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L. Tumarchenko*,
orcid.org/0000-0001-7973-7475,
Ye. Vyshnepolskyi,
orcid.org/0000-0002-8048-7976,
D. Pavlenko,
orcid.org/0000-0001-6376-2879

National University "Zaporizhzhia Polytechnic", Zaporizhzhia, Ukraine
*Corresponding author e-mail: hurina97@gmail.com

IMPROVING ACCURACY OF DUAL-PURPOSE NYLON PARTS FABRICATED BY FUSED DEPOSITION MODELING

Purpose. To analyze the dependence of the dimensional accuracy of polyamide 6 (Nylon 6, PA6) parts on the process parameters of additive manufacturing using fused deposition modeling (FDM) to ensure rapid repair of military and mining equipment in field conditions.

Methodology. The samples were fabricated using FDM method on a Prusa i3-type 3D printer, with G-code generated via Slic3rPE software. The material used in the study was Plexiwire Nylon (PA6) Filament ∅1.75 mm, compliant with ISO/ASTM 52903-1:2020. The study investigated the relationship between the technological parameters of the FDM process and the dimensional accuracy of the resulting parts. The following parameters were analyzed: layer height, printing speed, extrusion temperature, bed temperature, extrusion multiplier, deposited strand width, number of shells, infill pattern, infill density and number of solid top and bottom layers. The influence of these parameters on dimensional stability was assessed by measuring the linear dimensions "*a*", "*b*" and "*c*" in the respective coordinate planes "*X*", "*Y*" and "*Z*". The criterion for evaluating dimensional accuracy was the relative deviation of the measured dimensions from their nominal values. Experimental data were processed using TIBCO STATISTICA software to identify the most influential factors and the nature of their interactions.

Findings. It was established that the extrusion multiplier, infill density and infill pattern had the greatest influence on the dimensional accuracy of the printed parts. For the "*Y*" axis, the optimal parameters were extrusion multiplier of 1.1, printing speed of 40 mm/s, 100 % infill density, rectilinear infill pattern, deposited strand width of 0.49 mm, 4 shells and bed temperature of 100 °C. For the "*X*" and "*Z*" axes, the optimal parameters included an extrusion multiplier of 0.9, layer height of 0.15 mm and concentric infill pattern. Regression models were developed to predict the dimensional accuracy of parts along the three principal coordinate axes based on the selected process parameters.

Originality. Optimal combinations of FDM printing parameters for improving the dimensional accuracy of Nylon 6 parts suitable for use in field conditions were identified. The significant role of individual parameters in determining accuracy along specific coordinate axes was demonstrated.

Practical value. The proposed technological recommendations enable the production of functional replacement parts without the need for stationary repair facilities. This allows for the rapid repair of military and mining equipment using portable 3D printers in remote or hard-to-access locations, ensuring high dimensional accuracy, wear resistance, and functionality of the printed components.

Keywords: *fused deposition modeling, PA6, accuracy, process parameters, analysis of variance, regression analysis*

Introduction. Modern challenges related to the operation and maintenance of technical equipment under critical conditions drive the search for innovative solutions for rapid repair and part replacement. Over the past decade, additive manufacturing (AM) has evolved from a prototyping tool into a viable alternative to conventional subtractive manufacturing methods, gaining increasing significance in both academic and industrial domains. The need for rapid equipment repair in field conditions – where access to stationary repair facilities is limited or unavailable - has become particularly pressing. The use of high-performance polymers such as Nylon 6 (PA6), which is characterized by high strength, wear resistance, and chemical durability, enables the on-site fabrication of functional replacement parts. Military equipment operating under heavy loads in combat environments, as well as mining machinery exposed to harsh, high-load conditions, requires fast and efficient restoration methods that ensure the required accuracy and functionality of the replacement components.

The use of compact FDM printers within maintenance units deployed near the front line reduces the need to send military equipment to rear repair facilities, thereby increasing the efficiency and speed of restoration. For instance, modern firearms incorporate a substantial number of polymer components, the replacement of which – provided adequate manufacturing accuracy is achieved – can be ensured through this technology [1, 2]. Military equipment and hardware contain numerous plastic parts (e.g., buttons, plugs, sensor housings), the replacement of which in field conditions presents significant logistical challenges and leads to increased repair times. FDM printing enables the production of such components directly on-site [3]. Even more effective is the use of FDM printers for field repair of unmanned aerial vehicles (UAVs), which is especially relevant for small-scale models that frequently sustain damage during operation [4].

The use of FDM printing is equally relevant for restoring worn-out components of mining equipment, as mining sites are typically located far from centralized repair facilities [5]. A significant portion of the equipment used by miners in their professional activities includes polymer-based components. Under harsh operating conditions, these parts are prone to wear and require frequent replacement, which negatively impacts the pace of extraction processes. FDM printing offers an effective solution to these challenges [6].

The optimization of FDM process parameters to enhance the dimensional accuracy of functional parts represents a pressing scientific and practical task, the resolution of which will contribute to improved operational efficiency of military and mining equipment under extreme conditions.

Literature review. Fused Deposition Modeling (FDM) is a straightforward additive manufacturing (AM) technique in which a filament is extruded through a heated nozzle and deposited layer by layer onto a build platform to form the desired object [7]. This method typically employs thermoplastic polymer filaments. Among them, Nylon (PA6) demonstrates significant potential due to its high tensile strength and excellent wear resistance. However, the limited number of studies dedicated to this polymer, along with its specific processing characteristics, considerably restricts its broader application in 3D printing technologies.

Studies conducted by Xu Zhang and co-authors [8] demonstrate that polymer components made of pure polyamide and fabricated using FDM additive manufacturing technology exhibit significant geometric distortions and dimensional instability. The primary mechanism underlying these defects is the development of internal stresses generated during the structural organization of polymer macromolecules [8]. To minimize deformation processes, it is necessary to disrupt the molecular order and reduce the crystallization tendency of the polymer system [9, 10].

