https://doi.org/10.33271/nvngu/2025-2/121

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EFFECT OF HEAT TREATMENT ON THE MECHANICAL PROPERTIES OF NYLON PARTS IN ADDITIVE MANUFACTURING

Purpose. To investigate the effect of heat treatment on the mechanical properties of polyamide 6 (nylon) parts manufactured by means of Fused Deposition Modelling (FDM) method.

Methodology. A 3D printer (Profi+ model) was used for samples printing. The G-code was generated using Slic3rPE software. Heat treatment was performed in a laboratory electric furnace STM-1-10. The effect of factors such as heat treatment temperature, duration of exposure and type of cooling was investigated. The mechanical properties were evaluated by measuring tensile strength and elongation at break using a UIT STM 100S testing machine. The results were statistically analysed using the STATISTICA software package, enabling the identification of the most significant factors and their interactions.

Findings. The influence of heat treatment parameters on the tensile strength and elongation at break of nylon parts was investigated. The most significant factor affecting tensile strength was the temperature of heat treatment, followed by the duration of exposure and the interaction between mentioned factors. Elongation at break was most influenced by the duration of exposure, as well as combination of heat treatment temperature and cooling type. The interaction of duration of exposure and cooling type also contributed to the response function (elongation at break). The maximum improvement in tensile strength (+61.74 %) was achieved at a temperature of 130 °C, duration of exposure of 90 minutes. To enhance the elongation at break, heat treatment is recommended under the following parameters: temperature –110 °C, duration – 60 min, cooling – in the furnace down to 20 °C.

Originality. It was established that the combination of heat treatment parameters significantly improved the strength and ductility of nylon parts produced by FDM. It was determined that the most effective parameters were the following: temperature – 110–130 °C, duration of exposure – 60–90 min and gradual cooling in the furnace.

Practical value. The developed recommendations for heat treatment make it possible to improve the mechanical properties of nylon products manufactured by FDM technology. The results of the study open up new opportunities for the use of such parts in the military and dual-purpose products due to their improved strength and durability.

Keywords: *Fused Deposition Modelling, nylon, heat treatment, tensile strength, elongation at break, statistical processing*

Introduction. Nowadays, a lot of manufacturing sectors require high-quality parts with low cost and required mechanical properties [1]. Although subtractive technologies are of greater industrial importance due to their adaptability to mass production, new additive manufacturing (AM) technologies can significantly reduce the costs of product development, prototyping, design verification and manufacturing of individual parts [2]. Recently, the use of AM technologies in military and defence applications has been growing significantly. 3D printing makes it possible to produce complex parts and components that are difficult to manufacture using traditional production methods, especially in the field. Examples of successful use of additive technologies in military and defence applications include the production of prostheses, customised weapon components and the development of prototypes of new military products [3, 4]. Under martial law, Ukrainian companies develop and manufacture various weapons equipment using additive technologies. PJSC "Mayak" has developed a kit to improve the RKG-3 grenade of the former Soviet Union. This kit involves removing the grenade's handle and parachute and replacing it with a tail cone and stabilisers that can be printed using a 3D printer [3]. 3D Tech Additive produces holsters for AK-47 assault rifles, bullet magazines for repurposing spent shell casings, grenade bags, etc. [3]. Nylon is used to make components and spare parts for FPV drones, such as hexagonal female-to-female nylon poles. They are used to secure and increase the clearance between electronic components or printed circuit boards (PCB) on quadcopters and other systems. Since nylon is a moderately heat-resistant material that does not conduct electric current, it is possible to avoid shorting the tracks around the mounting point on the PCB. Other examples include the propellers of FPV drones, which are made of nylon, providing an optimal combination of strength and lightness, leading to an increase in overall drone performance.

There are different types of AM technologies [5, 6], among which Fused Deposition Modelling (FDM) is the most widespread. FDM works on the principle of material extrusion and uses thermoplastic materials such as poly(lactic acid) (PLA), acrylonitrile butadiene styrene (ABS), polyetheretherketone (PEEK), nylon (polyamide), poly(carbonate) (PC), etc. [7]. Compared to ABS and PLA, nylon (polyamide 6) demonstrates excellent chemical resistance, as well as higher tensile strength and Young's modulus. However, nylon (polyamide 6) is a highly hygroscopic material and its mechanical properties are adversely affected by moisture absorption. It should be noted that, compared to ABS and PLA, nylon has not been researched enough, which

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significantly limits its use [8]. Nonetheless, the demand for it in the aerospace and military sectors is very high.

