and interlayer cohesion, it is also necessary to achieve good adhesion between the polymer matrix and the fibres. This is achieved by choosing the appropriate build plate temperature and extrusion temperature. The material used in this device is a thermoplastic filament with a diameter of 2.85 mm wound on a reel and placed on a suitable material holder on the device (Fig. 1c.) and delivered to the extruder through special guides using a material feeder (Fig. 1d).

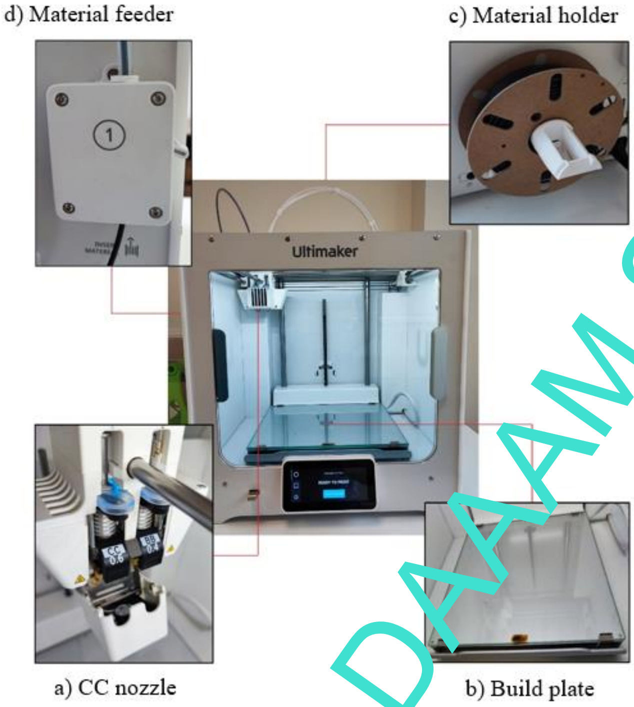

Fig. 1. Ultimaker S3 3D printer

A polymer composite material based on polyamide (PA6) reinforced with 10% short carbon fibres was used to make the test samples. One such commercially available filament material that can be used on the Ultimaker S3 printer is the "DSM Novamid® ID1030 CF10" material. The manufacturer of the material states that parts made by the FDM process from this material can have a strength close to that which can be achieved by injection moulding.

The dimensions of the specimens were determined in accordance with ISO 178 standard (standard test method for flexural properties of plastics) (Fig. 2.). Specimens was designed using Solidworks software. Models of test specimens were saved in STL format which then were imported into 3D printing software „Ultimaker Cura". Regarding the software and printing configurations, the toolpath calculation (G-code) was made. The machine reads the G code and prints the specimens according to the instruction provided (Fig. 3.).

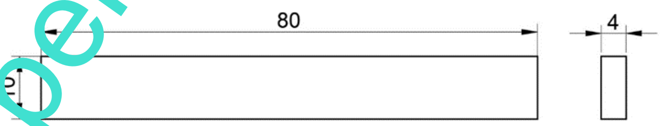

Fig. 2. Dimensions of the test specimen according to ISO 178

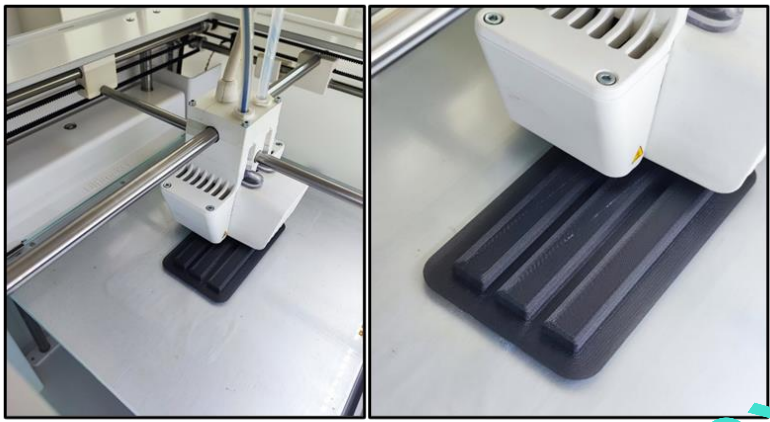

Fig. 3. Printing the specimens

After printing the samples, bending tests were performed with the aim of determining the flexural properties. For testing, the Schimadzu AGS-X universal testing machine was used, which achieves a maximum force of 10 kN. The test samples are placed between two bending measuring cells. The lower part of the measuring cells for bending has two cylindrical supports, and the upper measuring cell is movable and has one cylindrical edge that acts on the test sample (Fig. 4.). Distance between the supports is set to 64 mm and the test speed, in accordance with ISO 178, is 5 mm/min. All results and diagrams were tracked and saved using the "Trapezium" software (Fig. 4.).

