UDC 655.3.022.6; 655.343
DOI: 10.15587/1729-4061.2023.275913

IMPROVING PRINTED PRODUCTS MANUFACTURING TECHNOLOGY USING 3D PRINTING

Tetiana Rozum
PhD, Associate Professor
Department of Reprography*

Kateryna Zolotukhina
Corresponding author
PhD, Associate Professor*
E-mail: zolotuhina.ekaterina@lll.kpi.ua

Olga Kushlyk-Dyvulska
PhD, Associate Professor
Department of Mathematical Physics and Differential Equations**

Anastasiya Petryshyna
Department of Reprography*

Ivanna Marchuk
Postgraduate Student
Department of Reprography*

*Educational and Scientific Publishing and Printing Institute**
**National Technical University of Ukraine «Igor Sikorsky Kyiv Polytechnic Institute»
Peremohy ave., 37, Kyiv, Ukraine, 03056

The aim of the paper is to analyze the state of the printing industry in the current conditions, learn reproduction technologies on non-absorbent surfaces, and study modern technological processes of obtaining products based on 3D printing, which is the research object. The problem lies in the lack of general recommendations for using the above technology to produce printed products or their elements.

The main factors affecting the quality of finished products have been determined. The criterion to compare possible options for creating printed products was selected, namely, the examination method was considered. After processing the expert group summary, the consistency degree of opinions was determined using Kendall's concordance coefficient. The most significant factor was identified, and further research is focused on it. Layer-by-layer deposition modeling was chosen as the technology for creating the test. Test fragments were developed, and materials and equipment to run the experiment were selected. A quantitative and qualitative assessment of the quality of 3D printing was carried out.

Following the conducted research, the shortcomings were taken into account, and a number of recommendations for further creation of the forthcoming high-quality product were made. Those recommendations refer to the optimal line width (1.5 points and more), typeface origin and font size (20 points and above) for the reproduction of text information, and thickness of the element base of printed products (minimum 2.5–3 mm).

The above recommendations allow a 3D printing product and its elements to achieve a remarkable quality level and visual appeal, as well as enable enterprises to use it as the basis of technological instructions for applying modern technologies

Keywords: printing technologies, 3D printing, printed products, graphic images, font size, text information, binding, examination method, layer-by-layer deposition, ABS plastic

Received date 03.01.2023
Accepted date 15.03.2023
Published date 28.04.2023

***How to Cite:** Rozum, T., Zolotukhina, K., Kushlyk-Dyvulska, O., Petryshyna, A., Marchuk, I. (2023). Improving printed products manufacturing technology using 3D printing. Eastern-European Journal of Enterprise Technologies, 2 (1 (122)), 99–108. doi: https://doi.org/10.15587/1729-4061.2023.275913*

1. Introduction

According to the research of the monthly survey of enterprises «Ukrainian business during the war» of the Institute of Economic Research and Political Consultations, 2022, «How Ukrainian industry overcomes the challenges of the War» [1], a critical drop in production is recorded in a number of industries. As of July, 7 % of enterprises in the printing industry did not operate. Compared to the pre-war period, capacity utilization was as follows: 14 % of enterprises were loaded by less than 25 %, 7 % were loaded by 50–74 %, and the rest 57 % by 75–99 %. Optimism about the future was cautious across the board. The Index of expected changes in the business environment in almost all industries decreased from +0.16 in June to +0.09 in July. However, there are positive ratings in most industrial sectors, except for printing. The indicator of the financial and economic situation and expected changes was the same, at –0.38. Production expectations for three months are optimistic regardless of industry – all indicators are positive. Also, the expected index of production changes in the printing industry reached zero.

The comparison of the company's financial and economic situation with the same last year's period shows a significant economic decline [2] (November 2022) in all sectors. It's worth saying that the index of the current financial and economic situation for the printing industry was recorded as the highest (–0.54). Regarding business performance and short-term expectations, the index of production changes has a single positive value of 0.15 among all sectors and industries, which indicates the best situation in the printing industry. Production expectations reached a positive level of 0.09. The highest sales index for enterprises in the printing industry was also recorded (0.23). The index of export changes is the highest at a zero mark, and the printing industry has the highest index of expected export changes (0.25). A positive trend in the growth rate of new orders (0.45) was also reported. New orders grew most in the Kyiv region (0.23). The highest indicator of expectations for increasing receivables and payables was also in the printing industry. It was equal to zero. There is also a positive trend in the search for qualified and unskilled workers in the printing industry, and regional differences in the labor market were recorded. The recovery leader (missile fire, power supply problems) was also the printing industry, where 75 % of enterprises worked at almost full or full capacity in November. The industry consistently showed strong recovery rates, in particular 53 % in October and 61 % in September.

The functioning of the printing industry in wartime is crucial, being one of the factors in achieving a victory. The ability to make right production decisions, communication with business structures, and significant opportunities for digital laser and ink-jet printing technologies are extremely important tasks for today. The growth of digital printing, the penetration of IT into printing workflows, etc., are far from a complete list of tasks that require various tools to optimize working processes. And here, one of the critical factors is the ability to apply the acquired knowledge of fundamental disciplines in the applied printing industry.

Despite the circumstances, the industry remains afloat, modern technologies are supported, and hybrid products appear, combining diverse technological processes with various equipment and materials. Thus, traditional printed product elements are combined with the latest technologies, such as 3D printing. 3D printing technology is rapidly developing due to its availability, simplicity and ability to create objects of various shapes from numerous materials. However, the lack of scientifically based recommendations regarding the combination of technological support of traditional and modern processes requires additional research, so the study of 3D printing is an urgent scientific and technical task.

2. Literature review and problem statement

3D printing is one of today's most innovative technologies that have a consequential influence on all existing industries and fields of activity. Medicine, manufacturing, space research, etc. have undergone the greatest changes from 3D printing. A comparative analysis of existing 3D printing technologies with an indication of application areas, main capabilities, and brief description of operating principles is given in [3]. However, an analysis of technology relevance for specific industries must be detailed.

The work [4] shows the results of reducing material consumption, design flexibility, and competence in manufacturing complex structures using 3D printing technologies. However, calculations for the printing industry are not specified.

Even though the printing industry is a hotbed of various printing technologies, 3D printing is difficult to attribute to a particular type, not to mention traditional ones. However, innovations do not bypass the printing industry. Printed materials with the Braille reproduced using 3D printing is one such innovation. Research in [5, 6] confirms the possibility of using 3D printing in polygraphy. Reproduction of relief text by 3D printing greatly simplifies the communication between blind and partially sighted people in society. However, a three-dimensional object printed on a 3D printer as an element of printed products, such as a cover for a book, notebook, album, etc., or a decoration for these printed product samples has not yet been considered. In addition, 3D printing allows you to create relief images that can provide not only a visual component but also give pleasant tactile sensations.