However, the mechanical strength of FDM-printed parts is lower than that of parts produced by injection moulding or other traditional production methods due to the presence of voids and insufficient connection between layers and rasters [9, 10]. To eliminate these problems, optimisation of printing parameters, addition of fillers to the material and post-processing are used [7].

Different types of post-processing methods are usually used: some to improve the aesthetics of parts [11], others to improve mechanical properties. Studies have shown that immersing FDM-printed parts in an acetone solution improves the surface finish of the 3D printed part [12, 13], but worsens its mechanical properties. To improve the mechanical properties of 3D printed parts, it is advisable to use heat treatment, which can improve the mechanical characteristics of the part and reduce internal stresses generated during production [9].

Literature review. Heat treatment is a widespread method for improving the mechanical properties of printed parts. It attracts a lot of attention from researchers trying to understand its impact on the mechanical properties of polymers and composites.

Jayswal, et al. [9] examined the mechanical properties of heat-treated polylactic acid (PLA) filament. Their study demonstrated a significant improvement in mechanical performance compared to untreated samples. The increase in tensile strength was attributed to a reduction in voids formed during the 3D printing process and a decrease in residual stress caused by temperature fluctuations. In addition, heat treatment contributed to a significant increase in the thermal deformation temperature.

Singh, et al. applied heat treatment to enhance the quality characteristics of ABS parts. They observed that heating ABS above its glass transition temperature facilitated material reflow, effectively reducing porosity and interlayer gaps. Their findings indicated that the density of FDM-printed parts and the heat treatment temperature had a statistically significant impact on key output parameters, including surface roughness, hardness, dimensional accuracy, tensile strength, flexural strength, and impact strength. In contrast, heat treatment duration had a negligible effect [14].

Pagano, et al. [15] investigated the influence of heat treatment on the tensile properties of PLA samples in combination with various process parameters. The results confirmed that annealing improved the Young's modulus, worsened the elongation at break and did not affect the tensile ultimate stress. It was found that the improvement in Young's modulus was more significant for samples with a non-zero raster angle and the lower the extrusion temperature, the higher the increase in stiffness.

De Avila, et al. [16] studied the effect of heat treatment on the mechanical properties of FDM-printed PC, PMMA, and PEEK components. They found an increase in tensile strength by approximately 10 MPa for PC, 20 MPa for PMMA and little change for PEEK. Akhoundi, et al. [17] found that heat treatment on high temperature polylactic acid (HTPLA) increased the tensile strength by 2.5 %. Yang, et al. [18] explored different heat treatment conditions for PEEK material and found that variations in treatment modes and parameters had distinct effects on its mechanical performance.

According to the study by Hong, et al. [19], thermal annealing of PLA samples resulted in improved mechanical properties such as flexural and compressive strength. The study demonstrated that higher annealing temperatures and prolonged exposure significantly strengthened interlayer bonding. The most optimal results were achieved at 140 °C for 600 seconds. However, increasing the temperature increased the strength but significantly reduced the ductility of the material.

Although crystallinity occurs within the polymer, the bonding between the matrix and filler of composite materials can also be improved by heat treatment [20, 21]. Bhandari, et al. [22] found that annealing improved the interlayer tensile strength of CF-reinforced PLA and PETG composites. The tensile strength of both composites was doubled and tripled, respectively. Rangisetty, et al. [23] conducted a similar study using CF-reinforced ABS, PLA, and PETG. All composite samples were annealed for 60 minutes at different temperatures due to the different glass transition temperatures of the polymers. The results showed that the increase in tensile strength for CF-reinforced PLA, ABS and PETG was 16.8, 3.34 and 12.4 %, respectively.

Overall, these studies showed that heat treatment increased polymer crystallinity and improved the bonding between layers, resulting in increased strength of the samples, although with some reduction in ductility. Therefore, it is important to choose the optimal heat treatment parameters to improve mechanical properties without a significant loss of ductility.

Several studies have focused on examining the impact of heat treatment on the mechanical properties of carbon fibre-reinforced nylon composite parts [24, 25], while studies of the effect of heat treatment process parameters on the mechanical properties of pure nylon (PA6) parts are rather limited. Therefore, the study of the influence of the heat treatment process parameters on the mechanical properties of parts made of nylon (PA6) is an urgent scientific and technical task of modern mechanical engineering.