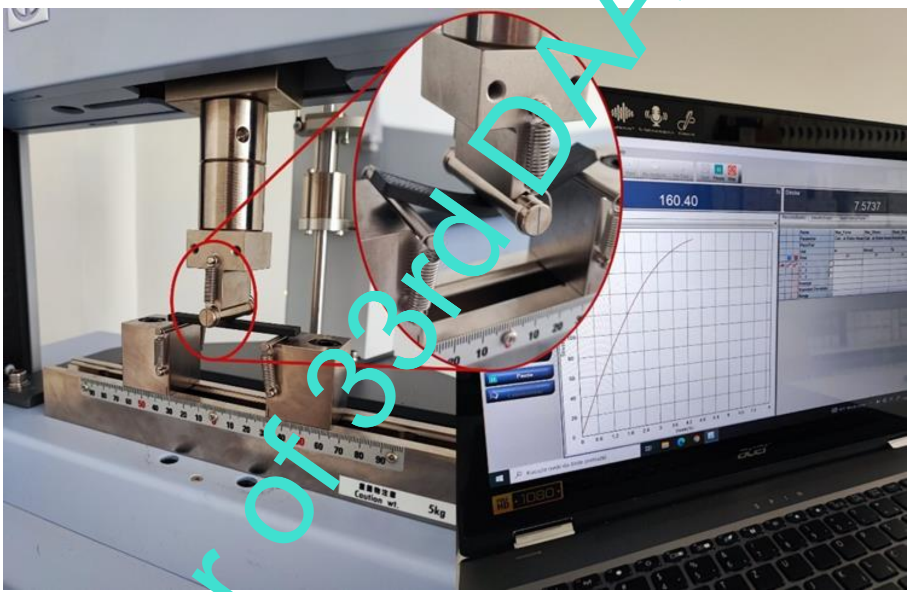

Fig. 4. Bending testing on Shimazu AGS-X

2.1 Design of experiments

To define the design of the experiment, a Taguchi robust plan was used which based on orthogonal arrays. The significance process parameters were tested by statistical analysis of the results. Selected input parameters (independent variables) and their variation levels are shown in table 1. Constant input parameters are given in table 2.

Factor	**Symbol**	**Unit**	**Level**		
			(1)	(2)	(3)
Layer thickness	A	[mm]	0,1	0,2	0,3
Wall thickness	B	[mm]	0,8	1,4	2
Raster angle	C	[º]	0	45	90
Printing speed	D	[mm/s]	40	60	80
Printing temperature	E	[ºC]	240	260	280
Build plate temperature	F	[ºC]	50	90	130

Table 1. Control factors and their levels

Infill	100 %
Orientation	Flat
Material	DSM Novamid® ID1030 CF10
Nozzle	Diamond nozzle (CC nozzle) with a diameter of 0.6 mm

Table 2. Constant process parameters

Based on the selected input factors and the defined levels of variation, an experimental matrix was formed in accordance with the used experimental methodology. According to the Taguchi method, for the analysis of the selected six numerical variables that vary on three levels, a total of 27 experimental tests are required based on the use of the standard orthogonal array L27 (3^6). The matrix of the experimental design according to the Taguchi design in coded form was given in table 3.