The expansion of additive manufacturing and open access to digital production facilities creates opportunities for personalization, creativity and manufacturing souvenirs using 3D printing. With a qualitative approach, the study [7] demonstrates the results of developing and personalizing souvenirs using new technologies. The advertising-souvenir segment is closely intertwined with printing, and the work [7] indicates the possibility to use additive technologies in this area.

The jet 3D printing technology is considered in [8]. The possibility to simultaneously print products using several printer heads to create heterogeneous complex structures for electronic devices is shown. However, this direction can be developed more widely and projected onto printed products, such as RFID labels.

In [9], the results of developing a methodology for manufacturing polymer threads embedded in a 550 μm radio frequency identification (RFID) chip using the extrusion process for 3D printing programs are presented. It is shown that 3D printing is suitable for manufacturing RFID elements that can be included in printed labels and the like and used as an element of product protection.

Issues related to manufacturing other printed product samples in combination with additive technologies still need to be solved. Since 3D printing in polygraphy for decor production is practically not considered, the study of using it to create elements of printed products, such as bindings, is relevant. The given analysis suggests that it is expedient to conduct a study to determine the best modes and parameters for reproducing image elements using 3D printing.

3. The aim and objectives of the study

The aim of the study is to develop a methodology for improving the process of manufacturing 3D printing products based on improving the technology of creating elements using 3D printers. This will make it possible to develop general 3D printing recommendations for producing printed product components and reducing the production cycle.

To achieve the aim, the following objectives are set:

– to classify materials, equipment, and technological capabilities of 3D printing;

– to perform mathematical processing of the results of comparing options for creating bindings by the three-dimensional printing method and to choose the most rational technological process;

– to determine the minimum permissible layer thickness for the qualitative and quantitative reproduction of image elements.

4. Research materials and methods

4. 1. Research methodology

The object of research is 3D printing technology in terms of manufacturing elements of printed products. The subject of the study is the modes and parameters of the production of elements of the final product.

Non-compliance with printing parameters leads to process instability, violation of reproduction of small and font elements, defective prints, lack of readability and perception of the general appearance of the graphic image. Consumables vary significantly in their composition. A detailed study of their physicochemical transformations under the influence of printing contact will reveal the patterns of the impact of factors on the stabilization of the printing process and normalization of the reproduction of image elements by 3D printing. Thus, it is possible to express the research hypothesis of forming readable, uniform image layers on the print, ensuring the stabilization of their reproduction by adjusting printing modes and parameters.

To choose the most rational technological option for producing 3D printing products, it is necessary to select a criterion to compare possible options for creating bindings using a three-dimensional printing method. With the use of 3D printing, the option of making a binding for a book block is considered. The book block is created using the traditional printing method.

The examination method (method of expert evaluations) is considered following the processing of information obtained by interviewing competent experts with sufficient knowledge to solve the investigated problem.

As you know, the examination process is divided according to general methods [10] into several stages:

– definition of the expert, his competence in this study;
– conducting a survey;
– processing of survey results;
– determining the consistency of experts' opinions.

To determine the degree of consistency of experts' opinions, M. Kendall's concordance coefficient is used (from the Latin concordance – to align, arrange):

$$W=\frac{12}{m^2\left(n^3-n\right)}\sum_{j=1}^{n}\left(\sum_{i=1}^{m}x_{ij}-\frac{m(n+1)}{2}\right)^2, \qquad (1)$$

where m is the number of experts, n is the number of factors, $\sum_{i=1}^{m}x_{ij}$ is the sum of the ranks of the factor numbered i. If there are related ranks in the rankings, the concordance coefficient is calculated using the formula (correction for equal ranks):

$$W=\frac{12}{m^2\left(n^3-n\right)-m\sum_{j=1}^{m}T_j}\sum_{j=1}^{n}\left(\sum_{i=1}^{m}x_{ij}-\frac{m(n+1)}{2}\right)^2, \qquad (2)$$

where T_j is the indicator of related ranks in the ranking of the j-th expert;

$$T_j=\sum_{k=1}^{H_j}\left(t_k^3-t_k\right), \qquad (3)$$

where H_j is the number of groups of equal ranks in the ranking of the j-th expert, t_k – the number of equal ranks for the k-th group of related ranks. If there are no equal ranks, formula (2) becomes formula (1).

4. 2. Researched materials and means used in the experiment

The main factors affecting the quality of finished products are technology, materials, equipment, personnel, measurements and input information.

For developing test fragments (Fig. 1), the main elements placed on the front side of the binding were selected: book title and author name, graphic element. Text information is provided using three fonts (Calibri, Times New Roman, and Monotype Corsiva): sans serif, serif, and decorative, with different sizes (12, 14, and 16 pt). Graphical information is provided using lines of different widths at angles.

The format of the theoretical book, for which the binding of the eighth type is made, 60×84/32, is chosen. The dimensions of the cardboard side are 96×144 mm.

Layer-by-layer deposition modeling was chosen as the technology for creating the test due to its low price and relatively good quality.

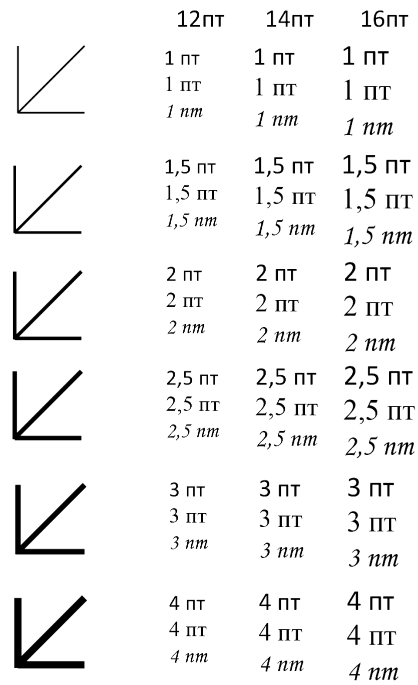


Fig. 1. Developed test items for conducting research

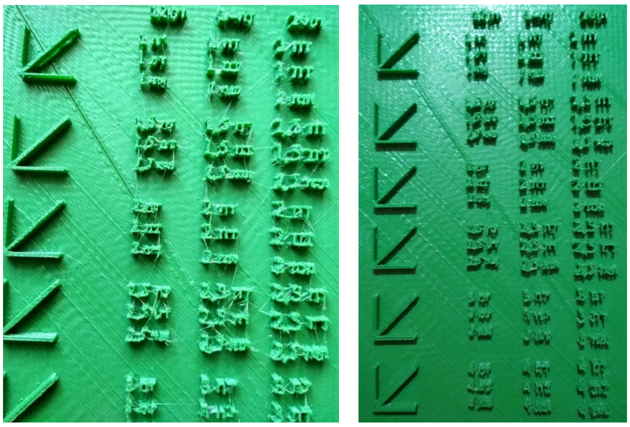
Printing was made on ABS plastic [11] using the Flashforge Creator Pro printer. The main printing parameters and modes are given in Table 1.