Materials and methods. The material used in the study was Plexiwire Nylon (PA6) Filament ∅1.75 ISO1133-1:2011. In the study the filament was pre-dried in a Creality DRY BOX 2.0 dryer for 3 hours at a temperature of 80 °C, according to the recommendations of manufacturer [26].

The geometry of the specimens conforms to the ISO 527-2:2012 standard. The specimens were fabricated using the Fused Deposition Modelling (FDM) technique on a Profi+ 3D printer. The G-code for printing was generated using Slic3rPE software. The working area of the 3D printer was 250 × 250 × 200 mm. The feeding system – bowden; the extruder type – single; the nozzle size -0.4 mm; the maximum extruder temperature – 280 °C; the maximum table temperature – 120 °C; the maximum printing speed – 100 mm/s.

The STATISTICA software package was used for statistical processing of the results.

The heat treatment of the samples was carried out in a laboratory furnace. The heat treatment of the samples consisted of heating the furnace to the specified temperature, waiting for the temperature to stabilise in the furnace and loading the sample. The temperature, duration of exposure, and type of cooling were set according to the experimental plan.

Table 1

FDM process parameters

FDM process parameters		Value
1	Layer height, mm	0.15
2	Printing speed, mm/s	40
3	Infill density, %	100
4	Infill pattern	concentric
5	Bed temperature, °C	100
6	Deposited strand width, mm	0.49
7	Number of shells	4
8	Number of top and bottom solid layers	4
9	Extrusion temperature, °C	265
10	Extrusion multiplier	0.9

The parameters of the FDM process for manufacturing the samples are shown in Table 1.

The influence of heat treatment parameters on the mechanical properties of the final product was studied by measuring tensile strength and elongation at break. The tests were conducted using the UIT STM 100S testing machine, designed to determine the mechanical characteristics of materials and products with a maximum load capacity of up to 100 kN.

Results and discussion. The aim of the study is to determine the complex effect of heat treatment parameters on the mechanical properties of PA6 parts. A full factorial experiment 3^3 was chosen for the study. The planning matrix and values of the response functions are shown in Table 2. The variation factors: temperature, duration of exposure, type of cooling. Heat treatment involves changing the structure of a material. Structural changes in thermoplastic polymers occur in the range between the melting and glass transition temperatures. For PA 6, the melting point is

Table 2

Heat treatment parameters and resulting response functions values

No.	Temp., °C	Duration of exposure, min	Type of cooling	σ, MPa	Elongation at break, %
0	–	–	–	24.91	9.71
1	130	60	at once	33.38	15.22
2	110	90	half of the temperature ($t/2$)	31.12	21.84
3	90	30	half of the temperature ($t/2$)	27.15	5.45
4	110	90	at once	31.93	20.48
5	130	60	half of the temperature ($t/2$)	32.36	9.39
6	90	30	drop to 20 °C	27.75	4.30
7	130	60	drop to 20 °C	32.42	22.32
8	90	30	at once	32.03	11.06
9	110	90	drop to 20 °C	28.56	9.96
10	90	60	drop to 20 °C	30.99	7.14
11	90	60	at once	31.54	21.38
12	130	90	half of the temperature ($t/2$)	39.06	3.94
13	110	30	at once	25.53	3.57
14	110	30	drop to 20 °C	27.84	9.21
15	110	30	half of the temperature ($t/2$)	29.87	11.48
16	130	90	drop to 20 °C	40.29	12.24
17	90	60	half of the temperature ($t/2$)	31.47	27.81
18	130	90	at once	37.36	10.35
19	110	60	half of the temperature ($t/2$)	32.38	30.76
20	110	60	at once	31.60	5.44
21	90	90	drop to 20 °C	28.28	10.36
22	110	60	drop to 20 °C	31.56	28.79
23	130	30	half of the temperature ($t/2$)	29.69	3.96
24	130	30	at once	28.75	2.07
25	130	30	drop to 20 °C	31.4	20.86
26	90	90	half of the temperature ($t/2$)	25.4	6.74
27	90	90	at once	30.53	25.98

Table 3

Results of the analysis of variance

Factor	SS	df	MS	F	p
Temperature (L)	86.9881	1	86.98805	41.35239	0.000005
Temperature (Q)	15.6494	1	15.64935	7.43939	0.013819
Duration of exposure (L)	58.7528	1	58.75280	27.92991	0.000050
Duration of exposure (Q)	9.6774	1	9.67740	4.60044	0.045860
1L by 2L	72.9640	1	72.96401	34.68564	0.000014
1L by 2Q	20.3852	1	20.38522	9.69073	0.006006
1L by 3L	11.4075	1	11.40750	5.42290	0.031726
1Q by 3Q	10.6408	1	10.64083	5.05844	0.037263
Error	37.8644	18	2.10358	–	–
Total SS	324.3296	26	–	–	–

Note: statistically significant values are highlighted in red.