Despite the technological challenges associated with processing, Nylon holds significant industrial potential due to its advantageous properties [11]. It has found wide application in the automotive industry for manufacturing components such as gears, bearings, and other parts, owing to its self-lubricating behavior, high wear resistance, and thermal stability. These characteristics, combined with its mechanical strength, make it a valuable material for military equipment components as well.

However, the promising prospects for PA6-based parts are not yet fully supported by the volume of research. Li and colleagues [12] investigated the properties of PA12, focusing on its rheological behavior, interlayer bonding quality, and mechanical performance in the context of FDM applications. They found that increasing the extrusion temperature reduces the melt viscosity, which improves interlayer adhesion. As a result, nearly dense PA12 parts were produced with tensile strength reaching up to 58.88 MPa. Liao et al. developed carbon fiber/PA12 composite filaments, achieving a tensile strength of up to 93.8 MPa [13].

The study by Vishwas M. and colleagues [14] concluded that the orientation angle and shell thickness are the most influential process parameters affecting the mechanical properties of ABS and nylon. They found that, for ABS, the highest tensile strength was achieved with a layer height of 0.2 mm, an orientation angle of 150°, and a shell thickness of 1.2 mm. In terms of dimensional accuracy, the optimal combination was a 0.2 mm layer height, a 300° orientation angle, and a 0.8 mm shell thickness. For nylon, the maximum tensile strength was observed with a 0.1 mm layer height, a 300° orientation angle, and a 1.2 mm shell thickness. To ensure dimensional accuracy, the best results were obtained with a 0.3 mm layer height, a 150° orientation angle, and a 0.4 mm shell thickness.

In the study by J. W. Stansbury and M. J. Idacavage [15], PA12 specimens were subjected to tensile testing to investigate the influence of various factors – such as infill percentage, layer height, number of contours, and their interactions – on mechanical properties, manufacturing time, and part weight using a Design of Experiments (DOE) approach. The analysis revealed that the layer height and the number of contours had a significant impact on fabrication time. In addition, the number of contours and infill density strongly influenced both mechanical performance and build time. An increase in the number of contours led to improved mechanical strength and greater part weight but also resulted in longer production time. Experimental results showed that the maximum tensile load (533 N) and elongation (595.5 %) were achieved at layer heights between 0.2 and 0.3 mm. Reducing the layer height at the same printing speed increased the cooling rate, which in turn significantly improved strength while decreasing elongation.

Liao and colleagues [16] investigated the mechanical properties, crystallization behavior, dynamic and thermal characteristics, as well as the micromorphology of PA66 specimens. They concluded that the crystallization behavior and mechanical performance of the samples were strongly dependent on the process parameters. The voids between polymer filaments decreased as the nozzle and bed temperatures increased, almost completely disappearing at bed and nozzle temperatures of 225 and 290 °C, respectively. The tensile strength of PA66 samples increased by 29.5 % (from 68.07 to 88.17 MPa) as the nozzle temperature rose from 270 to 290 °C. Moreover, the elongation at break significantly improved (from 2.38 to 13.17 %), indicating strain hardening and enhanced plastic deformation of the material.

In study [17], the authors assessed the dimensional accuracy and surface quality of a new polyamide 6 and a PA6-based composite containing 10 % filler, considering variations in printing speed and temperature. It was found that temperature, speed, and filler content significantly influenced their rheological behavior. Pure PA6 exhibited optimal performance at a lower extrusion temperature (240 °C) and a higher print speed (80 mm/s). In contrast, the PA6 composite with 10 % filler demonstrated the best surface quality at 240 °C and print speeds of 60–80 mm/s.

Lay, et al. [18] conducted a comparative study of the physical and mechanical properties of PLA, ABS, and PA6 manufactured using both FDM and injection molding. One of the key findings was that the crystallinity of PLA and Nylon 6 samples produced via FDM increased compared to those made by injection molding. However, tensile strength, Young's modulus, elongation at break, and impact strength were lower in FDM-printed parts than in molded ones. Notably, the percentage difference in Young's modulus for FDM-printed Nylon 6 was only 14 %, the lowest among the tested thermoplastics. These results indicate that Nylon 6 exhibits the smallest performance gap between FDM and injection molding compared to PLA and ABS.

In study [19], the mechanical properties of nylon parts fabricated using FDM were investigated. The results indicated that nozzle temperature and raster orientation are critical parameters directly influencing mechanical performance. The most favorable results were obtained at the highest nozzle temperatures combined with a diagonal raster orientation.

Ramesh M. and colleagues [20] studied the 3D printing of nylon components. Infill density was found to have the highest contribution coefficient affecting the mechanical properties of nylon during the printing process. A layer height of 0.1 mm influenced properties such as tensile, impact, and flexural strength, whereas Shore D hardness was increased at a layer height of 0.3 mm. The optimal average tensile strength under these conditions was 43.25 MPa, which fell within the predicted range. Similarly, for flexural strength, impact strength, and hardness, the values obtained under optimal parameters were also within the expected ranges. As demonstrated by the authors of [21], ensuring dimensional accuracy during the printing process, combined with appropriate post-processing, can significantly enhance the quality of the parts. Considerable attention in recent literature has been devoted to studying the effect of thermal treatment on the mechanical properties of PA6 parts manufactured via FDM. Study [22] presented an experimental investigation that identified optimal thermal treatment regimes to improve both the strength and ductility of nylon samples. The research emphasized the importance of considering cooling methods and the interaction of processing factors, which play a decisive role in enhancing the performance of PA6 parts.

In summary, most existing studies focus on the influence of process parameters on the mechanical properties of nylon parts, whereas investigations into their effects on dimensional accuracy and surface roughness remain relatively limited. Therefore, research on the impact of FDM process parameters on the accuracy of nylon components represents a relevant and timely scientific and engineering challenge in modern mechanical manufacturing.