As a result of selecting printing equipment, materials and modes, a test was created, shown in Fig. 2.

Table 1

Researched technological support

Equipment/ Material/ Mode	Characteristic/Indicator	Value
Flashforge Creator Pro X 3D printer [19]	Printing technology	Modeling by the method of layer-by-layer deposition
	Number of print heads	2
	Nozzle diameter, mm	0.4
	Construction area, mm	225×145×150
	Layer thickness, mm	0.1–0.5
	Print speed, mm/sec	40–100
	Platform	With heating
	Materials	ABS plastic, PLA plastic, PVA plastic
	Thread diameter, mm	1.75
	Display	Available
ABS plastic properties [20]	Glass transition temperature	About 105 °C
	Bending strength	41 MPa
	Ultimate tensile strength	22 MPa
	Tensile modulus	1,627 MPa
	Relative elongation	6 %
	Cooling shrinkage	Up to 0.8 %
	Material thickness	About 1.05 g/cm^3
Printing modes	Model height	6 mm
	Nozzle diameter	0.4 mm
	Layer thickness	0.3 mm
	Table temperature	50°
	Printing speed	60 mm/sec



a b

Fig. 2. Manufactured test fragments: *a* – immediately after printing; *b* – after additional processing

According to the given test (Fig. 2), the primary indicators were measured. Based on their analysis, recommendations and conclusions were made regarding the stable reproduction of image elements.

5. Results of research on the factors determining the reproduction quality of elements obtained on a 3D printer

5. 1. Classification of materials, equipment, and technological capabilities of 3D printing

The currently available 3D printing technologies were systematized based on the study of literature data, and the classification was created shown in Fig. 3 [12–15]. The classification is based on two criteria: the type of material and methods of influence. Materials are divided into photopolymers, plastic threads, powders, and sheet materials by type and ultraviolet, heat, glue, and pressure by influence methods.

Today, there are two main technological varieties: modeling by the method of layer-by-layer deposition of material and stereolithography. The process of layer-by-layer material deposition is the creation of three-dimensional objects by applying successive layers of material that repeat the contours of the digital model. Printing materials are usually thermoplastics, supplied as coils or threads. ABS plastic is the most popular material for this technology. It has many advantages: easy paintability, extensive color palette, and high printing speed. PLA (polyacrylic acid) takes the second place. It is entirely environmentally friendly and has the highest printing accuracy.

Technical materials are used for models that require increased resistance to various influences. PET (polyester) is used in the case of a simultaneous combination of strength and viscosity, and PC (polycarbonate) – to manufacture high-strength products operating under high loads. PC allows you to create light-transmitting products, it is more rigid and more robust than PET but less dense. PBT (polybutylene terephthalate) is characterized by high technical characteristics – abrasion resistance and low coefficient of friction. As a strong and flexible plastic, Nylon is used to make ropes, fabrics, strings for musical instruments, etc. Elastane and Plastan are rubber-based materials. Laywood and BronzeFill materials allow you to imitate wood and metal, respectively. Another type of material is decorative. Their primary purpose is to build additional technological elements during printing and then remove them [16]. The materials are summarised in Fig. 4.

The second production technology is stereolithography. The following types of materials are used for it: mock-up (for making models, prototypes, models), wax (making jewelery, dental products), medical (dental products, prostheses, implants), technical and decorative.

