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DETERMINING THE PARAMETERS FOR A 3D-PRINTING PROCESS USING THE FUSED DEPOSITION MODELING IN ORDER TO MANUFACTURE AN ARTICLE WITH THE REQUIRED STRUCTURAL PARAMETERS

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The mass application of FDM technology is slowed down due to the difficulty of selecting 3D printing parameters in order to manufacture an article with the required characteristics. This paper reports a study into the impact of 3D printing parameters (temperature, print speed, layer height) on mechanical parameters (strength, elasticity module), as well as on the accuracy of printing and roughness of the surface of a specimen based on thermoplastic (PLA plastic). Several batches of specimens were fabricated for this study in accordance with ASTM D638 and ASTM D695, which were tested for tension, geometric accuracy, and roughness. Based on the experimental data, regression analysis was carried out and the functional dependences of the strength, elasticity module, printing precision, roughness of a surface on 3D printing parameters (temperature, speed, thickness of the layer) were constructed. In addition, the derived mathematical model underlying a method of non-linear programming has established such printing parameters that could provide for the required properties of a structure. The analytical dependences reported in the current work demonstrate a high enough determination factor in the examined range of parameters. Using functional dependences during the design phase makes it possible to assess the feasibility of its manufacture with the required properties, reduce the time to work out the process of printing it, and give recommendations on the technological parameters of 3D printing. The recommendations from this study could be used to make PLA-plastic articles for various purposes with the required properties

Keywords: 3D printing, process parameters, FDM technology, tensile strength, manufacturing precision, PLA, layer thickness

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1. Introduction

Additive manufacturing (AM), also termed 3D printing, possesses a number of advantages over conventional industrial processes:

– fabricating articles of complex configuration, including those of composites, or from several materials at once. This makes it possible to obtain not only the structural parameters of an article but also implement some of its functional properties [1–3]. For example, printing electrical elements in conjunction with the structure;

– topological optimization of geometry and structure [4, 5];

– a quick transition from a model to its implementation.

The issue related to fabricating a structure that should comply with certain requirements by 3D printing is similar in many aspects to the problems related to manufacturing structures from composite materials [6]:

– the properties of the material are formed at the same time as the part printing process;

– there may be a mismatch between the characteristics of the printed article and those adopted during designing;

– it is not possible to directly determine the parameters of the material as one cannot cut a specimen from the part to test it. The use of witness specimens, which are printed next to the article, is more consistent with the indirect method.

Providing the required structural requirements for an article (the shape, precision of manufacture, no warping, surface quality) and the properties of the material could be achieved by the right choice of the process technological parameters.

Conventional technology uses parametric formulae that link an article's characteristics to the process parameters, which are based on data from a large number of experiments. For example, roughness in mechanical treatment is associated with the feed, speed, and depth of cutting. Building the parametric dependence of an article's property on the parameters of the 3D printing process makes it possible to choose the printing parameters unambiguously and reasonably, to reduce the cost of working out the printing process for the manufacture of an article with the required characteristics. To ensure a set of design properties, it is necessary to build a generalized function from the same parameters of the 3D printing process. After treating the generalized function with optimization methods, one can find such rational parameters of the process that would provide for a set of properties of the manufactured article. Therefore, building the functional dependence of a structure's properties on the technological parameters of the process is an important and relevant task.

Studies into the influence of technological parameters of the 3D printing process by the FDM method on the characteristics of a printed article have been carried out since the advent of this manufacturing method and are ongoing.

2. Literature review and problem statement

Work [7] reports a study of the strength characteristics of the specimens printed from ABS and PLA plastics, depending on the angle of orientation of the filling, the thickness of the printed layer, the temperature of the extruder. The results of the tests helped conclude that the strength of the printed specimens was higher than the strength of the material obtained during printing using other commercially available printers. Such comparison is not correct because the properties of the printed specimen material depend on both structural parameters and the technological parameters of printing.

Papers [8, 9] show that the angle of the filling print and the orientation of the specimen on the platform have a great impact on the mechanical properties of the specimen. The layering of the specimen received after printing reduces its strength characteristics compared to the specimens obtained by the press cast [10]. The results of experimental studies reported in [8–10] could be changed by the application of the theory of layered plates, whereby the filament is a reinforcement fiber while the angle of reinforcement is the angle of printing of the molten filament with the accepted thickness. This is the approach implemented in paper [11], which demonstrated a good alignment between the predicted elastic and strength characteristics derived from the analytical expressions of the theory and the experimental values.

However, there is no theoretical model that could describe the functional dependence of the roughness of the surface of a specimen [12] on the parameters of the printing process. It is also difficult to find a theory to construct an analytical relationship between the mechanical properties of the printed specimen material and the parameters of the process such as the speed of printing [13], the extrusion temperature [14], or the thickness of the plastic being fused [15]. Therefore, the authors of [12–15] experimentally selected print parameters that could provide for the necessary properties of an article. The inefficiency of such an approach relates to its cost, both of time and materials. At the same time, papers [13–15] examine the effect exerted on the properties of the printed specimen by only a single parameter of the process.

The comprehensive effect of the process's different parameters on the resulting properties of the printed specimen requires the joint application of an experimental and analytical approach. Among the possibilities of a comprehensive assessment of the parameters of 3D printing using the FDM technology affecting the properties of the finished structure is the approach reported in work [16]. The authors compared the results from testing the strength of printed specimens and the numerical values derived by a finite-element method. Models for the study involving a finite-element method were built using a structure corresponding to the printed specimen. Good agreement between the experimental and numerical values in the cited work makes it possible to use a finite-element model to determine the properties of printed articles. However, the condition of transferring numerical modeling results to the properties of a would-be printed article is that the settings for printing it must be identical to the settings for the specimen corresponding to the finite-element model. Of course, the properties of the article, obtained on the basis of a model, would not necessarily correspond to the required values. Therefore, this approach makes it possible to evaluate the properties of the material based on the model without additional experimental research but not to determine the parameters of printing that could implement the required characteristics of the article.