Materials and methods. The material used in the study was Plexiwire Nylon (PA6) Filament ∅1.75 mm, compliant with ISO/ASTM 52903-1:2020. It is characterized by high tensile strength combined with excellent resistance to elevated temperatures and aggressive chemicals, as well as anti-friction properties. Its main drawback is its high hygroscopicity.

The quality of 3D-printed parts is significantly influenced by storage conditions and pre-drying of the filament. In this study, the filament was pre-dried in a Creality DRY BOX 2.0 for 3 hours at 80 °C, following the manufacturer's recommendations. Previous studies have shown that for this material, reliable first-layer adhesion is essential; therefore, an ELASTAN-printed substrate was used to ensure proper bed adhesion.

The samples were printed on a Prusa i3-type 3D printer. The printer featured a Bowden extrusion system with a single extruder, a 0.4 mm nozzle diameter, a maximum extruder temperature of 280 °C, a maximum bed temperature of 120 °C, and a maximum print speed of 100 mm/s. The positioning accuracy was 0.0125 mm in the "*X*" and "*Y*" axes, and 0.0025 mm in the "*Z*" axis.

During sample fabrication (Fig. 1), two infill patterns were used: rectilinear and concentric (Fig. 2).

The influence of FDM process parameters on the dimensional accuracy of printed parts along the coordinate axes "*X*", "*Y*", and "*Z*" was investigated by measuring the dimensions "*a*", "*b*", and "*c*", which correspond to these axes. Measurements were performed using a micrometer with an accuracy of ±0.004 mm. Dimensional accuracy was evaluated based on the relative deviation from the nominal dimension in the respective direction. Data processing was carried out using TIBCO STATISTICA software.

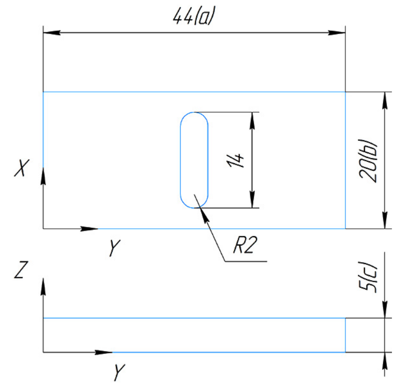
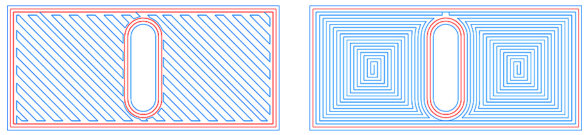


Fig. 1. Schematic of the specimen used in the experiment



a *b*

Fig. 2. Visualization of the rectilinear (a) and concentric (b) infill patterns used during specimen printing

Results and discussion. The aim of the study is to determine the combined influence of FDM process parameters on the dimensional accuracy of PA6 parts along the principal geometric axes. To minimize the total number of experiments, a fractional factorial design $2 \cdot 10^{-5}$ was selected. For each process parameter, two levels of variation were used (Table 1).

The response functions selected for the study were the dependent variables: relative deviation along the principal axes (δa, δb, δc). The implementation of a two-level fractional factorial experimental design and the obtained response values for PA6 specimens (Table 2) enabled subsequent analysis of variance and regression analysis.

Table 1

FDM process parameters and their levels of variation

FDM process parameters		Levels of variation	
		−1	+1
1	Layer height, mm	0.15	0.3
2	Printing speed, mm/s	40	80
3	Infill density, %	25	100
4	Infill pattern	rectilinear	concentric
5	Bed temperature, °C	100	120
6	Deposited strand width, mm	0.49	0.52
7	Number of shells	2	4
8	Number of top and bottom solid layers	2	4
9	Extrusion temperature, °C	255	265
10	Extrusion multiplier	0.9	1.1

The analysis of variance and regression analysis of the model confirm a strong influence of FDM process parameters and their interactions on the relative dimensional deviation along the "*Y*" axis (δa). The ANOVA results show that, for all main factors and several of their interactions, the calculated F-ratios significantly exceed the critical values (Table 3).

Analysis of the regression results (Table 4) indicates that the t-statistics for all presented coefficients exceed the critical value at the corresponding degrees of freedom (df = 14).

The coefficient of determination ($R^2 = 0.98$) and the adjusted coefficient of determination (Adj. $R^2 = 0.95$) indicate the high quality of the developed regression model, as it explains over 98 % of the variation in the dependent variable. The small magnitude of the residual variance (0.01), compared to the variance of the factors, further confirms the adequacy of the constructed model.

To illustrate the ranking of factors by their relative influence on the dimensional deviation along the "*Y*" axis, a Pareto chart is presented (Fig. 3).

It was found that the extrusion multiplier had the greatest influence on dimensional accuracy along the "*Y*" axis. The relative deviation of dimension "*a*" was also noticeably affected by the interaction between infill density and extrusion multiplier, printing speed, infill density, the interaction between layer height and printing speed, among others (Fig. 3).