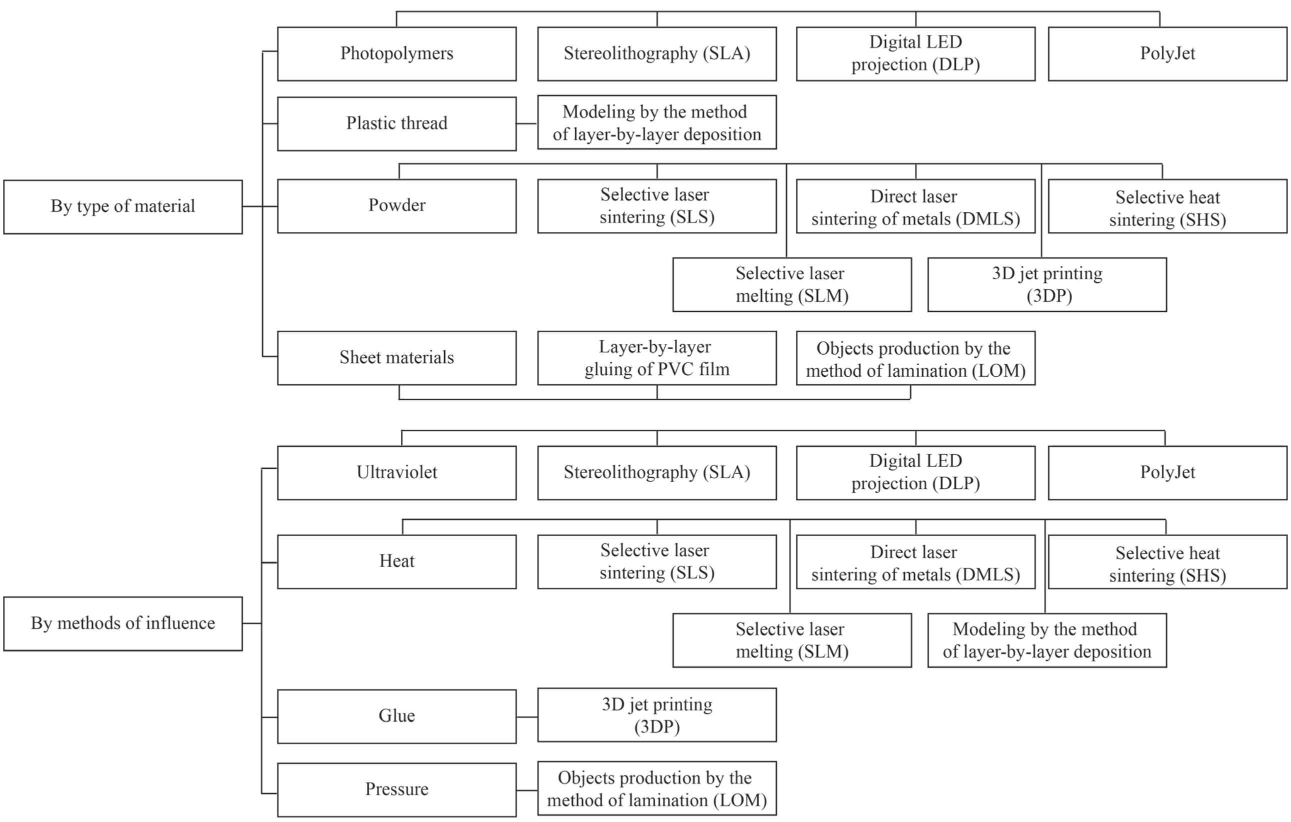


Fig. 3. Classification of 3D printing technologies

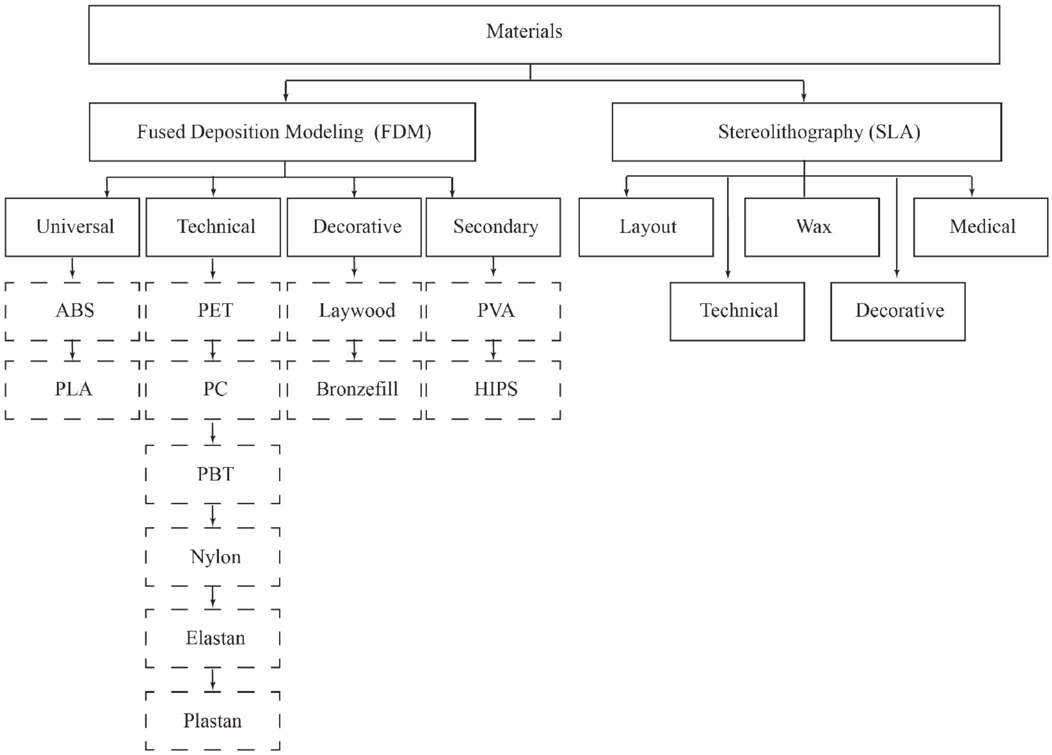


Fig. 4. Classification of 3D printing materials

These materials can and even should be used in printing. They can be used for decorating various products and making stamps for embossing and cutting. This will help to reduce the manufacturing process and save time [17–19].

5. 2. Mathematical processing of the results of comparing options for creating bindings by the three-dimensional printing method

Individual assessments in a group of experts are applied by filling in questionnaires. A survey was conducted taking into account the following criteria: cost ($K1$), quality ($K2$), process productivity ($K3$), material use ($K4$), profit ($K5$), product cost ($K6$), and work time expenditures ($K7$). It is proposed to carry out the following evaluation: assign a rank to each considered criterion from the most significant to the least but within the range from 1 to 4 (the least important criterion is assigned a rank equal to 4). Table 2 was obtained, which shows the results of 7 experts.

After determining the final opinion of the working group of experts, it was necessary to decide on the degree of consistency of the experts' opinions. Weighting factors were calculated, normalized ranks were determined (Table 2), and T_j values were calculated.

Table 2

Assigning criteria ranks by experts

Experts	Criteria						
	$K1$	$K2$	$K3$	$K4$	$K5$	$K6$	$K7$
1	4^7	1^1	1^2	3^5	2^3	2^4	3^6
2	4^7	2^3	1^1	2^4	1^2	3^5	3^6
3	3^5	1^1	2^3	1^2	4^7	3^6	2^4
4	4^6	1^1	2^2	2^3	3^4	3^5	4^7
5	2^2	2^3	1^1	2^4	3^6	4^7	2^5
6	4^6	1^1	1^2	3^4	2^3	4^7	3^5
7	3^5	2^2	1^1	2^3	2^4	3^6	4^7

Consider filling on the example of expert 1 according to Table 2: rank 1 is repeated twice, as it was assigned to the second and third criteria ($K2$, $K3$), which had ranks 1 and 2, respectively. Accordingly, the normalized rank of these objects is the arithmetic mean, equal to $(1+2)/2=1.5$. This value in the new matrix will be in the first row in the second and third cells (under $K2$, $K3$).

Rank 2 is repeated twice in the first line, as it was assigned to the fifth and sixth criteria ($K5$, $K6$), which had places 3 and 4, respectively. Accordingly, the normalized rank is: $(3+4)/2=3.5$. This value in the new matrix will be in the first row in the 5th and 6th cells. Rank 3 is assigned places 5 and 6, and the value $(5+6)/2=5.5$ will occupy the fourth and seventh cells in the new matrix, where the number 3 was in the original matrix. The fourth rank, repeated once, corresponds to place 7, which is its normalized value.

Normalized ranks for other experts are determined in the same way. The last row of this table contains the sums of normalized ranks for each criterion. The T_j column is entered in the matrix, which is used to assess the reliability of the results. According to formula (3), for experts 1, 2, 3, 4 and 6, its values are the same since the values of three ranks were repeated twice, and one was not repeated:

$$T_j = 3\cdot\left(2^3-2\right)=18,\ j=1,2,3,4,6.$$

For the fifth expert: $T_5=4^3-4=60$, for the seventh we have $T_7=(3^3-3)+(2^3-2)=30$.