No.	**Controlled input factors**					
	A	**B**	**C**	**D**	**E**	**G**
1	1	1	1	1	1	1
2	1	1	1	1	2	2
3	1	1	1	1	3	3
4	1	2	2	2	1	1
5	1	2	2	2	2	2
6	1	2	2	2	3	3
7	1	3	3	3	1	1
8	1	3	3	3	2	2
9	1	3	3	3	3	3
10	2	1	2	3	1	2
11	2	1	2	3	2	3
12	2	1	2	3	3	1
13	2	2	3	1	1	2
14	2	2	3	1	2	3
15	2	2	3	1	3	1
16	2	3	1	2	1	2
17	2	3	1	2	2	3
18	2	3	1	2	3	1
19	3	1	3	2	1	3
20	3	1	3	2	2	1
21	3	1	3	2	3	2
22	3	2	1	3	1	3
23	3	2	1	3	2	1
24	3	2	1	3	3	2
25	3	3	2	1	1	3
26	3	3	2	1	2	1
27	3	3	2	1	3	2

Table 3. Experimental matrix in coded form

3. Results and Discussions

During the examination of the flexural mechanical properties of the test samples made of the material "Novamid® ID1030 CF10" it was not possible to unambiguously determine the character of the material's behaviour. Depending on the process parameters, some samples showed a brittle behaviour without a pronounced yield point, while some samples showed a plastic behaviour (Fig. 5.). In each case, the material broke and the maximum flexural stress could be clearly determined which occurred before break.

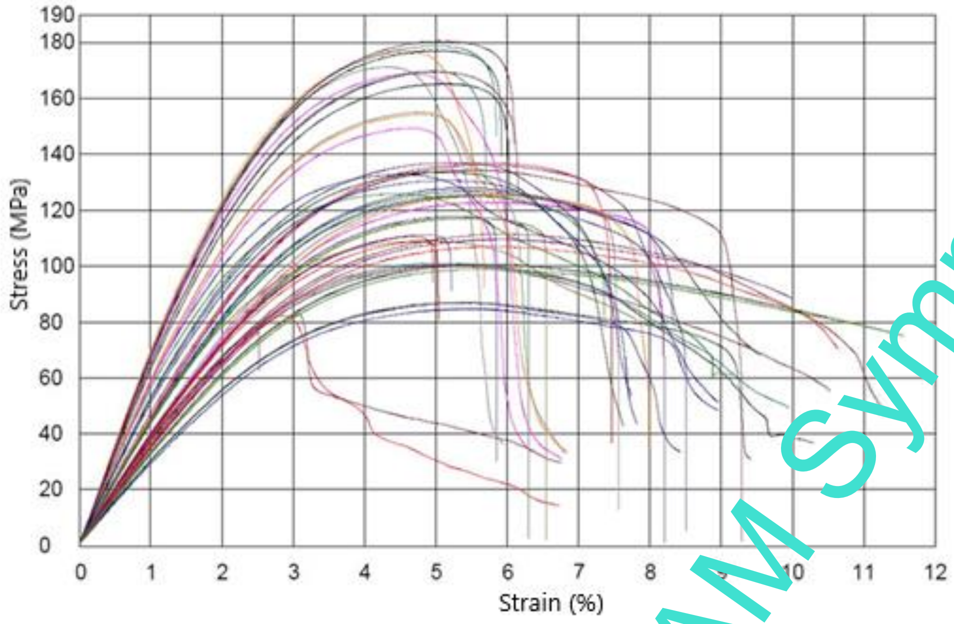

Fig. 5. The stress–strain curves of the test samples

The flexural strength test was carried out according to the previously defined matrix of the experiment plan. For each experimental test, three repeated measurements were performed, and the mean values of the maximum flexural stress σ_{fm}, as well as the values of the signal-to-noise ratio (*S/N*) are shown in table 4.