250 °C and the glass transition temperature is 53 °C. According to these values, heat treatment temperatures of 90, 110, 130 °C were selected. Tensile strength and elongation at break were selected as the objective functions.

To determine the degree of statistically substantiated influence of the heat treatment parameters on the formation of response functions, an analysis of variance was performed (Table 3) based on a full factorial experiment. To depict the ranking of factors by their relative influence and importance, an analysis was performed using Pareto diagrams (Fig. 1).

The following factor designations were used in the analysis of variance: *1* – heat treatment temperature; *2* – duration of exposure; *3* – type of cooling. Effect designations: *L* (Linear) – linear effect; *Q* (Quadratic) – quadratic effect.

According to the analysis of variance (Table 3) and the Pareto diagram (Fig. 1), it was found that the greatest influence on the tensile strength was exerted by heat treat temperature, duration of exposure and pair interaction of these factors.

Statistical data processing was performed on the basis of a given mathematical model, and its quality was assessed by plotting the predicted and observed values for the response function (Fig. 2).

The predicted values (Fig. 2) did not have a high discrepancy with the values obtained experimentally, so the model obtained from the point of view of statistical processing was sufficiently adequate and could be used to predict the value of the tensile strength depending on a particular combination of heat treatment parameters.

Based on the data from the experimental studies and their statistical processing, graphical dependencies were constructed that showed the independent effect of significant heat treatment parameters on the formation of tensile strength of samples (Figs. 3–4).

Figs. 3, 4 show the effect of heat treatment temperature and duration of exposure on the tensile strength of the samples.

Experimental study demonstrated that the maximum tensile strength was attained at a heat treatment temperature of 130 °C (Fig. 3). This phenomenon was attributed to the optimal balance between the amorphous and crystalline phases, which enhanced intermolecular interactions and facilitated the relaxation of residual internal stresses generated during the printing process. At lower temperatures, recrystallization pro-

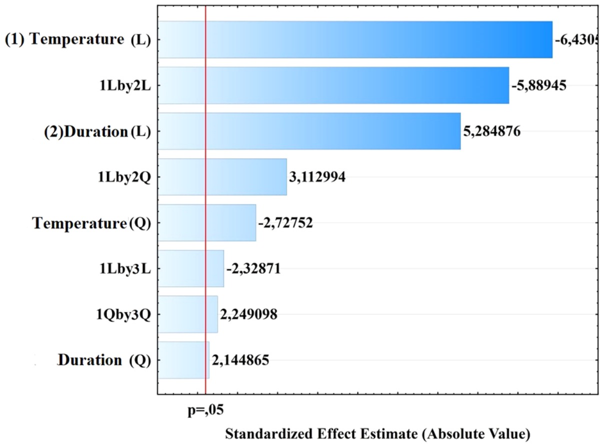

Fig. 1. Pareto diagram of the effect of heat treatment parameters on the tensile strength of samples