Since the most critical criterion has the lowest rank (this condition is preserved during normalization), it will correspond to the minimum sum of normalized ranks, meaning that all experts evaluated this criterion with a relatively small number.

According to Table 3, the first place and the most significant advantage should be attributed to the third criterion. The second place belongs to the second criterion and the third to the fourth. The fourth place goes to the fifth, the fifth place to the seventh, the sixth place to the sixth, and the seventh place to the first criterion.

Table 3

Standardization of ranks for each criterion

Experts	Criteria							T_j
	*K*1	*K*2	*K*3	*K*4	*K*5	*K*6	*K*7	
1	7	1.5	1.5	5.5	3.5	3.5	5.5	18
2	7	3.5	1.5	3.5	1.5	5.5	5.5	18
3	5.5	1.5	3.5	1.5	7	5.5	3.5	18
4	6.5	1	2.5	2.5	4.5	4.5	6.5	18
5	3.5	3.5	1	3.5	6	7	3.5	60
6	6.5	1.5	1.5	4.5	3	6.5	4.5	18
7	5.5	3	1	3	3	5.5	7	30
Total	41.5	15.5	12.5	24	28.5	38	36	180

Accordingly, the *K*3 criterion was recognized as the most critical – process productivity, the second – quality, the third – material use.

The concordance coefficient *W* was calculated according to formulas (2), (3), which varies from zero to one. As is well known, given $W=0$, there is complete inconsistency, and $W=1$ – complete unity of experts' opinions. When $W>0.5$, the experts' opinions are consistent by more than 50 %, and the survey results can be used in further work. When $W<0.5$, the opinion is not consistent, a new expert survey should be conducted. According to (2), Table 3 and $m=n=7$, we have:

$$W=\frac{12\cdot 759}{7^2\left(7^3-7\right)-7\cdot 180}\approx 0.6.$$

The value of the concordance coefficient indicates a moderate degree of consistency in the opinions of experts who participated in the survey.

To check the significance [20] of the concordance coefficient at a given significance level $\alpha(0.05;\ 0.01)$, the actual $\chi^2_{act}=m(n-1)W$ and critical $\chi^2_{cr}=(n-1,\alpha)$ values are calculated (according to tables of Pearson's critical points). If $\chi^2_{act}>\chi^2_{cr}$, the rank connection between experts' opinions is considered significant, the concordance coefficient can be trusted, and its conclusions are valid. If it is the other way around: $\chi^2_{act}<\chi^2_{cr}$, then the hypothesis is accepted that there is no rank correlation between the opinions of all experts.

The actual and critical values of the criterion were calculated:

$$\chi^2_{act}=7\cdot 6\cdot 0.6=25.2.$$

When $\chi^2_{cr}=(n-1,\alpha)=(6,0.01)=16.8$, (for $\alpha=0.05$ $\chi^2_{cr}=12.6$), and $\chi^2_{act}>\chi^2_{cr}$, respectively, it is possible to consider the concordance coefficient as statistically significant, recognize the experts' opinions as consistent and trust the conclusions obtained on its basis.

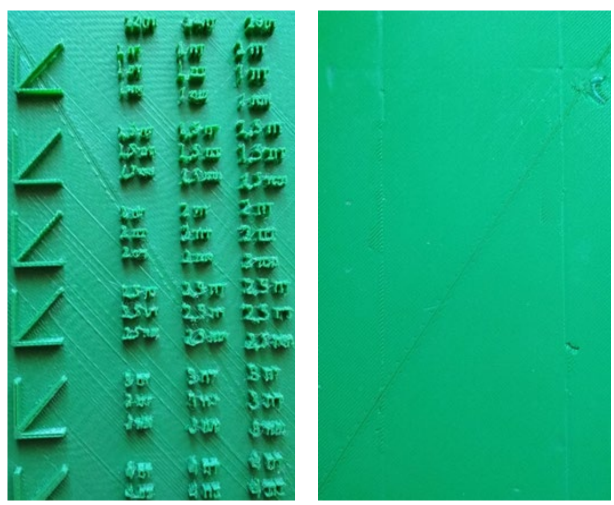
5. 3. Quantitative and qualitative evaluation of the quality of 3D printing

As evidenced in the previous paragraph, it was considered how exactly the elements are displayed on the finished model to evaluate the quality of three-dimensional printing, the second most important indicator. To do this, the presence of distortions, incorrectly created or missing layers, the quality of binding layers together, etc. were checked. For this, visual and instrumental (electron microscope) methods of product quality assessment were used.

A visual quality assessment of the binding base was made. It is a parallelepiped with sides of 96×144 mm and a height of 3 mm. The dimensions of the base have not changed, and the edges are even without missing elements or air bubbles. However, a defect was found: the diagonal of the rectangle, which is visible on the front and back of the part (Fig. 5). This type of distortion can occur due to an incorrect algorithm for setting the beginning of the creation of the part base, where the contours of the figure are first created, as well as due to an insufficiently heated extruder at the beginning of work with the part.

Small details are not reflected on the binding. Numerous plastic threads cannot be removed as they are located inside small elements.

An instrumental assessment of the reproduction quality of lines of different widths at different angles was also carried out. For this, the line width was photographed and measured by an electron microscope and compared with the initial data. The result of measuring all lines is listed in Table 4. Each group of lines was considered separately (Fig. 6).



a *b*

Fig. 5. Diagonal distortion of the part base in the front and back

Table 4

Results of measuring lines of different widths at different angles

Inclination angle	Line width in points											
	1 pt		1.5 pt		2 pt		2.5 pt		3 pt		4 pt	
	Before	After	Before	After	Before	After	Before	After	Before	After	Before	After
0°	0.35	0.54	0.53	0.91	0.70	1.01	0.88	1.01	1.06	1.45	1.41	1.71
45°	0.35	0.77	0.53	1.09	0.70	1.20	0.88	1.36	1.06	1.57	1.41	2.04
90°	0.35	0.69	0.53	0.58	0.70	1.05	0.88	1.02	1.06	1.42	1.41	1.69