No.	Controlled input factors						Output	
	A	B	C	D	E	G	σ_{fm}	S/N
1	0,1	0,8	0	40	240	50	77,13	37,74
2	0,1	0,8	0	40	260	90	117,43	41,40
3	0,1	0,8	0	40	280	130	125,93	42,00
4	0,1	1,4	45	60	240	50	100,60	40,05
5	0,1	1,4	45	60	260	90	126,70	42,05
6	0,1	1,4	45	60	280	130	136,80	42,72
7	0,1	2	90	80	240	50	132,33	42,43
8	0,1	2	90	80	260	90	176,33	44,93
9	0,1	2	90	80	280	130	180,20	45,12
10	0,2	0,8	45	80	240	90	86,97	38,79
11	0,2	0,8	45	80	260	130	111,17	40,92
12	0,2	0,8	45	80	280	50	100,90	40,08
13	0,2	1,4	90	40	240	90	154,80	43,80
14	0,2	1,4	90	40	260	130	168,20	44,51
15	0,2	1,4	90	40	280	50	137,00	42,73
16	0,2	2	0	60	240	90	108,63	40,72
17	0,2	2	0	60	260	130	123,13	41,81
18	0,2	2	0	60	280	50	114,03	41,14
19	0,3	0,8	90	60	240	130	150,13	43,53
20	0,3	0,8	90	60	260	50	133,20	42,49
21	0,3	0,8	90	60	280	90	143,90	43,16
22	0,3	1,4	0	80	240	130	105,67	40,48
23	0,3	1,4	0	80	260	50	89,80	39,07
24	0,3	1,4	0	80	280	90	105,97	40,50
25	0,3	2	45	40	240	130	121,00	41,66
26	0,3	2	45	40	260	50	111,00	40,91
27	0,3	2	45	40	280	90	123,53	41,84

Table 4. The experimental data

Based on the data shown in table 4 and through the analysis of mean values, the character of the influence of FDM process parameters on the maximum flexural stress σ_{fm} was presented. The diagram of the partial influences of the analysed input parameters was shown in the form of a graphic in figure 6.

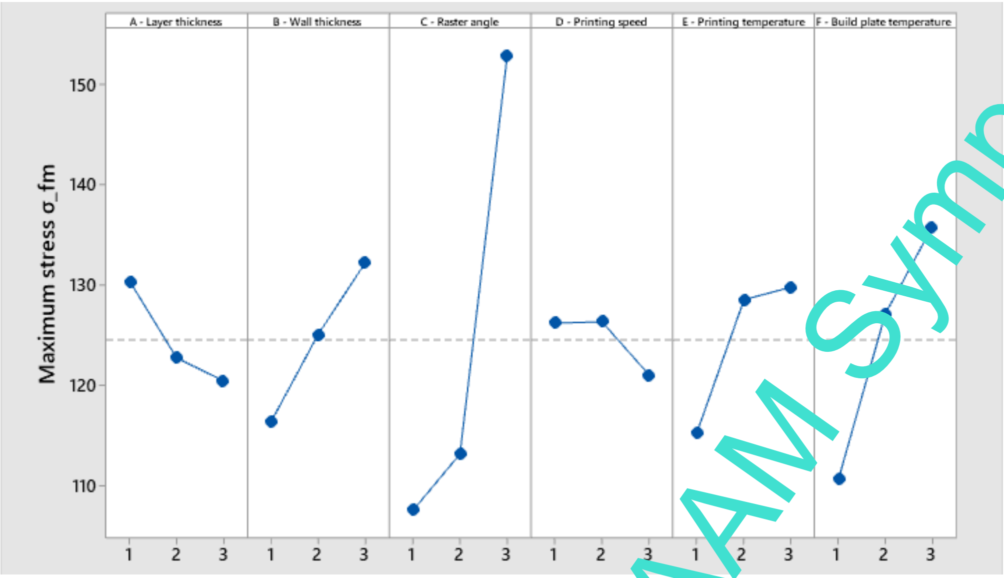

Fig. 6. Diagram of the partial influences of the analysed input parameters

Analysing the diagrams shown, it can be concluded that all analysed parameters have a clear influence on the flexural strength, where it can be seen that the raster angle has the greatest influence on the range of variability of the mean values of the maximum stress, i.e., that the raster angle has the greatest influence on the flexural strength. This influence can be explained with the direction of deposition of the material in the XY plane, which has the greatest influence on the anisotropic behaviour of the material in the XY plane. From the diagram it can be seen that the value of the maximum flexural stress increases with the increase of the raster angle and that the maximum stress is at a raster angle of 90°. After the raster angle, the build plate temperature had the greatest influence on the flexural strength. During flexural tests, shear stresses occur between individual layers of material. In order to prevent delamination between individual layers of material under shear stresses, a stronger cohesion between the layers of material is required. Increasing the printing temperature enables better melting of the material and stronger bonding to the previous layer. However, if the temperature of the previous layer is much lower than the temperature of the material that has just been applied, due to large temperature gradients, thermal stresses can occur within the material, which can reduce the interlayer strength. By increasing the build plate temperature, the temperature difference (gradient) between the temperature of the previous layer and the temperature of the newly applied material is reduced. This results in a stronger interlayer cohesion and, therefore, a higher total flexural strength. The layer thickness, walls thickness and printing speed had a smaller influence on the flexural strength than the other analysed parameters. It can be observed that by increasing layer thickness and printing speed, the flexural strength decreases.