Another likely option to assess the impact of 3D printer settings on the final properties of the article when applying the FDM technology is to plan a multifactorial experiment and use the regression analysis method to evaluate the results of experimental data. This method makes it possible to derive an empirical dependence that relates the properties of a manufactured structure to the parameters of the process.

An example of this approach implementation is given in [17]; the analytical functions of the strength and accuracy of specimen sizes are based on Taguchi's methods and the function response surface. The angle of specimen position at printing, the thickness of the printing layer, and the temperature of the extrusion are taken as the technological parameters that provide the properties of the specimen under consideration. In work [18], the functions are built already on the angle of the specimen print, the temperature of the extrusion, and the speed of printing, depending on the strength and elasticity module of the specimen. The authors of [19] derived functional dependences of adhesive strength on print speed, extrusion temperature, and print platform temperature. Work [20] examines five parameters of the process, such as the thickness of the layer, the location of the specimen at printing, the raster angle, the raster width, and the air gap. Tensile strength, bending strength, and impact strength of the specimen are the reactions to their influence in this case. The empirical models reported in [18–20], which link the reaction and process parameters, were built using an analysis of variance (ANOVA). Functional dependences of the ultimate tensile strength and deformation limit when stretching printed parts were built in [21] using the method of the surface response depending on the thickness of the layer, the orientation of the article, and the density of the filling.

Thus, the cited works describe the possibilities of building functional dependences of the parameters of the 3D printing process. The parameters of the printing process, considered in [17–21], are important for making an article with the required properties, geometry, and quality. However, it should be noted that the choice of parameters should be reasonable. Some parameters, such as the position of the specimen, the angle of the filling print, the filling density could be determined in advance using a theory of layered plates [11]. Other parameters should provide not only the required properties but also take into consideration the economic costs of the 3D printing process. Therefore, it is necessary to have a toolset that would help reasonably choose the material and technological parameters for a particular article with the required characteristics at minimal production costs. In addition, the disadvantage of the above papers is an incomplete choice of controlled properties of the structure. For many articles, including aviation, in addition to the implementation of mechanical characteristics, the quality of the surface is an important factor. For example, a deviation from the preferred roughness value could increase the cost of making a part by refining its surface and increasing the mass. Therefore, a reasonable choice of article properties, printing parameters, and the construction of functional dependence linking them to each other are expedient and necessary for the manufacture of an article of the required quality at minimal production costs.

3. The aim and objectives of the study

The aim of this study is to determine the optimal parameters of the fusion deposition modeling, which could provide the required properties of the manufactured structure (precision, strength, roughness of the surface). This would further reduce the cost of designing and manufacturing a structure by 3D printing with the required properties and expand the market for its application.

To accomplish the aim, the following tasks have been set:

– based on the results of the experiment for the selected technological parameters of the 3D printing process, to build regression dependences of article quality factors that determine the desired article property (accuracy, strength, roughness of the surface);

– to analyze the resulting functional dependences and prepare recommendations for selecting the values of the printing parameters that would provide the required structural properties.

4. The study materials and methods

4. 1. Choosing the material to print specimens

3D-printing involving fused deposition modeling makes it possible to fabricate articles from a variety of thermoplastic materials – from conventional thermoplastics (PLA and ABS) to technical materials (PA, TPU, and PETG) with enhanced characteristics (PEEK and PEI).

The mechanical properties, the accuracy of an article, and the cost of the article directly depend on the material from which a structure is made. Even the coloration of the polymer affects the parameters of the finished article, as the dye is a filler that not only changes color but could also change the properties of the article. This study task was solved by using the red-colored PLA thermoplastic as the material most common for 3D printing involving the FDM technology. It should be noted that the application of another material would not change the algorithm for determining the process parameters that provide for the properties of a structure. Using other materials could change the range of values of the technological parameters within which there are the optimal printing parameters that ensure the maximum (minimum) values of the required article property.

4. 2. Selecting 3D printing process parameters and building an article quality factor function

Our analysis of literary sources [7–24] reveals that the researchers' focus is on several basic parameters of the 3D printing process that affect the properties of an article.

From the very beginning of the use of 3D printing by layer-by-layer filament fusion, it was noticed that printing is similar to the process of laying up reinforced fibers in the manufacture of a composite article. Thus, the anisotropy of the material in the article takes place at the 3D-printing by the FDM method. Depending on the position of a specimen on the platform, its mechanical properties would change during 3D printing [7–11]. At the same time, calculating the dependence of the mechanical properties of articles on the angle of the filament printing involving the FDM technology could help properly place the specimen on a desktop to provide for the required properties of the article.

Another printing process parameter is to fill a specimen: the scheme and its density. The filling scheme is typically linear, diamond-shaped, or hexagonal. Filling density is measured as a percentage and could vary from values where only a part's contour is printed to complete filling, which corresponds to a monolithic structure. A study reported in [11] has shown that the filling scheme has no effect on the mechanical characteristics of a specimen at the same density of filling the specimen with the material. The density of the internal filling of a part affects the duration of the manufacturing process and the strength of the article, so the choice of the appropriate value of the filling density is based on the trade-off between these parameters.