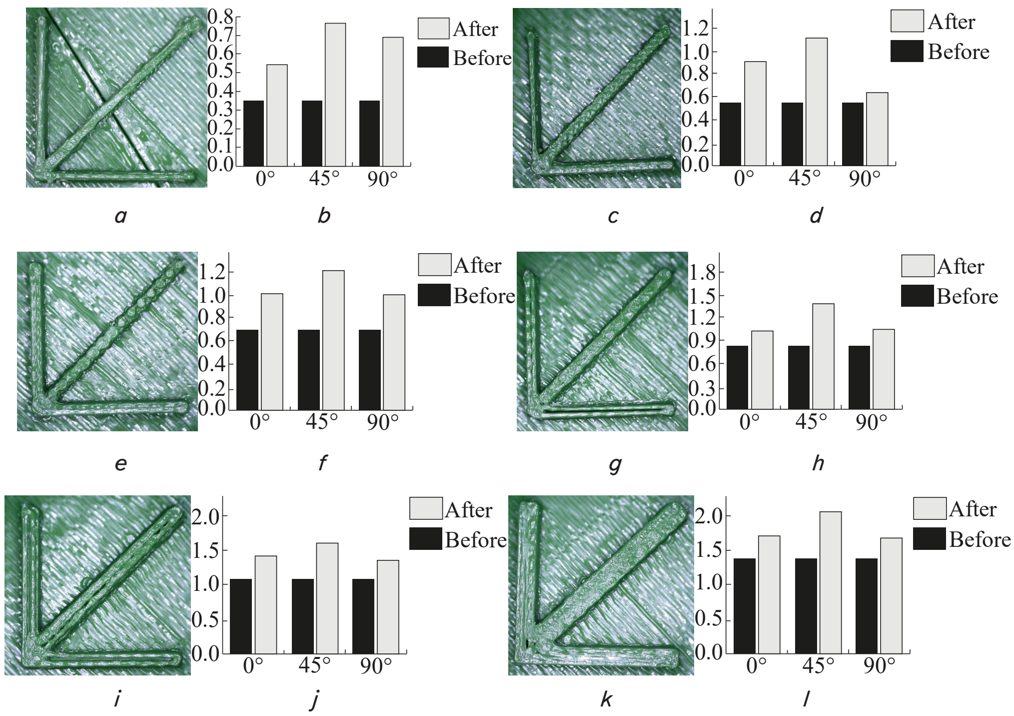


Fig. 6. Demonstration of a group of lines under a microscope and the diagram of line width change before and after printing: *a* — 1 pt line; *b* — 1 pt line change diagram; *c* — 1.5 pt line; *d* — 1.5 pt line change diagram; *e* — 2 pt line; *f* — 2 pt line change diagram; *g* — 2.5 pt line; *h* — 2.5 pt line change diagram; *i* — 3 pt line; *j* — 3 pt line change diagram; *k* — 4 pt line; *l* — 4 pt line change diagram

Visually, the group of lines with a width of 1 pt (Fig. 6, *a*) is acceptable. However, as can be seen from the diagram (Fig. 6, *b*), all lines have increased in size almost twice, and the line at a 45° angle is almost not attached to the base.

The second group of lines with a width of 1.5 pt and the measurement results are shown in Fig. 6, *c*, *d*. The line at a 45° angle was the most distorted. It increased by almost 2.5 times in size, while the line at a 90° angle was almost unchanged. The line at a 0° angle from the base demonstrated a 2-fold increase in width, but in the middle of the height, it loses the trend due to one missed layer and becomes thinner.

The third group of lines with a 2 pt width distorted (Fig. 6, *e*, *f*) by a total of 0.3–0.5 mm, the worst printed line at a 45° angle, which turns into a set of unconnected dots.

The fourth group of lines with a width of 2.5 pt and the measurement results are shown in Fig. 6, *g*, *h*. Visually, the 0° and 45° lines appear to be printed well, but under the microscope, it can be seen that the 0° and 90° lines have voids inside. The width of the lines is practically unaffected, but distortions are present.

The lines of the fifth group with a 3 pt width (Fig. 6, *i*, *j*) are printed the worst. All three lines have voids as vast as the outlines of the line. The distortion starts from the middle of the layers. The width of the lines is not affected much, but the voids clearly distort them.

The sixth group of lines with a 4 pt width (Fig. 6, *k*, *l*) was reproduced very well, where the distortion of the line width is not so significant compared to the rest of the groups. There are no unprinted lines, the edges are clear and even, and there are no missing layers. The lines are securely attached to the base.

The evaluation of the fonts confirmed their poor quality, so they need to be more readable, and there is a lot of plastic between different parts of the font drawing.

Each group of fonts is considered separately, using the example of reproduction of 1 pt and 2.5 pt inscriptions.

The first group of 12-point fonts is shown in Fig. 7, *a*, *b*.

This group of fonts, as mentioned earlier, was reproduced the worst. Numbers and letters are poorly reproduced. Under a microscope, you can see that the outlines of the letters are barely visible. Handwritten fonts were reproduced the worst, the letters cannot be distinguished at all.

The second group of 14-point fonts is shown in Fig. 8, *a*, *b*.

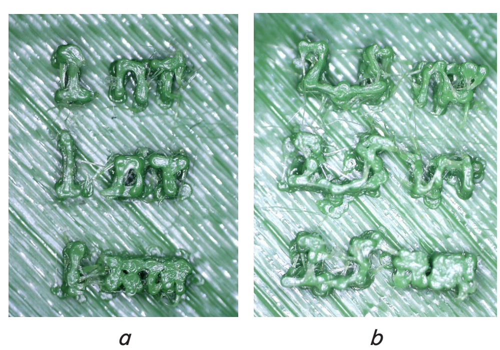


Fig. 7. 12-size fonts under a microscope: *a* — 1 pt; *b* — 2.5 pt

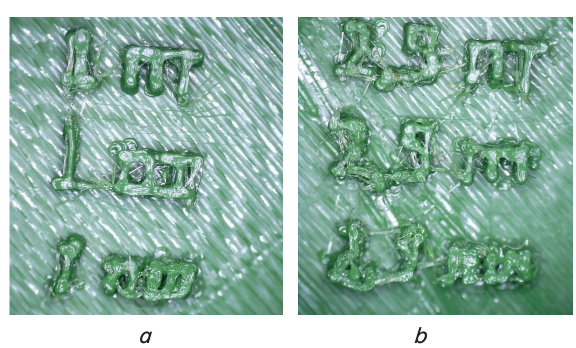
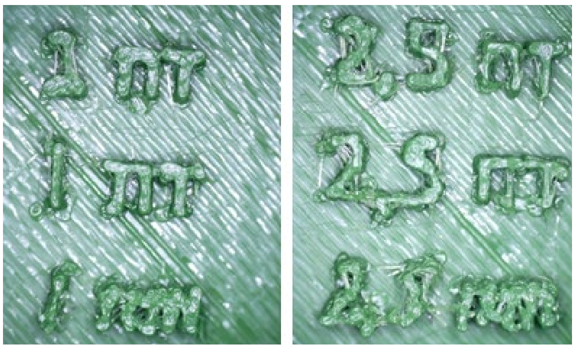


Fig. 8. 14-size fonts under a microscope: *a* — 1 pt; *b* — 2.5 pt

This group of fonts was reproduced better. Sans Serif fonts can be read. The serifs were not displayed properly in Serif fonts, so the letters are poorly reproduced. Handwritten fonts are unreadable at all.