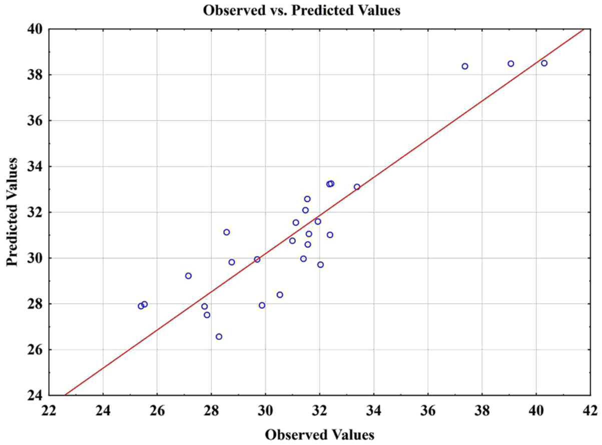

Fig. 2. Correspondence of predicted values to observed values

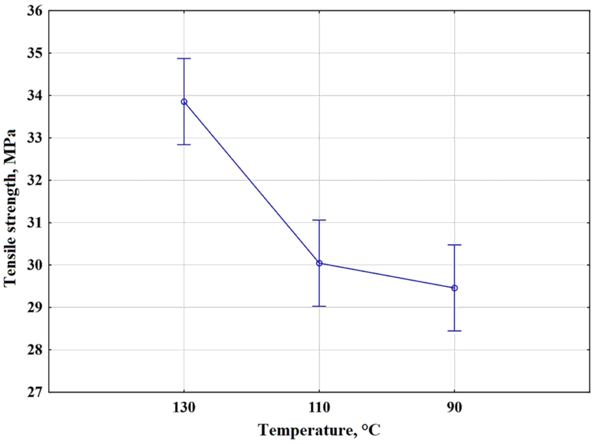

Fig. 3. Tensile strength dependence on heat treatment temperature

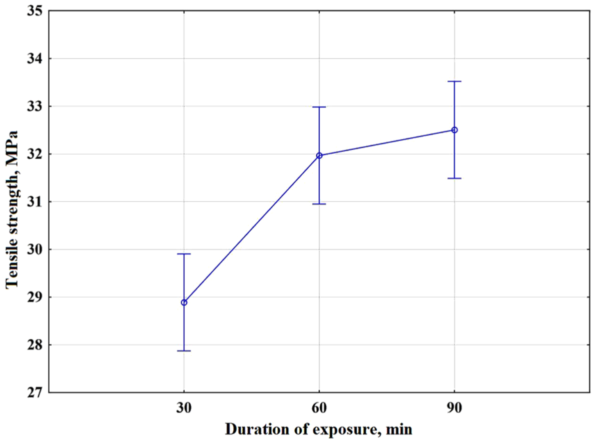

Fig. 4. Tensile strength dependence on duration of exposure

cesses were insufficient to establish a stable structure, potentially leading to a deterioration in mechanical properties.

Beyond the temperature regime, the duration of heat treatment is a critical parameter. It was determined that the highest tensile strength values were observed after a duration time of 90 minutes (Fig. 4). This can be explained by the gradual stabilization of the crystalline structure, the alleviation of residual internal stresses, and the optimization of intermolecular interactions. Although shorter duration times also contributed to an improvement in strength compared to untreated samples, those effect was less pronounced due to the incomplete progression of structural transformations.

The contour plot (Fig. 5) illustrates the correlation between tensile strength, heat treatment temperature and duration of exposure time in the furnace. The results indicated that an increase in mentioned parameters corresponded to an enhancement in tensile strength, reaching its peak in regions characterized by elevated temperatures and extended duration time (red zone). Conversely, minimum tensile strength values were observed at lower temperatures and shorter duration times (green and blue zones).

Thus, a heat treatment temperature of 130 °C and a duration time of 90 minutes was optimal for achieving the maximum tensile strength of polyamide 6 products manufactured by means of FDM. Despite the fact that the factor ‘type of cooling’ did not statistically show a significant effect on the tensile strength of the samples, it is recommended to gradually cool the products of polyamide 6 in the furnace to avoid the formation of repeated residual stresses and geometry deformations caused by temperature gradients.

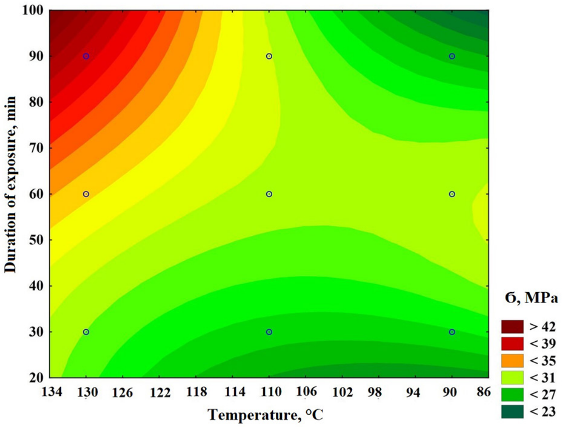

Fig. 5. Correlation of tensile strength with heat treatment temperature and duration of exposure

Thus, samples Nos. 12 and 16 exhibited the highest tensile strength values following heat treatment, reaching 39.06 and 40.29 MPa, respectively. This corresponds to an increase of 56.80 and 61.74 %, respectively, compared to the tensile strength of the untreated sample.