While the above parameters of the 3D printing process could be quantified and related to the article's properties via analytical dependences, the speed of printing, the temperature of the polymer supplied, and the thickness of the fused layer do not have such dependences. There are recommendations on the values of these parameters; they change in a wide range. For example, the printing speed could vary from 30 to 120 mm/s [12–19]; a part's roughness, strength characteristics, properties depend on this parameter. High speed ensures process performance while low speed provides better material extrusion, which is especially important when filling the polymer with special additives [22], as well as the high strength characteristics of the specimen's material [19]. The printing temperature is in the value range dependent on the filament material used. At the same time, high temperature provides better fluidity and, therefore, obtaining a more homogeneous material with reduced porosity [16]. Rising temperatures above a certain value lead to the degradation of the polymer and the deterioration of the properties of the specimen [23]. The thickness of the fused layer also exerts a contradictory effect on the characteristics of the process and the properties of the article. Works [15–19] show that reducing the thickness of the printed layer increases the strength of the specimen; study [24] demonstrated experimentally that there is such a thickness of the fused layer after which there is no significant increase in strength. In this case, the temperature of the extrusion, T, °C, the speed of printing, V, mm/sec, and the layer thickness, H, mm, would accept values for each material in 3D printing in order to obtain the required properties of an article. It should also be noted that these parameters make it possible to both obtain a certain geometry and shape of an article and determine the cost of its manufacture. Printing time would decrease as the layer thickness and printing speed increase while energy consumption grows as the extrusion temperature increases. Therefore, the temperature of the extrusion, T, °C, the speed of printing, V, mm/sec, and the layer thickness, h, mm were chosen as factors included in the function that determines the required property of an article.

The chosen parameters possess different dimensionalities, which causes some difficulties in their further formalization within a mathematical model. Therefore, first, it is necessary to bring the influence factors to a dimensionless form. In addition, each factor would be associated with the base value over the interval (range) that could be set up during the 3D printing process. The choice of the basis underlying those factors does not matter because it would affect only the scaling coefficients of the mathematical model of regression, which are later used to move to absolute values. The conversion coefficients to dimensionless forms are:

– the relative speed of printing,

$$X_1 = V' = \frac{V}{V_0}, \tag{1}$$

where V_0=90 mm/sec;

– the relative temperature of extrusion,

$$X_2 = T' = \frac{T}{T_0}, \tag{2}$$

where T_0=185 °C;

– the relative thickness of the layer:

$$X_3 = h' = \frac{h}{h_0}, \tag{3}$$

where h_0=0.3 mm.

The initial parameters are represented by the mean value recommended by the manufacturer for a given parameter at 3D printing using PLA plastic.

To find the factors (1) to (3) of the 3D printing process that determine the required value of an article's property, one could use a method of multiple regressions (regression analysis) [25]. A function of the i-th quality factor of the 3D printing process could then be represented in the following form:

$$\tilde{N}_i = \alpha_0 + \sum_{i=1}^{n} \alpha_i X_i + \sum_{i=1}^{n} \sum_{i=1}^{n} \alpha_{ij} X_i X_j, \tag{4}$$

where $i=1...n$ are the sampling numbers; α_i is the regression coefficients showing the average value of a quality factor change as 3D printing variables (V', T', h') increase, per measurement unit; α_0 is a free part of the equation that also needs to be determined.

To find the regression coefficients, each printing parameter was examined on a four-tier scale, as shown in Table 1, in accordance with the possible range of their changes [11, 18, 21] and a printer's limitations:

$$0.1 \le h \le 0.4,$$

$$175 \le T \le 210, \tag{5}$$

$$70 \le V \le 170.$$

Table 1

3D printing variable parameter values

Level	Layer thickness, h, mm	Printing speed, V, mm/sec	Printing temperature, T, °C
#0 (basic)	0.3	90	185
#1	0.1	70	175
#2	0.2	120	200
#3	0.4	170	210

Thus, within each group of manufactured specimens, only one 3D printing parameter (Table 2) changed at the same time.

Table 2

3D printing parameters for specimens

Specimen group	Layer thickness, h, mm	Printing speed, V, mm/sec	Printing temperature, T, °C
#0 (basic)	0.3	90	185
#1/1	0.1	90	185
#1/2	0.2	90	185
#1/3	0.4	90	185
#2/1	0.3	70	185
#2/2	0.3	120	185
#2/3	0.3	170	185
#3/1	0.3	90	175
#3/2	0.3	90	200
#3/3	0.3	90	210

The built specimen printing plan makes it possible to use only a truncated regression model that takes the following form [25]:

$$\tilde{N}_i = \alpha_0 + \alpha_1 X_{i1} + \alpha_2 X_{i2} + \\ + \alpha_3 X_{i3} + \alpha_4 X_{i1}^2 + \alpha_5 X_{i2}^2 + \alpha_6 X_{i3}^2 \tag{6}$$

or, in a matrix form,

$$(\tilde{N}) = [X](\alpha), \tag{7}$$

where $(\tilde{N})$ is the vector-column of an effective attribute's values; $[X]$ is the matrix of argument values (3D printing effects settings); (α) is the vector column of unknown regression coefficients that is to be determined.

The first column of the X matrix indicates a unit of measurement of the free part of the equation, as it is assumed that there is a variable 3D printing effect, which in all experiments takes values equal to unity. To evaluate the column vector (α), the most often used is the method of the least squares, whereby the vector-column $(\tilde{\alpha})$ is taken as an estimate, which minimizes the sum of squared deviations of the $\tilde{N}$ matrix values from their model values. According to the method, the vector-column of regression coefficient values is derived from the following formula:

$$(\tilde{\alpha}) = \left([X]^T [X]\right)^{-1} [X]^T (\tilde{N}). \tag{8}$$

Implementation of the step-by-step regression algorithm makes it possible to build regression equations for quality factors, depending on the printing parameters for the accepted material. Factors of the quality of the manufactured article are taken to be its mechanical properties (ultimate tensile strength and elasticity module), size accuracy, and roughness of the surface. The impact of printing parameters on each article quality factor is independently investigated. The fabrication of specimens in order to experimentally determine a quality factor value was in line with the printing plan (Table 2) and standard requirements. Three specimens were printed in each group.