The third group of 16-point fonts is shown in Fig. 9, *a*, *b*. Sans Serif fonts are reproduced legibly and without distortion in this group, and the letters are almost without deformations. The serifs can be recognized in Serif fonts, but the quality of the letters still needs to be improved. Handwritten fonts are very distorted and unreadable.



a *b*

Fig. 9. 14-size fonts under a microscope: *a* — 1 pt; *b* — 2.5 pt

After analyzing all the elements of the test part, it is recommended to use a line with a 1.5–2 pt width for small elements, and 3 pt line width for larger items. The fonts were not displayed well enough. 16 pt Sans Serif fonts were reproduced best.

As a result of the research and further test analysis, errors were taken into account, two binding layouts were created in one color and in two colors.

The result is shown in Fig. 10.

a *b*

Fig. 10. Prototype made by 3D printing: *a* — ready-made prototype of a one-color binding; *b* — finished prototype of a two-color binding

The binding prototype has a clear image and legible text, embossed elements that are visually appealing and pleasant to the touch. Therefore, using additive technologies in printing to produce elements of printed products is an acceptable and quite fast option compared to traditional technologies. In addition, this method ensures product strength and durability.

6. Discussion of the results of studying the reproduction quality of elements obtained by 3D printing

Based on the conducted research, printing of the test model and binding in two different versions, all the shortcomings were taken into account, a list of recommendations for further creation of high-quality plastic bindings was created.

It is necessary to choose equipment and materials that can create the selected model. It is essential to consider the printing accuracy of equipment, nozzle diameter, and printer structure. Regarding the material, for parts with tiny elements, it is better to use PLA plastic to prevent a large number of plastic threads. For parts with larger elements, you can safely use ABS plastic (Table 1).

When creating images from lines of different widths, the minimum width of small lines should be greater than 1.5 or 2 pt. To create larger elements, it is necessary to use 3 pt lines or more (Fig. 6).

When creating the model and further setting printing parameters, it is necessary to take into account that lines at a 45° angle are most distorted, regardless of the line width. It is also essential to highlight the design of the future binding when specifying the direction of movement of the printer axes. Lines that are perpendicular to the direction of travel are also strongly distorted.

When choosing fonts, the best choice is to use 20 pt or bigger Sans Serif fonts. If Serif fonts are needed, choose 36 pt and higher sizes to reproduce them correctly. When selecting decorative fonts, using bold fonts without small elements is recommended. It is better to avoid handwritten fonts (Fig. 7–9).

When choosing the layer thickness, it is necessary to consider the part's complexity, namely the presence of small elements. The greater the number of small elements, the thinner the layer should be. This is due to smooth transitions, but it is also necessary to choose a suitable material to avoid a large number of plastic threads.

When choosing the thickness of the binding base, it is necessary to select a thickness of at least 2.5–3 mm to avoid deformation and for sufficient strength of the base.

To create inside-out bindings (images and letters do not protrude above the base, but sink into it), it is necessary to choose the correct base thickness and not use small elements. The larger the elements, the better because with small elements, everything will be tightened with plastic threads and spoil the appearance of the part.

It is also possible to use plastic of different colors, but the number of colors must match the number of print heads. The plastic must be melted to the same temperature to reliably bond the elements. When changing the thread, for example, the plastic cools and becomes hard, making the bond unreliable. When using plastics of several colors, plastics with the same properties must be used. These limitations should be taken into account when planning manufacturing processes and analyzing production capabilities. At the stage of creating a technical task, it is necessary to examine the limitations that can be imposed on the finished product when used. For example, the printed product's weight may increase due to the use of plastic elements. If it is a mass production that requires distribution and mass shipping to customers, this may affect the cost of logistics. Therefore, using bulk elements created by 3D printing is appropriate for small-scale, one-off, exclusive production.

To reduce the visibility of creating layers and filling the model (plastic supply lines), it is possible to process plastic using acetone.

Unlike [5, 6], where additive technologies were considered only in terms of Braille font reproduction, the obtained result of manufacturing other printed product components allows expanding the palette of structural elements. This becomes possible using ABS plastic and 3D printing. The manufactured elements are characterized by strength and design originality and are appropriate for exclusive gift printing products. Combining 3D printing with classic printing technologies is an acceptable solution to obtain long-lasting printed products or publications with added value. This approach expands the range of so-called hybrid technologies – the combination of two or three technological solutions in one production process to create an original or complex product. This was mainly implemented in the offset printing method. However, 3D printing today can be combined with the digital method in the production of books on demand in a single copy, with the stencil method, etc. The obtained results are adequate both from a practical and theoretical point of view. Taking them into account will ensure that the textual and pictorial information on the element created by 3D printing meets the above requirements. Otherwise, the result may be unsatisfactory in readability and design attractiveness. The expected results can also include increased demand for printed products due to the combination of porous and non-absorbent materials, providing a 3D effect and volume to printed products. The direction of combining plastic fragments with elements of a printed Pop-Up book is fascinating. Based on the book, you can expect a mix of printed editions with 3D-printed playing cards, items, souvenirs, and more. In the future, this can become an excellent entertainment or educational product for a children's audience.

The limitations of this study include using a specific model of a 3D printer and its consumables. The results obtained using a different material and technical base may differ somewhat from those given in the study. However, given the application of the chosen technology and compliance with the recommended modes, the recommendations can be unchanged and relevant for other similar equipment and materials.

The development of this research can be the use of 3D printing in the development of RFID elements and their implementation in packaging and labels. Also, producing single samples of printed products with elements printed on a 3D printer can be cost-effective and fast in obtaining an exclusive, original design.

7. Conclusions

1. 3D printing technologies (by type of material and methods of influence) and materials (FDM, SLA) that can be used to manufacture elements of printed products are systematized and classified. Based on the classification of materials, equipment, and technological capabilities, possible combinations of elements in the «original-layout-imprint» system were determined. To manufacture printed product elements following the above classification, modeling by the layer-by-layer deposition method should be chosen. ABS plastics are combined with this technology. With such a combination of material and technical support, the technological process will be productive, and the product quality will be high.