Taking into account the statistically significant coefficients, the regression model describing the influence of FDM process parameters on the relative deviation along the "*Y*" axis in natural units is as follows

$$\delta a = 4.97 - 39.07 \cdot LH - 0.04 \cdot PS + 0.01 \cdot ID - 1.03 \cdot EM - 0.01 \cdot BT + 0.01 \cdot ET - 4.56 \cdot IP - 12.0 \cdot DSW + 0.09 \cdot LH \cdot PS - 0.93 \cdot LH \cdot IP - 0.02 \cdot LH \cdot ID + 6.67 \cdot LH \cdot EM + 53.33 \cdot LH \cdot DSW + 0.53 \cdot LH \cdot NS - 0.0001 \cdot PS \cdot ID + 0.03 \cdot PS \cdot EM + 0.02 \cdot ET \cdot IP + 0.005 \cdot EM \cdot ID,$$

where *LH* is a layer height, mm; *PS* is printing speed, mm/s; *ID* is infill density, %; *EM* is an extrusion multi-

Table 2

Obtained response function values

No.	δa, %	δb, %	δc, %	No.	δa, %	δb, %	δc, %	No.	δa, %	δb, %	δc, %
1	–0.68	0.2	–1.60	12	–1.0	–0.9	0.2	23	–0.8	1.3	–2.6
2	–0.77	0.6	0.40	13	0.07	0.7	0.0	24	–1.1	1.4	2.0
3	–0.75	0.7	–1.60	14	–1.27	0.6	0.2	25	0.4	3.8	5.8
4	–0.80	0.9	–0.80	15	–1.36	0.2	–3.8	26	–0.18	1.9	12.4
5	–0.73	–0.4	–1.80	16	–1.34	–0.7	2.4	27	–0.16	2.2	9.0
6	–0.82	–0.8	–0.80	17	–0.70	0.5	–1.8	28	0.07	1.5	10.0
7	–0.98	–1.2	–6.40	18	–0.41	1.0	4.6	29	0.36	3.5	3.0
8	–0.80	0.3	1.00	19	–0.98	0.4	–1.8	30	0.02	2.6	10.2
9	–0.30	0.4	–2.00	20	–0.25	1.2	6.8	31	–0.6	1.9	9.0
10	–0.45	0.8	–0.20	21	–0.68	0.6	0.0	32	0.0	1.4	9.8
11	–1.23	–0.5	–2.60	22	–0.86	0.0	5.8	–	–	–	–

Table 3

Results of analysis of variance

Factor	*SS*	*df*	*MS*	*F*	*p*
(2)Printing speed	0.825612	1	0.825612	81.5060	0.000000
(3)Infill pattern	0.231200	1	0.231200	22.8245	0.000295
(4)Infill density	0.825613	1	0.825613	81.5060	0.000000
(5)Extrusion multiplier	1.665313	1	1.665313	164.4028	0.000000
(6)Extrusion temperature	0.072200	1	0.072200	7.1277	0.018308
(7)Bed temperature	0.088200	1	0.088200	8.7073	0.010529
(9)Number of shells	0.441800	1	0.441800	43.6153	0.000012
1 by 2	0.515112	1	0.515112	50.8529	0.000005
1 by 3	0.135200	1	0.135200	13.3472	0.002607
1 by 4	0.099012	1	0.099012	9.7747	0.007431
1 by 5	0.094613	1	0.094613	9.3403	0.008544
1 by 8	0.112813	1	0.112813	11.1371	0.004887
1 by 9	0.057800	1	0.057800	5.7061	0.031541
2 by 4	0.369800	1	0.369800	36.5074	0.000030
2 by 5	0.072200	1	0.072200	7.1277	0.018308
3 by 6	0.259200	1	0.259200	25.5887	0.000175
4 by 5	1.232450	1	1.232450	121.6698	0.000000
Error	0.141813	14	0.010129	–	–
Total SS	7.239950	31	–	–	–

Table 4

Regression model parameters and their statistical estimates

Factors and their interactions	Regression equation coefficient	Student’s t-value	Lower bound of the 95 % confidence interval	Upper bound of the 95 % confidence interval
Mean/Interc.	–0.598750	–33.6533	–0.636909	–0.560591
(2) Printing speed	–0.160625	–9.0281	–0.198784	–0.122466
(3) Infill pattern	–0.085000	–4.7775	–0.123159	–0.046841
(4) Infill density	0.160625	9.0281	0.122466	0.198784
(5) Extrusion multiplier	0.228125	12.8220	0.189966	0.266284
(6) Extrusion temperature	0.047500	2.6698	0.009341	0.085659
(7) Bed temperature	–0.052500	–2.9508	–0.090659	–0.014341
(9) Number of shells	0.117500	6.6042	0.079341	0.155659
1 by 2	0.126875	7.1311	0.088716	0.165034
1 by 3	–0.065000	–3.6534	–0.103159	–0.026841
1 by 4	–0.055625	–3.1265	–0.093784	–0.017466
1 by 5	0.054375	3.0562	0.016216	0.092534
1 by 8	0.059375	3.3372	0.021216	0.097534
1 by 9	0.042500	2.3887	0.004341	0.080659
2 by 4	–0.107500	–6.0421	–0.145659	–0.069341
2 by 5	0.047500	2.6698	0.009341	0.085659
3 by 6	0.090000	5.0585	0.051841	0.128159
4 by 5	0.196250	11.0304	0.158091	0.234409

plier; *BT* is a bed temperature, ˚C; *ET* is an extrusion temperature, ˚C; *IP* is an infill pattern; *DSW* is a deposited strand width, mm; *NS* is the number of shells.

As shown in Fig. 4, an increase in layer height from 0.15 to 0.3 mm at a printing speed of 40 mm/s was accompanied by a greater negative deviation from the nominal value of dimension “*a*”. At a printing speed of 80 mm/s, this deviation remained higher throughout the entire range. The best dimensional accuracy was achieved with the combination of a 0.15 mm layer height and a 40 mm/s printing speed.

Fig. 5 presents the relationship between dimensional accuracy and the combination of infill density and extrusion multiplier. The use of an extrusion multiplier of 1.1 together with 100 % infill provided the smallest deviation from the nominal value of dimension “*a*”, whereas at a lower multiplier (0.9), changes in infill density had little effect on the outcome.