4. 3. Experiment to determine quality function coefficients

To assess the accuracy of dimensions and to determine mechanical properties (ultimate tensile strength, elasticity module), the experimental specimens were modeled on the basis of the ASTM D638 IV type standard for tensile tests. Specimens to assess surface quality (roughness) were modeled according to the ASTM D695 standard for compression plastic testing. The PLA plastic was chosen as the material for printing.

For all specimens, the following printing parameters remained constant: construction direction, filling percentage, filling patterns. The direction of the construction Z means that the layers were stacked parallel to the *X*-*Y* plane (Fig. 1).

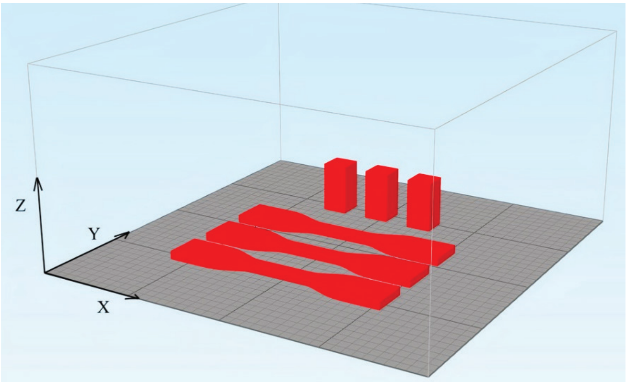


Fig. 1. Location of specimens on the platform when printing a batch

The percentage of filling corresponded to 100 % – a solid body. The type of filling was diamond-shaped patterns. The color of the specimens is red.

4. 3. 1. The quality factor: mechanical properties of the printed specimen material

Testing the specimens (Fig. 2) for tension was conducted according to ASTM D638, the speed of movement was in the range of 1 to 5 mm/min. The average values of mechanical characteristics for each group of specimens are given in Table 3.

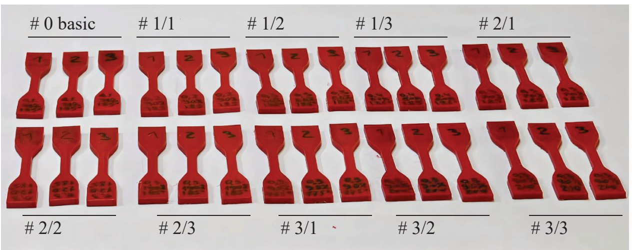


Fig. 2. Specimens for mechanical testing and printing accuracy assessment

Table 3

Average strength and elasticity module values for each group of specimens

Specimen group	Ultimate tensile strength (UTS) σ_{UTS}, MPa	Elasticity module *E*, MPa
#0 (basic)	45.96	2732.80
#1/1	29.16	2396.41
#1/2	41.75	2618.26
#1/3	42.98	2865.46
#2/1	39.13	2567.04
#2/2	40.27	2679.81
#2/3	39.03	2614.96
#3/1	35.18	2241.58
#3/2	42.60	2459.88
#3/3	46.11	2634.35

The average ultimate tensile strength and elasticity module's dependences of the tension of specimens (Table 3) on the technological parameters of 3D printing are shown in Fig. 3.

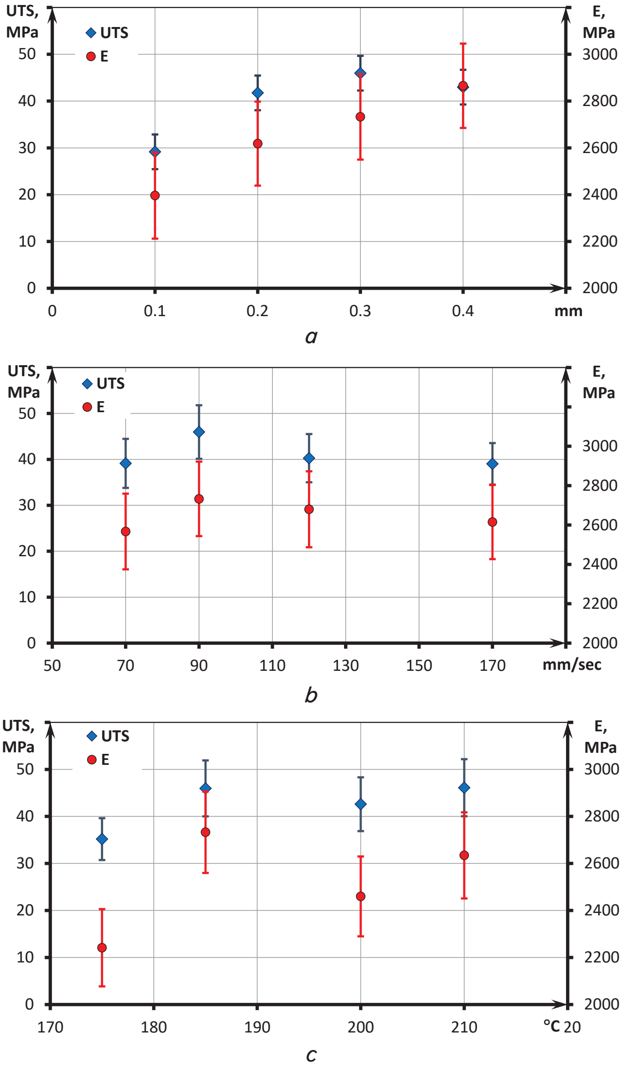


Fig. 3. The results of mechanical tests for the tension of different batches of specimens depending on: *a* – the thickness of the print layer; *b* – printing speed; *c* – extrusion temperature

Fig. 3, *a* shows that the increase in the thickness of the layer almost proportionally increases the mechanical properties of the printed specimens. The temperature of extrusion (Fig. 3, *c*) produces a similar effect, that is, with the increase in temperature, mechanical properties increase. At the same time, the speed of printing, as it follows from Fig. 3, *b*, has little effect on the mechanical properties of the specimens.