To assess the significance of heat treatment parameters in determining the response function (elongation at break), an analysis of variance was conducted (Table 4). Additionally, to illustrate the ranking of factors based on their relative influence and importance, a Pareto diagram analysis was performed (Fig. 6).

It was determined that the most significant factor influencing the elongation at break (Fig. 6) was the duration of exposure time. Additionally, the pairwise interactions between duration of exposure and type of cooling, as well as between temperature and type of cooling, exhibited a substantial effect on the elongation at break.

The adequacy of the obtained statistical model was checked on the basis of a graph of the correspondence of the predicted values to the observed ones (Fig. 7).

The predicted values (Fig. 7) did not have a high discrepancy with the values obtained experimentally, so the resulting statistical model was sufficiently adequate and could be used to predict the value of elongation at break depending on a particular combination of heat treatment parameters.

The parameter that, according to the analysis of variance, showed an independent effect on the elongation at break was the duration of exposure. The graph of the dependence of the elongation at break on the duration of exposure is presented in Fig. 8.

Based on the graph of average values, the highest percentage of elongation at break was observed at a duration time of 60 minutes, while the lowest was recorded at 30 minutes (Fig. 8).

Visualisation of the effect of heat treatment parameters combinations on the formation of elongation at break of samples is shown in Figs. 9–10. Type of cooling

Table 4

Results of the analysis of variance

Factor	SS	df	MS	F	p
Temperature (Q)	72.315	1	72.3148	2.53159	0.130010
Duration of exposure (L)	138.500	1	138.5003	4.84861	0.041764
Duration of exposure (Q)	376.834	1	376.8338	13.19218	0.002060
1L by 3L	345.613	1	345.6133	12.09922	0.002876
1L by 3Q	64.695	1	64.6952	2.26485	0.150692
1Q by 3L	58.217	1	58.2169	2.03806	0.171518
1Q by 3Q	208.667	1	208.6668	7.30500	0.015087
2L by 3L	146.441	1	146.4405	5.12659	0.036928
2Q by 3Q	101.850	1	101.8501	3.56557	0.076177
Error	485.604	17	28.5649	–	–
Total SS	1,998.735	26	–	–	–

Note: statistically significant values are highlighted in red.

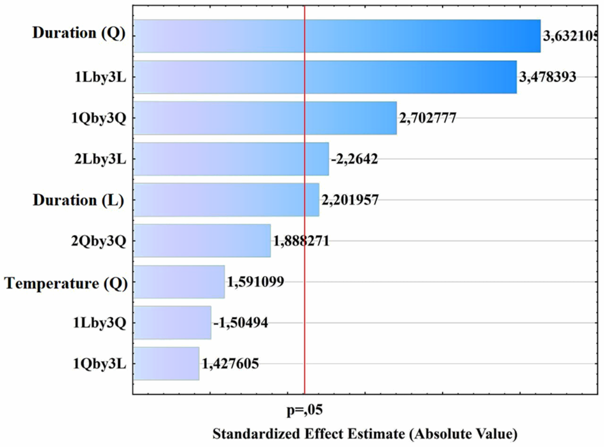

Fig. 6. Pareto diagram of the effect of heat treatment parameters on the elongation at break of samples

(Fig. 9–10): *1* – at room temperature, *2* – in the furnace to half the heat treatment temperature, *3* – in the furnace to 20 °C.

Fig. 9 shows that the maximum value of the elongation at break can be achieved when combining a heat treatment temperature of 110 °C and cooling – 'in the furnace to 20 °C', which is explained by the fact that the sample requires gradual cooling in the furnace to avoid creating new internal stresses and deformation of the part geometry. According to the graph of the dependence (Fig. 10) of the elongation at break percentage on the duration of exposure and type of cooling, the maximum value was obtained at 60 minutes of exposure and cooling – 'in the furnace to 20 °C'.