Based on the individual values of the maximum stress σ_{fm}, the values of the signal-to-noise ratio (*S/N*) were calculated for each experimental test, based on which the significance of the influence of individual factors on the flexural strength was determined, and then the average values of the signal-to-noise ratio (S/N_{avg}) for individual levels of all six analysed input parameters were determined (Table 5.).

Level	A	B	C	D	E	F
1	42,05	41,12	40,54	41,84	41,02	40,74
2	41,61	41,77	41,00	41,96	42,01	41,91
3	41,51	42,28	43,63	41,37	42,14	42,53
Range	0,54	1,16	3,09	0,60	1,12	1,79
Rank	6	3	1	5	4	2

Table 5. Mean values of the signal-to-noise ratio

Based on the previous table, a ranking of the dominant input parameters can be performed, which confirms that the most dominant influence on the flexural strength has the raster angle, followed by the build plate temperature, the wall thickness and the printing temperature. Layer thickness and printing speed have the least influence. The previous table can also be displayed using a diagram of the partial influence of individual input parameters on the mean value of the signal-to-noise ratio (S/N_{avg}) (Fig. 7.). From these diagrams it is possible to determine the optimal parameters that achieve the maximum value of flexural strength.

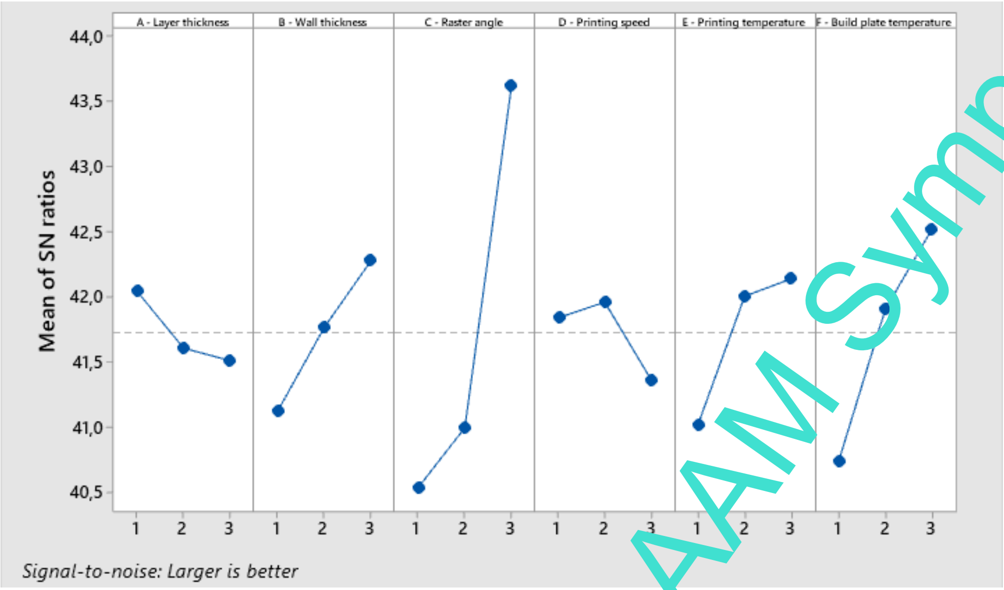

Fig. 7. Plot of mean values of the signal-to-noise ratio

Optimal values of process parameters were adopted for those levels at which S/N_{avg} is maximum. In this case, the optimal parameters for maximizing flexural strength would be:

- layer thickness: 0,1 mm,
- wall thickness: 2 mm,
- raster angle: 90º,
- printing speed: 60 mm/s,
- printing temperature: 280 °C,
- build plate temperature: 130 ºC.

In order to determine the statistical significance of the analysed FDM parameters, data processing was performed through analysis of variance (ANOVA) for a significance level of 5%. By analysing the influence of individual parameters through ANOVA analysis, the percentage contribution of parameters on the experimental results can be obtained. The results of the ANOVA analysis of the signal-to-noise ratio *S/N* are shown in table 6.