4. 3. 2. The quality factor: fabrication accuracy

To assess the impact of printing parameters on the accuracy of fabrication, specimens (Fig. 2) were measured and compared with a CAD-model's sizes. Nine basic measurements were performed for each specimen. The following measurements were selected: overall length (*OL*), overall width (*OW*1, *OW*2), thickness at ends and in the regular zone (*TS*1, *TS*3, *TS*2), and width in the regular zone (*W*1, *W*2, *W*3) (Fig. 4). The widths in the regular zone were brought to one average value (*W*).

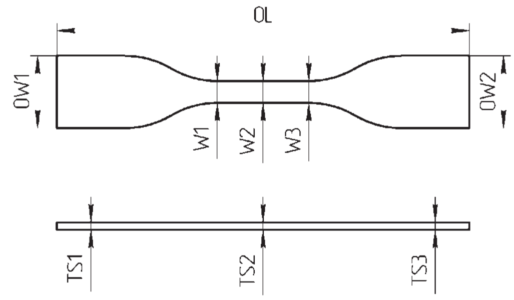


Fig. 4. Specimen measurement zones

As a result of the comparison of the size of the specimens obtained with a CAD model (*OL*=114.30 mm, *OW*=19.05 mm, *W*=6.50 mm, and *TS*=4.06 mm), absolute and relative dimension errors obtained during printing were determined (Tables 4, 5).

The absolute error of the size of the selected measurements for a group of specimens dependent on the parameters of 3D printing is shown in Fig. 5.

Fig. 5 shows that the deviation of the size of the printed specimen depends on the thickness of the fused layer (Fig. 5, *a*) and remains almost constant when changing the printing speed (Fig. 5, *b*) and the temperature of extrusion (Fig. 5, *c*).

Table 4

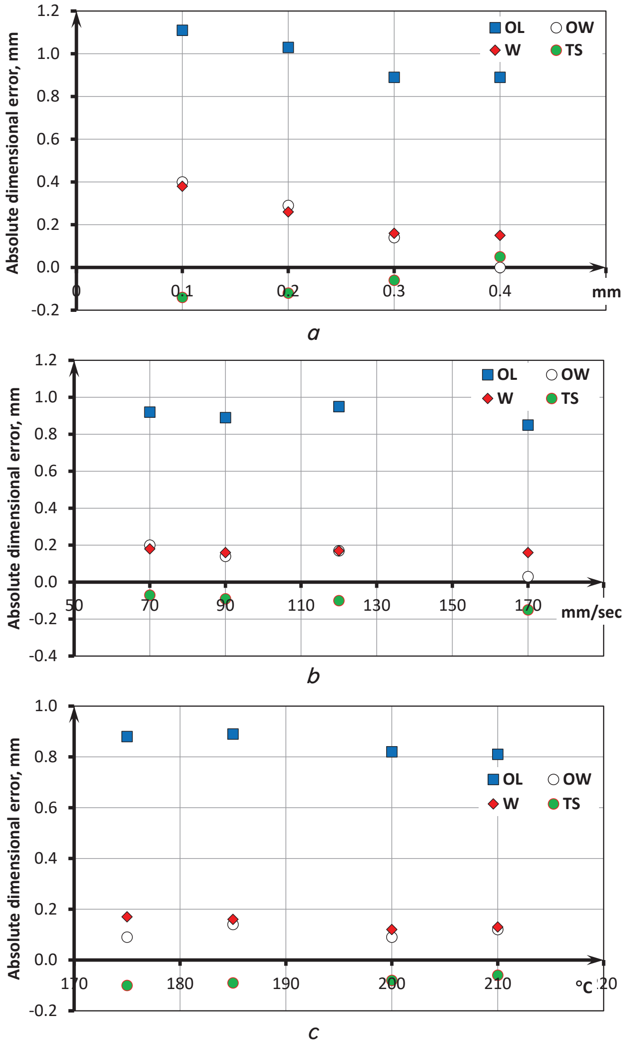
Size error values for a group of specimens (overall length and overall width)

Specimen group	*OL*, mm	*OL* error		*OW*, mm	*OW* error	
		Δ_E, mm	$\lvert\Delta_E\rvert$ %		Δ_E, mm	$\lvert\Delta_E\rvert$ %
CAD-model	114.30	–	–	19.05	–	–
#0 (basic)	113.41	0.89	0.779	18.91	0.14	0.735
#1/1	113.19	1.11	0.971	18.65	0.40	2.100
#1/2	113.27	1.03	0.901	18.76	0.29	1.522
#1/3	113.41	0.89	0.779	19.05	0.00	0.000
#2/1	113.38	0.92	0.805	18.85	0.20	1.050
#2/2	113.35	0.95	0.831	18.88	0.17	0.892
#2/3	113.45	0.85	0.744	19.02	0.03	0.157
#3/1	113.42	0.88	0.770	18.96	0.09	0.472
#3/2	113.48	0.82	0.717	18.96	0.09	0.472
#3/3	113.49	0.81	0.709	18.93	0.12	0.630

Table 5

Size error values for a group of specimens (regular area width and thickness)