It was also found that increasing the number of shells to 4 significantly improved accuracy across all

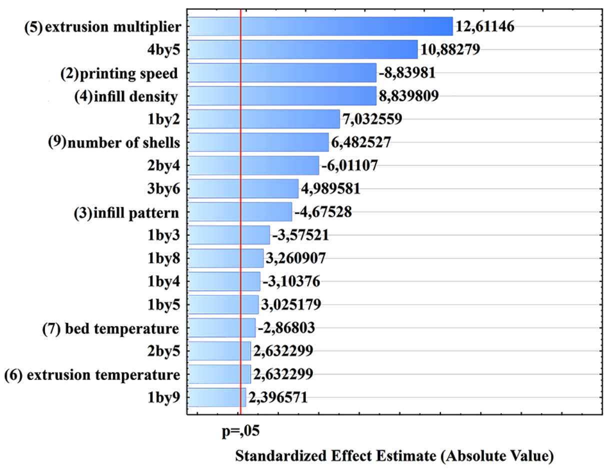


Fig. 3. Pareto chart of the FDM process parameters influence on the relative dimensional deviation along the “Y” axis

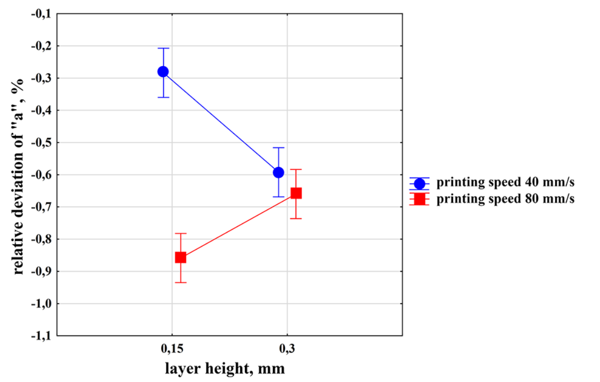


Fig. 4. Effect of layer height and printing speed on the relative deviation of dimension “a”

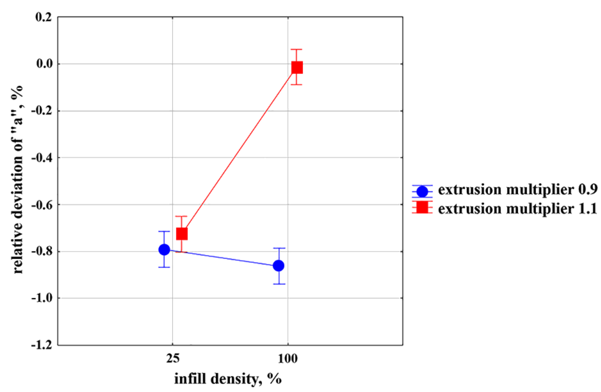


Fig. 5. Effect of infill density and extrusion multiplier on the relative deviation of dimension “a”

examined parameter combinations. At an infill density of 25 %, printing speed had minimal impact on accuracy; however, at 100 % infill, increasing the speed led to a deterioration in results. An extrusion temperature of 265 °C resulted in the smallest deviation from the nominal value of dimension "*a*", whereas at 255 °C, the rectilinear infill pattern was more suitable – using a concentric pattern under these conditions increased dimensional error.

The effect of the infill pattern varied considerably with layer height: at 0.3 mm, the concentric pattern produced the highest deviation, while the rectilinear pattern yielded the lowest. At 0.15 mm, the infill pattern had little effect on accuracy. Similarly, the influence of extrusion width depended on layer height: at 0.3 mm, increasing the width reduced dimensional error, whereas at 0.15 mm, the smallest deviation was observed at a width of 0.49 mm.

The optimal combination of parameters that resulted in the smallest deviation from the nominal value of dimension "*a*" included: 100 % infill density, a layer height of 0.15 mm, an extrusion multiplier of 1.1, a printing speed of 40 mm/s, an extrusion temperature of 265 °C, and a bed temperature of 100 °C. The infill pattern was rectilinear, and the number of shells was 4.

The results of the analysis of variance (Table 5) and the Pareto chart (Fig. 6) illustrate the magnitude of the standardized effects of FDM process parameters and their interactions on dimensional accuracy along the "*X*" axis. Positive values indicate that an increase in the factor leads to an increase in the response function, while negative values represent an inverse relationship.

The relative deviation of dimension "*b*" (Fig. 6) was most strongly influenced by the extrusion multiplier. Infill density also had a significant impact, both as an individual factor and through interactions with other parameters, including printing speed with infill density, infill density with an extrusion multiplier, and layer height with infill density.

Regression analysis of the experimental results (Table 6) made it possible to determine the dependence of the response function (relative deviation of dimension "*b*") on the investigated factors. A regression model was developed for the response function that accounts for the main statistically significant effects and their pairwise interactions.

The regression model describing the influence of FDM process parameters on the relative deviation of dimension along the "*X*" axis in natural units is as follows

Table 5

Results of analysis of variance

Factor	*SS*	*df*	*MS*	*F*	*p*
(4)Infill density	5.04031	1	5.04031	16.49117	0.000399
(5)Extrusion multiplier	19.84500	1	19.84500	64.92996	0.000000
1 by 4	1.90125	1	1.90125	6.22061	0.019313
2 by 4	5.36281	1	5.36281	17.54634	0.000285
4 by 5	4.88281	1	4.88281	15.97585	0.000471
Error	7.94656	26	0.30564	–	–
Total SS	44.97875	31	–	–	–

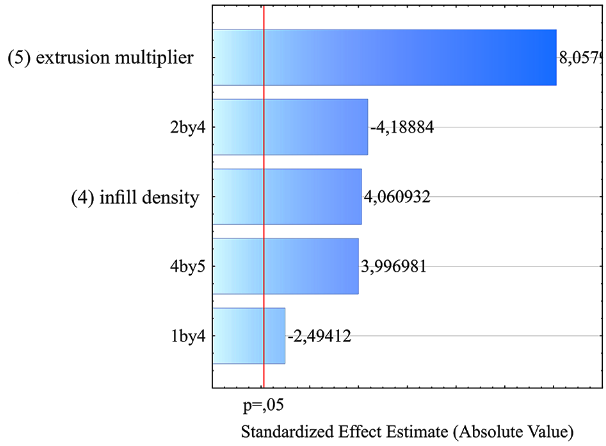


Fig. 6. Pareto chart of the FDM process parameters influence on the relative dimensional deviation along the "X" axis

$$\delta b = -4.47 - 0.04 \cdot ID + 1.4 \cdot EM + 5.33 \cdot LH + $$
$$+ 0.03 \cdot PS + 0.1 \cdot ID \cdot EM - 0.09 \cdot LH \cdot ID - $$
$$- 0.0005 \cdot PS \cdot ID,$$

where LH is a layer height, mm; PS is printing speed, mm/s; ID is infill density, %; EM is an extrusion multiplier.