Source	DF	Seq SS	Contribution	Adj SS	Adj MS	F-Value	P-Value
A	2	1,466	1,72%	1,466	0,7330	2,41	0,126
B	2	6,072	7,12%	6,072	3,0361	10,00	0,002
C	2	50,137	58,76%	50,137	25,0686	82,55	0,000
D	2	1,790	2,10%	1,790	0,8948	2,95	0,086
E	2	6,756	7,92%	6,756	3,3778	11,12	0,001
F	2	14,859	17,41%	14,859	7,4297	24,47	0,000
Error	14	4,252	4,98%	4,252	0,3037		
Total	26	85,332	100,00%				

Table 6. The results of the ANOVA analysis of the signal-to-noise ratio

According to the results presented in table 6, it can be determined which members are statistically significant. Based on the p-value, statistically significant parameters, for a significance level of 5%, are those parameters whose p-value does not exceed 0.05. Therefore, statistically significant parameters would be: wall thickness (*B*), raster angle (*C*), printing temperature (*E*) and build plate temperature (*F*). The influence of the analysed parameters can also be estimated based on the percentage contribution of each parameter in the total variation of the experimental results. This confirms that the raster angle has the greatest impact on flexural strength with a contribution of 58.76%. On second place is the build plate temperature with contribution of 17.41%. Although the parameters of the wall thickness and the printing temperature do not have a great percentage contribution in the total variation of the results, based on their p - values they are classified as statistically significant parameters. The layer thickness and printing speed, due to their p-value as well as the small percentage contribution in the total variation of the results, are statistically insignificant and their influence compared to the other analysed parameters is negligible. The error percentage of 4.98% is relatively small and it can be assumed that it arose as a result of external uncontrolled influences, i.e., noise.

4. Conclusion

The aim of this work was to optimize selected FDM process parameters (layer thickness, raster angle, wall thickness, printing speed, printing temperature and build plate temperature) to improve flexural strength of carbon fibre reinforced polyamide parts. Optimization of the selected parameters was carried out using Taguchi analysis, and the statistical significance of the analysed parameters was checked using ANOVA analysis Based on the conducted experimental research on the influence of selected FDM process parameters on the flexural strength of parts made of polyamide reinforced with short carbon fibres, the following conclusions can be drawn:

1. Using Taguchi analysis, optimal parameters were determined with the aim of maximizing flexural strength. The optimal parameters are: minimum value of layer thickness (0.1 mm), maximum value of wall thickness (2 mm), raster angle in the direction of load (90°), average value of printing speed (60 mm/s), maximum value of printing temperature (280 °C), maximum value of the build plate temperature (130 °C).
2. Based on the results of the ANOVA analysis of the *S/N* ratio, the dominant parameters with respect to flexural strength were selected and ranked. Four statistically significant parameters were singled out and ranked according to dominance: raster angle, build plate temperature, printing temperature and wall thickness. The parameters layer thickness and printing speed are marked as statistically insignificant.
3. The highest value of the flexural strength is achieved for a raster angle of 90°. With a contribution of 58.76% and p-value of 0.000, it represents the most dominant and statistically significant parameter in the analysis of the influence on flexural strength.
4. The influence of the build plate temperature is directly proportional to the maximum flexural stress. By increasing the build plate temperature, the temperature difference (gradient) between the temperature of the previous layer and the temperature of the new deposited material is reduced. This results in a stronger interlayer cohesion and, therefore, a higher flexural strength.
5. The influence of the printing speed is inversely proportional to the value of the maximum flexural stress. At higher printing speed, an insufficient amount of material is deposited, which prevents a strong cohesion between the raster and the previously applied layers of material.
5. The influence of the wall thickness is directly proportional to the value of the maximum flexural stress. The highest value of flexural strength is achieved with a wall thickness of 2 mm.
6. Based on the results of the ANOVA analysis, it is concluded that the influences of layer thickness and printing speed are statistically insignificant parameters.

The future research is to investigate the effect of different polymer composite materials (type of polymer matrix, fibre type, fibre length and fibre content) on the mechanical properties of FDM printed parts.

5. Acknowledgments

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