Specimen group	*W*, mm	*W* error		*TS*, mm	*TS* error	
		Δ_E, mm	$\lvert\Delta_E\rvert$ %		Δ_E, mm	$\lvert\Delta_E\rvert$ %
CAD-model	6.50	–	–	4.06	–	–
#0 (basic)	6.34	0.16	2.462	4.12	–0.06	1.478
#1/1	6.12	0.38	5.846	4.20	–0.14	3.448
#1/2	6.24	0.26	4.000	4.18	–0.12	2.956
#1/3	6.35	0.15	2.308	4.01	0.05	1.232
#2/1	6.32	0.18	2.769	4.13	–0.07	1.724
#2/2	6.33	0.17	2.615	4.16	–0.10	2.463
#2/3	6.34	0.16	2.462	4.21	–0.15	3.695
#3/1	6.33	0.17	2.615	4.16	–0.10	2.463
#3/2	6.38	0.12	1.846	4.14	–0.08	1.970
#3/3	6.37	0.13	2.000	4.12	–0.06	1.478



a

b

c

Fig. 5. The absolute dimension error (mm) values in a specimen group for the selected measurements dependent on: *a* – layer thickness; *b* – printing speed; *c* – extrusion temperature

4. 3. 3. The quality factor: surface roughness

The roughness measurement (R_a, R_z, and R_q) was carried out at the profilograph SURFTESTSJ-210 along the side surface for each specimen in the central zone in accordance with ISO 4287-1997. Measurement parameters are as follows:

speed, 0.5 mm/s; wavelength (λ_C=0.8 mm, λ_S=2.5 µm); sliding force, less than 400 mN; the force of measurement/tip of the probe, 4 mN; the number of sampling lengths N=5.

The average roughness values for different printing modes are given in Table 6.

The average surface roughness values for different printing settings of specimen groups are shown in Fig. 6.

Table 6

Average values of specimen roughness, µm

Specimen	Average roughness measurement value			Note
	R_a	R_z	R_q	
#0 (basic)	23.044	115.937	27.598	The specimen is unsatisfactory
#1/1	7.288	39.536	8.841	–
#1/2	13.621	65.778	16.435	The specimen is unsatisfactory
#1/3	31.272	139.070	37.473	The specimen is unsatisfactory
#2/1	20.175	88.530	24.002	The specimen is unsatisfactory
#2/2	20.592	89.075	24.561	–
#2/3	20.451	89.734	24.329	–
#3/1	–	–	–	–
#3/2	20.804	92.743	24.805	–
#3/3	21.055	92.381	25.102	–

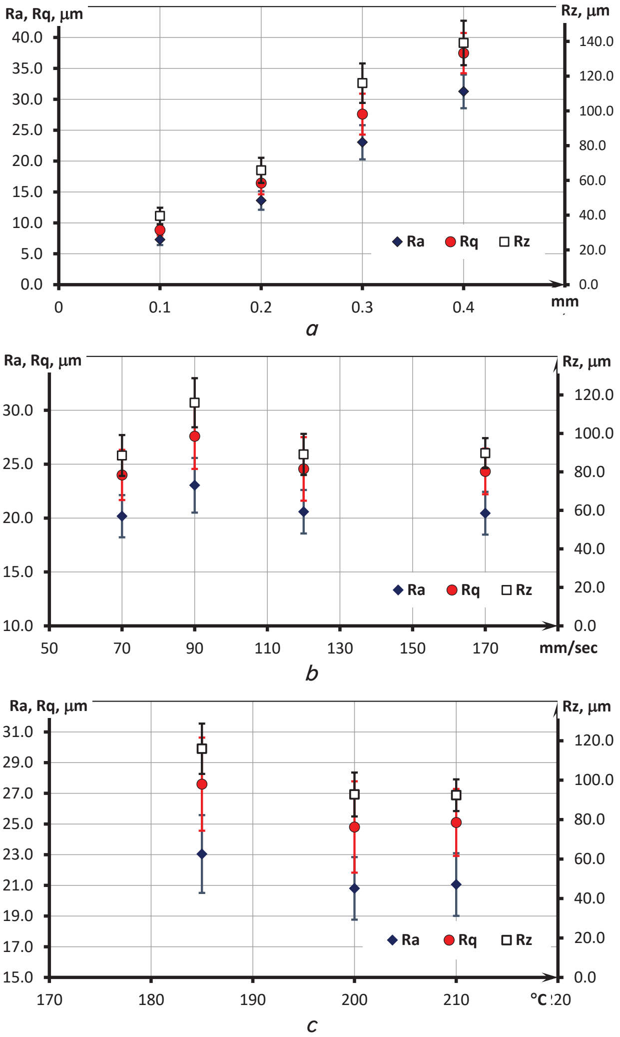


Fig. 6. The roughness values (R_a, R_q, and R_z) for different specimens depending on: *a* – the thickness of the print layer; *b* – printing speed; *c* – extrusion temperature

Fig. 6, *a* shows that there is a direct correlation between the roughness of the surface and the thickness of the printed layer, that is, the greater the value of thickness, the higher the roughness value. The speed of printing has almost no effect on roughness. However, when the polymer extrusion temperature rises, the roughness of the surface decreases, but slightly.

5. Results of studying the quality factor functional dependence

5. 1. Determining a regression dependence of the quality factors of an article made by a method of layer-by-layer fusion