The high coefficient of determination ($R^2 = 0.82$) indicates that the model explains 82 % of the variation in the dependent variable. This demonstrates the model's suitability for prediction and interpretation of factor effects. Analysis of the regression coefficients confirmed their statistical significance, as the t-statistics for all presented coefficients exceed the critical value at the corresponding degrees of freedom.

The interaction between infill density and extrusion multiplier showed that, with an increase in the extrusion multiplier (up to 1.1), the influence of infill density on the relative deviation of dimension "*b*" became more pronounced (Fig. 7). This suggested a potential synergistic effect between these parameters, which should be considered when selecting printing settings. The investigation of the layer height effect revealed that increasing it from 0.15 to 0.3 mm altered the relative deviation of dimension "*b*" depending on infill density: for low infill (25 %), the deviation increased, whereas for 100 % infill

Table 6

Regression model parameters and their statistical estimates

Factors and their interactions	Regression equation coefficient	Student's t-value	Lower bound of the 95 % confidence interval	Upper bound of the 95 % confidence interval
Mean/Inter.	0.831250	8.50557	0.630363	1.032137
(4)Infill density	0.396875	4.06093	0.195988	0.597762
(5)Extrusion multiplier	0.787500	8.05791	0.586613	0.988387
1 by 4	–0.243750	–2.49412	–0.444637	–0.042863
2 by 4	–0.409375	–4.18884	–0.610262	–0.208488
4 by 5	0.390625	3.99698	0.189738	0.591512

it decreased (Fig. 8). This may be attributed to a reduction in the number of layers, which leads to fewer accumulated errors during the printing process.

Regarding the effect of printing speed, the results indicated that increasing this parameter from 40 to 80 mm/s led to a decrease in the relative deviation of dimension "*b*" at 100 % infill density, while for 25 % infill, the deviation remained nearly unchanged (Fig. 9).

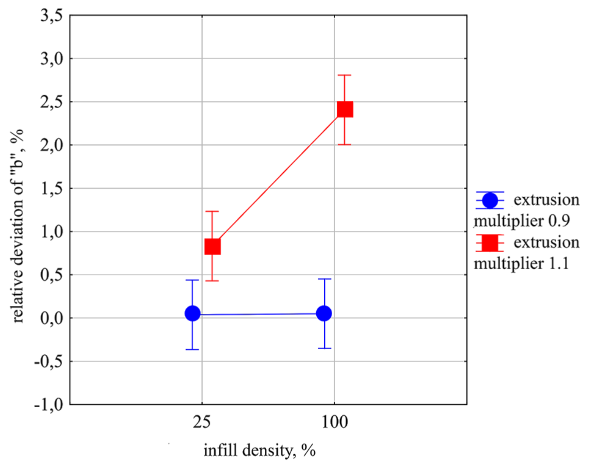


Fig. 7. Effect of infill density and extrusion multiplier on the relative deviation of dimension "b"

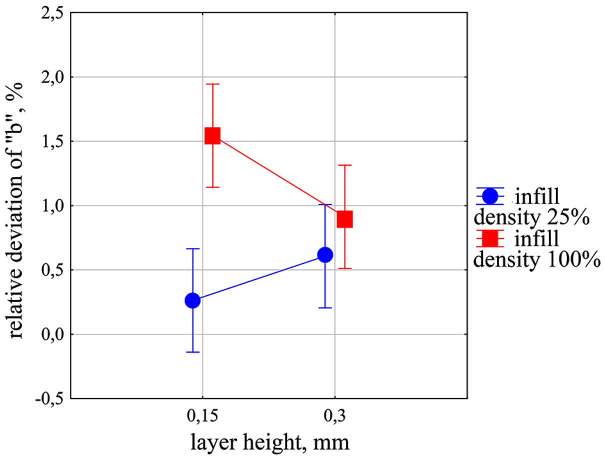


Fig. 8. Effect of layer height and infill density on the relative deviation of dimension "b"

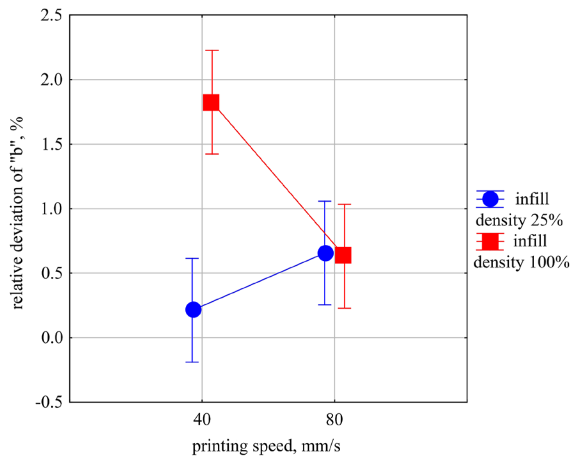


Fig. 9. Effect of printing speed and infill density on the relative deviation of dimension "b"

This may be attributed to the reduced thermal exposure time, which minimizes the effects of thermal expansion and shrinkage.