Analysing Figs. 9–10, it is possible to distinguish sample No. 22, after heat treatment of which the value of the elongation at break increased as much as possible compared to the value of the untreated sample. The heat treatment parameters for sample No. 22 were as follows: temperature –110 °C, duration of exposure – 60 min, cooling – 'in the furnace to 20 °C'. Based on the data from the experimental study and their statistical processing regarding the effect of heat treatment parameters on the percentage of elongation at break, it was

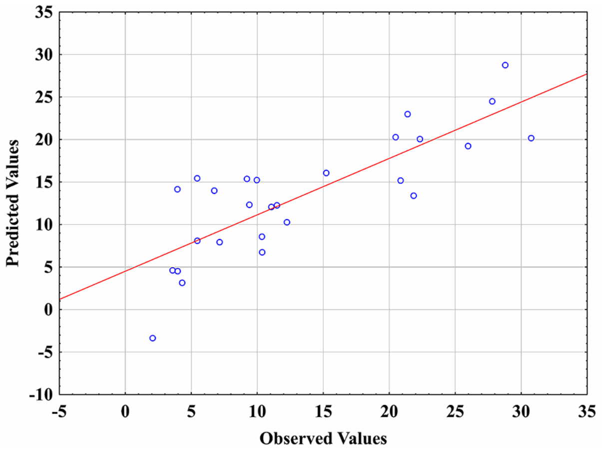

Fig. 7. Correspondence of predicted values to observed values

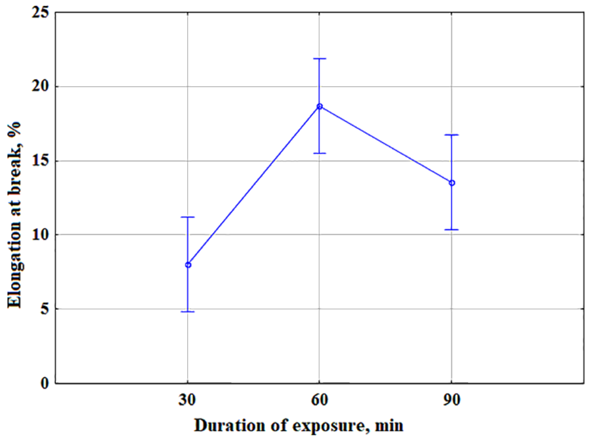

Fig. 8. Elongation at break dependence on the duration of exposure

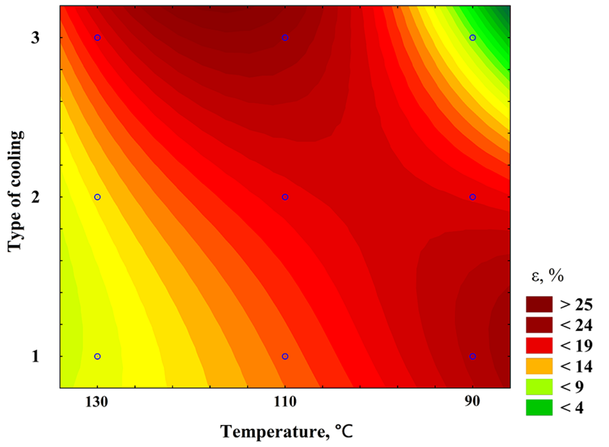

Fig. 9. Elongation at break dependence on heat treatment temperature and cooling type

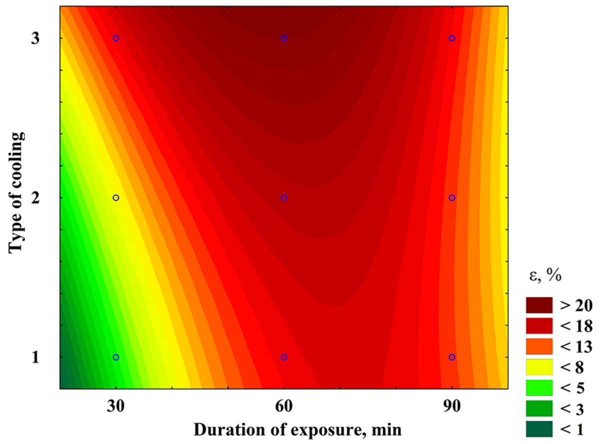

Fig. 10. Elongation at break dependence on duration of exposure and type of cooling

found that the optimal heat treatment parameters for nylon parts produced by FDM would be the parameters specified for sample No. 22.