Our implementation of the algorithm of a stepwise regression analysis of the experimental results given in Tables 3–6 has made it possible to build a regression equation for quality factors depending on the accepted printing parameters for the selected PLA material:

$$\sigma_{UTSnl} = -545.375 + 43.935h' + 23.01V' + 1018T' - \\ - 19.392h'^2 - 9.421V'^2 - 468.38T'^2, \qquad (9)$$

$$E_{nl} = -32.500 - 146.686h' + 765.099V' + 65.430T' + \\ + 318.02h'^2 - 268.065V'^2 - 30.970T'^2, \qquad (10)$$

$$\Delta^{W}_{E\,nl} = 5.152 - 10.438h' - 1.04V' + 13.062T' + \\ + 4.055h'^2 + 0.331V'^2 - 8.56T'^2, \qquad (11)$$

$$\Delta^{T}_{E\,nl} = 30.369 - 2.179h' - 0.3V' - 47.661T' - \\ - 0.103h'^2 + 0.774V'^2 + 21.071T'^2, \qquad (12)$$

$$R_{anl} = 111.373 + 10.606h' + 8.34V' - 210.54T' + \\ + 7.986h'^2 - 3.37V'^2 + 97.095T'^2, \qquad (13)$$

$$R_{znl} = 668.171 + 50.509h' + 56.371V' - 1.236T' + \\ + 29.548h'^2 - 24.022V'^2 + 554.604T'^2, \qquad (14)$$

$$R_{qnl} = 141.181 + 11.993h' + 10.98V' - 266.748T' + \\ + 9.894h'^2 - 4.436V'^2 + 122.841T'^2. \qquad (15)$$

Based on the resulting functions of quality factors (9) to (15), it is possible to determine the optimal values of the parameters of the 3D printing process (V', T', h') that would ensure the required properties of an article ($\tilde{N}_{opt}$). Solving such a problem does not pose fundamental difficulties while the solution algorithms are well-known from literary sources, such as [26, 27]. By stating a non-linear programming optimization problem to determine the optimal parameters of the 3D printing process (V, T, h) within the specified range of values for parameters (10) in the form of (16) to (21), we derived the solutions by using Lagrange multipliers, as well as in the Mathcad environment applying the embedded extremum search functions, which are given in Table 7.

$$\sigma_{UTSnl} \to \max, \qquad (16)$$

$$E_{nl} \to \max, \qquad (17)$$

$$\Delta^{W}_{E\,nl} \to \min, \qquad (18)$$

$$R_{anl} \to \min, \qquad (19)$$

$$R_{znl} \to \min, \qquad (20)$$

$$R_{qnl} \to \min. \qquad (21)$$

Table 7

Results from solving a problem on finding the 3D printing process parameters (*V, T, h*)

Optimal values of 3D printing process parameters			Objective function values, $(\tilde{N}_{opt})$
Layer thickness, *h*, mm	Printing speed, *V*, mm/sec	Printing temperature, *T*, °C	
0.34	109.94	201.03	$\sigma^{\max}_{UTSnl} = 46.64\ \text{MPa}$
0.4	128.437	195.402	$E^{\max}_{nl} = 2971.43\ \text{MPa}$
0.386	141.344	210	$\Delta^{W\min}_{Enl} = 1.582\ \%$
0.4	70	209.32	$\Delta^{TS\min}_{Enl} = 0.575\ \%$
0.1	170	200.576	$R^{\min}_{anl} = 5.395\ \mu\text{m}$
0.1	170	206.117	$R^{\min}_{znl} = 20.621\ \mu\text{m}$
0.1	170	200.863	$R^{\min}_{qnl} = 6.382\ \mu\text{m}$

5. 2. Analysis of the functional dependences of quality factors and recommendations for selecting printing parameters

Our analysis of the resulting printing parameters, which provide the required value of an article's properties after its manufacture (Table 7) reveals that they are quite consistent with the results reported in works [9, 11, 12, 18, 21, 22] for the material within the class considered. This demonstrates the acceptability of our results and allows us to suggest the following recommendations on 3D printing involving a PLA plastic.

While the most important for the production are mechanical parameters and stability of sizes in the *X*-*Y* plane at optimal printing time and energy consumption, the thickness of the layer then should be in the range of 0.3...0.4 mm; the printing speed chosen is high enough, 100...140 mm/sec; and the extrusion temperature is determined from the range of 200...210 °C.

To meet the requirement for a surface low roughness, the following printing parameters are required: the thickness of the layer must be chosen to equal 0.1 mm; the printing speed should exceed 170 mm/s; the extrusion temperature should correspond to the range of 200...206 °C.

To meet the requirement for dimension stability along the *Z* axis (the thickness of an article), the following parameters of printing must be satisfied: the thickness of the layer, 0.4 mm; the printing speed, 70 mm/s; the extrusion temperature, 210 °C.

It is possible to minimize printing time and energy consumption at satisfactory article quality in the following way: the thickness of the layer should be in the range of 0.3...0.4 mm; the printing speed is chosen from the interval of 140...170 mm/s; and the extrusion temperature is determined from the range of 200...210 °C.

6. Discussion of results of studying the 3D printing process parameters

This study has made it possible to assess the impact of the technological parameters of the 3D printing process on the structural properties of specimens and to reasonably accept them as generalized parameters of the process in the function of the article quality criterion. It should be noted that the degree of their influence on the properties of an article was different:

a) The thickness of the layer. Increasing the thickness of the print layer:

– improves the mechanical properties, that is the lowest layer thickness value corresponds to the minimum ultimate tensile strength and Young modulus values. The difference between the minimum and maximum values exceeded 15 MPa for the ultimate tensile strength and 400 MPa for the Young modulus;

– decreases size deviations along both the *X*-*Y* plane and the build axis (thickness). At the same time, the relative deviations (errors) of the length and width did not exceed 2 % while the relative deviation (error) of thickness did not exceed 3.5 %;

– increases roughness. The lowest layer thickness value corresponds to the minimum values of R_a, R_z, and R_q. The difference between the minimum and maximum values of R_a was 23 μm, R_z – 100 μm, and R_q – 29 μm.

b) The speed of printing in the study range has little impact on the examined properties of printed specimens:

– the values of the mechanical characteristics of the specimen material, the roughness of its surface, and the deviations of size remain almost constant;

– the difference between the minimum and maximum values for R_a and R_q was less than 3 μm; as regards R_z, there was a larger difference of 28 μm;

– the deviations in size values were up to 1.05 % for *OL* and *OW*, and for *W* and *TS* – up to 2.7 %. The exceptions were specimens printed at a maximum printing speed of 170 mm/s, which yielded a specimen thickness deviation of 3.7 %.