Analysis of the graphical dependencies illustrating the influence of printing parameters on the accuracy of dimension "*b*" showed that the smallest deviation from the nominal value was achieved using an extrusion multiplier of 0.9, an infill density of 25 %, a layer height of 0.15 mm, and a printing speed of 40 mm/s. This combination provided a stable deviation value close to zero with minimal variation, indicating improved geometric accuracy in the corresponding direction.

The summarized results of the analysis of variance (Table 7) and the Pareto chart (Fig. 10) demonstrate the influence of individual FDM process parameters and their interactions on the dimensional accuracy along the "*Z*" axis. Positive standardized effect values indicate an increase in the response function with an increase in the respective parameter, while negative values represent an inverse relationship.

Based on the experimental results, a regression analysis was performed (Table 8), which enabled the identification of the relationship between the response function (relative deviation of dimension along the "*Z*" axis) and the investigated parameters. The developed model included the main factors with statistically significant effects, as well as their pairwise interactions.

The regression model describing the influence of FDM process parameters on the relative deviation of

Table 7

Results of analysis of variance

Factor	*SS*	*df*	*MS*	*F*	*p*
(1) Layer height	124.8200	1	124.8200	42.0215	0.000001
(4) Infill density	120.1250	1	120.1250	40.4409	0.000001
(5) Extrusion multiplier	310.0050	1	310.0050	104.3653	0.000000
3 by 7	16.8200	1	16.8200	5.6626	0.024954
4 by 5	79.3800	1	79.3800	26.7238	0.000021
Error	77.2300	26	2.9704	–	–
Total SS	728.3800	31	–	–	–

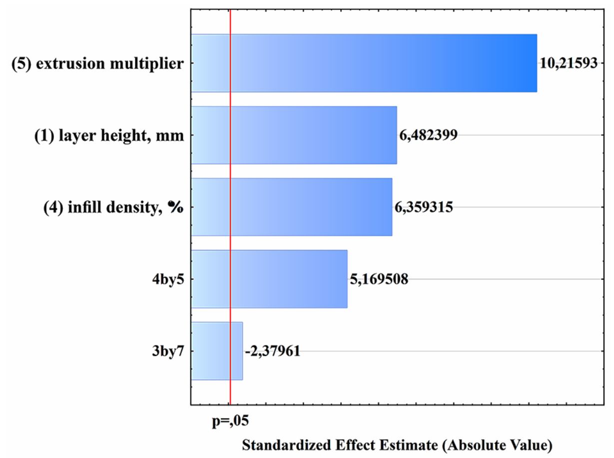


Fig. 10. Pareto chart of the FDM process parameters influence on the relative dimensional deviation along the "Z" axis

Regression model parameters and their statistical estimates

Factors and their interactions	Regression equation coefficient	Student's *t*-value	Lower bound of the 95 % confidence interval	Upper bound of the 95 % confidence interval
Mean/Interc.	2.025000	6.64651	1.39874	2.651261
(1)Layer height	1.975000	6.48240	1.34874	2.601261
(4)Infill density	1.937500	6.35932	1.31124	2.563761
(5)Extrusion multiplier	3.112500	10.21593	2.48624	3.738761
3 by 7	–0.725000	–2.37961	–1.35126	–0.098739
4 by 5	1.575000	5.16951	0.94874	2.201261

dimension along the "*Z*" axis in natural units is as follows

$$\delta c = -11.91 - 0.07 \cdot BT \cdot IP + 0.42 \cdot EM \cdot ID + \\ + 4.77 \cdot EM - 0.37 \cdot ID + 8.03 \cdot IP + 26.4 \cdot LH,$$

where LH is a layer height, mm; ID is infill density, %; EM is an extrusion multiplier; BT is a bed temperature, °C; IP is an infill pattern.

To assess the adequacy of the model, statistical criteria and residual analysis methods were applied. The coefficient of determination (R^2) was 0.89 (89 %), and the adjusted coefficient of determination (Adj. R^2) was 0.87 (87 %). These high values indicated that the model was of sufficiently good quality and had strong explanatory power for the variation in the dependent variable.

All factors included in the model were found to be statistically significant, as confirmed by p-values less than 0.05 in the regression analysis. The results of the analysis of variance also indicate a low residual variance, further supporting the adequacy of the regression model.

The analysis of the influence of FDM printing parameters on dimensional accuracy along the "*Z*" axis revealed a trend similar to that observed for the "*X*" axis. As shown in Fig. 11, increasing the extrusion multiplier from 0.9 to 1.1 resulted in a significant increase in the deviation of dimension "*c*", particularly under 100 % infill density. When the extrusion multiplier was set to 0.9, changes in infill density had no effect on accuracy – the average values remained close to zero.

Fig. 12 presents the effect of layer height on the relative deviation of dimension "*c*". As the layer height increased from 0.15 to 0.3 mm, a noticeable rise in deviation along the "*Z*" axis was observed. Thus, using the minimum layer height provided enhanced geometric accuracy in the vertical direction.

The summarized results obtained from statistical analysis made it possible to identify the optimal parameters for minimizing the deviation of dimension "*c*". The most effective combination was an extrusion multiplier of 0.9, an infill density of 25 %, and a layer height of 0.15 mm.

Additionally, it was established that the infill pattern significantly affects accuracy along the "*Z*" axis. The best results were achieved using a concentric infill pattern in combination with a bed temperature of 120 °C. When the bed temperature was reduced to 100 °C, accuracy deteriorated considerably, indicating the importance of thermal stabilization during layer formation in the vertical plane.

Conclusions. Based on the conducted experimental study, it was established that the geometric accuracy of parts fabricated using FDM with Nylon 6 material strongly depended on the combination of process parameters. Through analysis of variance and regression analysis, the most influential factors were identified, including extrusion multiplier, infill density and infill pattern.