Summarizing, the tensile strength of nylon parts was maximized at higher heat treatment temperatures and longer exposure times, ensuring structural stability. In contrast, ductility increased at lower temperatures and controlled cooling, enhancing the material's deformation capability. A high temperature of 130 °C improved tensile strength but reduced ductility due to excessive crystallization. The optimal balance between strength and ductility can be achieved within the temperature range of 110–130 °C, with an exposure time of 60–90 minutes and gradual cooling. Thus, optimizing heat treatment parameters allows for the precise adjustment of nylon's mechanical properties based on specific application requirements. If high strength is the priority, a temperature of 130 °C with a 90-minute exposure is recommended, whereas improved ductility is best achieved at 110 °C with a 60-minute exposure and gradual cooling.

Conclusions. On the basis of the experimental study, the influence of heat treatment parameters on the mechanical properties of the samples was evaluated. The analysis of the tensile strength and percentage of elongation at break values obtained on printed samples made it possible to determine the influence of the most important and significant factors and their interactions on the specified mechanical properties of the samples. The influence of these factors and their combinations on the mechanical properties of the obtained samples was considered using analysis of variance.

It was determined that heat treatment at 130 °C for 90 minutes provided the maximum improvement in tensile strength. In this work, an increase in the tensile strength value by 61.74 % was achieved, compared to the strength value of the unheated nylon sample. The type of cooling in this study did not have a significant effect on the tensile strength.

It was found that the duration of exposure of 60 minutes and cooling – 'in the furnace to 20 °C' – was optimal for increasing the percentage of elongation at break. Based on the data from the experimental study and their statistical processing regarding the effect of heat treatment parameters on the percentage of elongation at break, it is recommended to heat treat nylon parts produced by FDM at the following settings: temperature –110 °C, duration of exposure – 60 min, cooling – 'in the furnace to 20 °C', which allows for maximum increase in the percentage of elongation at break.

The research findings can be utilized for the development of practical recommendations on the heat treatment of nylon products, contributing to the expansion of additive manufacturing capabilities and the improvement of printed part quality.

Acknowledgements. *The work was supported by the National Research Foundation of Ukraine (project No. 2023.04/0098 "Development of practical recommendations for expanding the use of additive technologies for the production of parts and field repair of military equipment", 0124U003918).*

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Вплив термічної обробки на механічні властивості деталей з нейлону в адитивному виробництві

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Мета. Дослідження впливу параметрів термічної обробки на механічні властивості деталей із поліаміду 6 (нейлону), виготовлених методом пошарового наплавлення (Fused Deposition Modeling, FDM).

Методика. Зразки друкували методом FDM на 3D-принтері моделі Profi+ із використанням програмного забезпечення Slic3rPE для підготовки G-коду. Термічну обробку виконували в лабораторній електричній печі STM-1-10. Досліджували вплив таких факторів, як температура термообробки, тривалість витримки, тип охолодження. Механічні властивості оцінювали шляхом вимірювання міцності на розрив і відносного подовження за допомогою випробувальної машини UIT STM 100S. Статистичний аналіз результатів проводили у програмному комплексі STATISTICA, що дозволило визначити найбільш значущі фактори та їх взаємодії.

Результати. Досліджено вплив параметрів термічної обробки на міцність на розрив і відносне подовження деталей із нейлону. Найбільший вплив на міцність на розрив має температура термічної обробки, тривалість витримки в печі і парна взаємодія зазначених факторів. На відносне подовження найбільше впливає час витримки зразків у печі, а також парна взаємодія температури термообробки з типом охолодження. Взаємодія часу витримки з типом охолодження також показала внесок у формуванні функції відгуку (відносне подовження) Максимальне покращення міцності на розрив (+61,74 %) досягнуто при температурі 130 °C, витримці 90 хв. Для підвищення відсотка відносного подовження рекомендовано проводити термообробку за параметрами: температура –110 °C, час – 60 хв, охолодження – у печі до 20 °C.

Наукова новизна. Встановлено, що комбінування параметрів термічної обробки значно покращує міцність і пластичність деталей із нейлону, виготовлених методом FDM. Визначено, що найбільш ефективними є параметри: температура 110–130 °C, витримка 60–90 хв і охолодження в печі.

Практична значимість. Розроблені рекомендації щодо термічної обробки дозволяють підвищувати механічні властивості виробів із нейлону, створених за технологією FDM. Це відкриває нові можливості для застосування таких деталей у військовій сфері та виробництві виробів подвійного призначення завдяки покращеній міцності й довговічності.

Ключові слова: *Fused Deposition Modelling, нейлон, термічна обробка, міцність, відносне подовження, статистична обробка*

The manuscript was submitted 15.10.24.