However, increasing the speed of printing reduces the time of article fabrication, which reduces production costs.

c) The extrusion temperature has a significant impact on the mechanical characteristics of the specimen material but does not exert a significant effect on the value of the deviation of the size and roughness of the surface:

– as the extrusion temperature rose, the difference between the minimum and maximum values was more than 10 MPa for the ultimate tensile strength, and more than 400 MPa for the Young modulus. This phenomenon is explained by the improvement of fusion inside the extruded layer and between layers, which improves cohesive strength in the specimen. However, temperature increases are limited to polymer destructive processes, energy consumption, etc.;

– the values of deviations in specimen sizes at different extrusion temperatures do not exceed 0.9 % of the total length and width of the specimen and are less than 2.5 % in its thickness;

– the difference between the minimum and maximum values for R_a and R_q was close to 2.5 μm; however, for R_z, the difference was 23.6 μm.

Unlike the experimental process parameter selection methods reported in [7–10, 11–16, 22–24], the analytical expression significantly reduces the cost of determining the values of the printing parameters that provide the required article property. In order to construct an experimental database underlying the empirical dependences built, this experiment was planned in a similar way to that proposed in works [17–21]. However, in contrast to those studies, the parameters of the 3D printing process (*V*, *T*, *h*) that have been adopted in the work would allow further assessment of the economic component of the printing process.

The resulting optimal values for the technological parameters of printing on specimens could be used without restrictions for other articles, provided they are made of a PLA plastic. If another material is used for 3D printing, a set of studies similar to those reported in the current work must be performed to establish a quality factor functional dependence on printing parameters. Upon solving the problem of linear mathematical programming, one can find the optimal values for the parameters of the 3D printing process that could provide for the required properties of the new printing material.

Constructing the models for a nonlinear regression analysis requires a significant increase in the number of specimens in order to obtain test results for different groups of technological parameters. That would increase labor-intensity, expenditures, as well as time costs. Therefore, at this stage, the equation of quadratic regression was accepted as a functional dependence. Accidental observational errors beyond each other's control were also not taken into consideration when building the model.

In the future, a more complete regression analysis may be carried out to clarify the functional dependence of an article's quality criterion on the technological parameters of printing. All this would lead to an increase in the experiment plan and additional costs. At the same time, it is not safe to say that those costs would significantly improve the accuracy in determining printing parameters. In addition, a model with a large number of variables complicates regression analysis. First, evaluating all possible regression models becomes an extremely complex computational task. Second, even if competitive models have been evaluated, it may turn out that the only optimal model does not exist, and there are some equally good ones. It is also possible to introduce other printing parameters into a functional dependence, such as the filling density, the temperature of the substrate table, and, for high-temperature plastics, the temperature in the printing chamber.

At the same time, there remain unresolved issues related to determining the optimal parameters of 3D printing in terms of assessing the process manufacturability in general. Such an assessment could be carried out taking into consideration the set of components of quality and weights that link them to the considered manufacturability function:

$$f(R) \to \sum_{i=1}^{n} k_i R_i(h,T,V), \qquad (22)$$

where *h* is the thickness of the fused layer, mm, *T* is the process temperature, °C; *V* is the printing speed, mm/sec; *i* is the number of components for the function $f(R)$; R_i is the quality factor function, k_i is the coefficient that would have a certain weight for each component.

Weight coefficients for different applications would vary due to different requirements in these industries. In the aerospace industry, for example, the main requirements are lightness, high strength, and high precision of articles. Even so, for some aviation elements, accuracy would be more important than other parameters, while for other articles the determining factor could be mass or strength. Therefore, assessing manufacturability is a big enough task that requires a comprehensive approach, many experiments, and/or a large database. Studies into these issues could be carried out in the future, based on the reported methodology for determining the optimal parameters of the 3D printing process by the FDM method, which ensure the selected component of the quality of a manufactured article.

7. Conclusions

1. Based on an experimental assessment of the effect of printing speed, extrusion temperature, and thickness of the fused layer exerted on the properties of specimens (precision, strength, roughness of the surface), we have built a multiple regression model of the second order. To find the regression coefficients, each printing parameter was examined on a four-tier scale in the range of values recommended by the filament manufacturer, taking into consideration a printer's technological limitations: printing speed, from 70 to 170 mm/s; extrusion temperature, from 175 to 210 °C; the thickness of the fused layer, from 0.1 to 0.4 mm. Our analysis of the resulting regression dependences to determine the strength of the material and its module of elasticity at stretching, the accuracy of specimen fabrication, and the roughness of its surface for the 3D printing parameters considered has revealed that they exert an almost equal effect. The statistical estimate of the consistency of regression equations with the experimental data based on the determination coefficient was at least 0.786 for material strength, and 0.93–0.988 for the remaining parameters under consideration.

2. By solving the problem of non-linear programming, we have derived such printing parameters that could ensure the required structural properties. Our analysis has made it possible to suggest the following recommendations on 3D printing involving a PLA plastic for articles with different purposes:

– with improved mechanical characteristics and stability of sizes at optimal printing time and energy consumption – the recommended thickness of the layer is in the range of 0.3...0.4 mm, printing speed – 100...140 mm/s, extrusion temperature – 200... 210 °C;

– with satisfactory quality at minimal printing time and energy consumption – it is recommended to increase the printing speed to 140...170 mm/s, while other parameters remain the same as in the first case;

– with the low roughness of the surface – it is recommended to reduce the thickness of the layer to 0.1 mm and to set the printing speed to exceed 170 mm/s at an extrusion temperature of 200...206 °C.

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