Specifically, along the "*Y*" axis, the highest accuracy was achieved with the following parameters: extrusion multiplier of 1.1, printing speed of 40 mm/s, 100 % infill density, rectilinear infill pattern, deposited strand width of 0.49 mm, 4 shells, and a bed temperature of 100 °C. For the "*X*" axis, optimal values included an extrusion multiplier of 0.9, a layer height of 0.15 mm, and a concentric infill pattern, although the effects of printing speed and infill density were found to be ambiguous. Along the "*Z*" axis, the highest accuracy was ensured by the combination of a 0.15 mm layer height, a bed temperature of 120 °C, a concentric infill pattern, and an extrusion multiplier of 0.9.

The study revealed a complex interaction between FDM process parameters, demonstrated by the significant effect of their pairwise combinations on dimensional accuracy. This synergistic effect must be taken into account during process optimization. The devel-

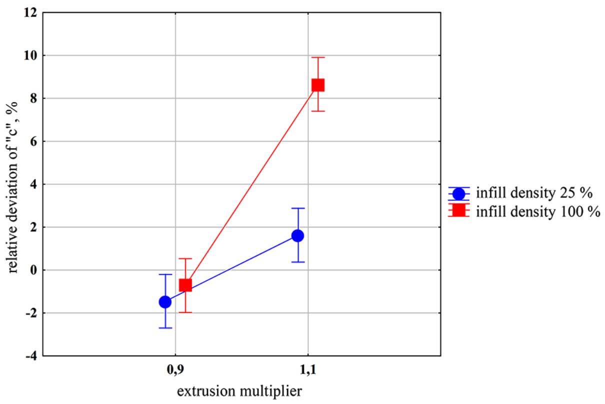


Fig. 11. Effect of extrusion multiplier and infill density on the relative deviation of dimension "c"

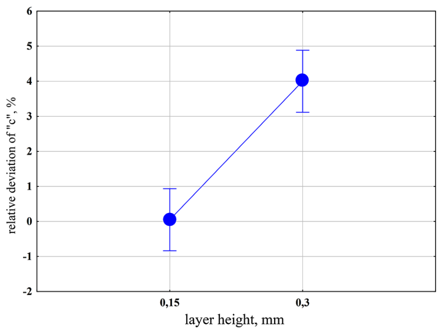


Fig. 12. Effect of layer height on the relative deviation of dimension "c"

oped regression models enable the prediction of dimensional accuracy under various parameter combinations, which greatly facilitates printing process tuning under resource constraints and minimizes material waste.

The practical value of the obtained results lies in the ability to rapidly produce accurate and functional components for military and mining applications, where precision, production speed, and dimensional stability are critical.

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Підвищення точності деталей подвійного призначення з нейлону методом пошарового наплавлення

Л. О. Тумарченко, Є. В. Вишнепольський, Д. В. Павленко*

Національний університет «Запорізька політехніка», м. Запоріжжя, Україна

* Автор-кореспондент e-mail: hurina97@gmail.com

Мета. Аналіз залежності точності геометричних параметрів виробів із поліаміду 6 (Nylon 6, PA6) від технологічних параметрів адитивного виробництва методом пошарового наплавлення для забезпечення оперативного ремонту військової й гірничодобувної техніки в польових умовах.

Методика. Зразки друкували методом пошарового наплавлення (FDM) на 3D-принтері типу Prusa i3 із використанням програмного забезпечення Slic3rPE для підготовки G-коду. У дослідженні використовували матеріал – Plexiwire Nylon (PA6) Filament ∅1,75 ISO/ASTM 52903-1:2020. Досліджено взаємозв'язок між технологічними параметрами процесу FDM і геометричною точністю отриманих виробів. Аналізу підлягали наступні параметри: висота шару, швидкість друку, температура екструзії, температура платформи, екструзійний множник, ширина укладання нитки, кількість стінок, схема заповнення, щільність заповнення й кількість суцільних верхніх і нижніх шарів. Оцінка впливу технологічних параметрів на розмірну стабільність здійснювалась через вимірювання лінійних параметрів зразків «*a*», «*b*», «*c*» у відповідних координатних площинах «*X*», «*Y*», «*Z*». Критерієм оцінки точності слугувало відносне відхилення отриманих розмірів від проєктних значень. Обробка експериментальних даних виконувалась у програмному забезпеченні TIBCO STATISTICA з метою ідентифікації найбільш впливових факторів і характеру їх взаємодії.

Результати. Встановлено, що на точність виготовлення деталей найбільший вплив мають: екструзійний множник, щільність і схема заповнення. Для осі «*Y*» оптимальними параметрами є: екструзійний множник 1,1, швидкість друку 40 мм/с, щільність заповнення 100 %, прямолінійна схема заповнення, ширина укладання нитки 0,49 мм, кількість стінок 4 і температура платформи 100 °С. Для осей «*X*» і «*Z*» – екструзійний множник 0,9, висота шару 0,15 мм, концентрична схема заповнення. Побудовані регресійні моделі для прогнозування точності виробів у напрямку трьох основних координатних осей залежно від режимних параметрів.

Наукова новизна. Уперше визначені оптимальні комбінації параметрів FDM-друку для підвищення точності деталей із Nylon 6, придатних для експлуатації в польових умовах. Виявлена значущість параметрів друку саме у формуванні точності в окремих координатних напрямках.

Практична значимість. Запропоновані технологічні рекомендації забезпечують можливість виготовлення функціональних замінних деталей без використання стаціонарних ремонтних засобів. Це дозволяє здійснювати оперативний ремонт військової й гірничої техніки за допомогою портативних 3D-принтерів у важкодоступних умовах, гарантуючи високу точність, зносостійкість і функціональність надрукованих деталей.

Ключові слова: *Fused Deposition Modelling, PA6, точність, параметри процесу, дисперсійний аналіз, регресійний аналіз*

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