2. The main factors affecting the quality of finished products are determined. A criterion to compare possible options for creating them was selected. Namely, the examination method was considered, and the degree of consistency of experts' opinions was determined using the M. Kendall concordance coefficient. The most significant factor is singled out – process productivity. The second important thing is quality. The third is material selection. The productivity of the 3D printing process is crucial when deciding to use it as part of hybrid technologies for manufacturing printed products. The speed of printing a volumetric element and the availability of the material and technical base allow you to produce the product quickly and combine it with the main product.

3. Using the method of layer-by-layer deposition, test fragments were developed, materials and equipment for the experiment were selected, and quantitative and qualitative assessment of the quality of 3D printing was carried out. Recommendations have been developed that significantly improve the quality, visual appeal of elements and the product as a whole manufactured by 3D printing. The minimum width of small lines that form the image should be more than 1.5 pt. Using lines at a 45° angle should be limited. Using Sans Serif fonts of 20 pt and above will allow you to create a readable text image. However, if necessary, 36 pt and higher Serif fonts and even decorative fonts can be used. The thickness of the product that will be combined with the main printed product depends on its complexity and purpose. The recommendations formed can be the basis of technological instructions used by enterprises with the involvement of modern technologies.

Conflict of interest

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

Financing

The study was performed without financial support.

Data availability

The manuscript has no associated data.

References

1. Yak ukrainska promyslovist dolaie voienni vyklyky. Available at: https://zn.ua/ukr/promyshliennost/jak-ukrajinska-promislovist-dolaje-vojenni-vikliki.html
2. Ukrainskyi biznes pid chas viyny (2022). Nove shchomisiachne opytuvannia pidpryiemstv, 7, 43. Available at: https://business.diia.gov.ua/uploads/5/27491-rezul_tati_s_omogo_somisacnogo_opituvanna_kerivnikiv_promislovih_pidpriemstv_ukrains_kij_biznes_v_umovah_vijni.pdf

3. Muraviov, O. V., Nyzhnyk, Yu. M., Petryk, V. F., Protasov, A. G., Syeryy, K. M. (2021). Current state and development prospects of additive technologies. Scientific Notes of Taurida National V.I. Vernadsky University. Series: Technical Sciences, 5, 114–119. doi: https://doi.org/10.32838/2663-5941/2021.5/18
4. Sai Saran, O., Prudhvidhar Reddy, A., Chaturya, L., Pavan Kumar, M. (2022). 3D printing of composite materials: A short review. Materials Today: Proceedings, 64, 615–619. doi: https://doi.org/10.1016/j.matpr.2022.05.144
5. Havenko, S. F., Hadzhynova, S. Ye., Labetska, M. T., Havenko, M. M. (2017). Research of influence of modern technologies of braille reproduction on tactile perception of information by blind and visually impaired people. Printing and publishing, 2, 107–116. Available at: http://nbuv.gov.ua/UJRN/Pivs_2016_2_14
6. Labetska, M., Havenko, M. (2017). Application of 3D Technologies in Inclusive Environment. Technology and Technique of Typography (Tekhnolohiia I Tekhnika Drukarstva), 1 (55), 47–54. doi: https://doi.org/10.20535/2077-7264.1(55).2017.95073
7. Anastasiadou, C., Vettese, S. (2019). «From souvenirs to 3D printed souvenirs». Exploring the capabilities of additive manufacturing technologies in (re)-framing tourist souvenirs. Tourism Management, 71, 428–442. doi: https://doi.org/10.1016/j.tourman.2018.10.032
8. Lee, D. K., Sin, K. S., Shin, C., Kim, J.-H., Hwang, K.-T., Kim, U.-S. Et al. (2023). Fabrication of 3D structure with heterogeneous compositions using inkjet printing process. Materials Today Communications, 35, 105753. doi: https://doi.org/10.1016/j.mtcomm.2023.105753
9. Pekgor, M., Nikzad, M., Arablouei, R., Masood, S. (2021). Sensor-based filament fabrication with embedded RFID microchips for 3D printing. Materials Today: Proceedings, 46, 124–130. doi: https://doi.org/10.1016/j.matpr.2020.06.456
10. Kushlyk-Dyvulska, O. I., Kushlyk, B. R. (2014). Osnovy teoriyi pryiniattia rishen. Kyiv: NTUU «KPI», 94. Available at: http://ela.kpi.ua/handle/123456789/6917
11. Khatri, N. R., Egan, P. F. (2023). Energy Absorption of 3D Printed ABS and TPU Multimaterial Honeycomb Structures. 3D Printing and Additive Manufacturing. doi: https://doi.org/10.1089/3dp.2022.0196
12. Chadha, U., Abrol, A., Vora, N. P., Tiwari, A., Shanker, S. K., Selvaraj, S. K. (2022). Performance evaluation of 3D printing technologies: a review, recent advances, current challenges, and future directions. Progress in Additive Manufacturing, 7 (5), 853–886. doi: https://doi.org/10.1007/s40964-021-00257-4
13. Kumar, L. J., Pandey, P. M., Wimpenny, D. I. (Eds.) (2019). 3D Printing and Additive Manufacturing Technologies. Springer, 311. doi: https://doi.org/10.1007/978-981-13-0305-0
14. Sandhu, K., Singh, S., Prakash, C., Subburaj, K., Ramakrishna, S. (Eds.) (2022). Sustainability for 3D Printing. Springer Tracts in Additive Manufacturing. Springer, 194. doi: https://doi.org/10.1007/978-3-030-75235-4
15. Hui, J., Zhang, H., Lv, J., Lee, C.-H., Chen, C., Yan, Z. et al. (2023). Investigation and Prediction of Nano-Silver Line Quality upon Various Process Parameters in Inkjet Printing Process Based on an Experimental Method. 3D Printing and Additive Manufacturing. doi: https://doi.org/10.1089/3dp.2022.0292
16. Perritano, J. (2018). 3D Printing. Saddleback Educational Publishing. Available at: https://worldcat.org/en/title/1020618227
17. Popescu, D., Amza, C. G. (2022). 3D Printing onto Textiles: A Systematic Analysis of the Adhesion Studies. 3D Printing and Additive Manufacturing. doi: https://doi.org/10.1089/3dp.2022.0100
18. Gibson, I., Rosen, D., Stucker, B. (2015) Additive Manufacturing Technologies: 3D Printing, Rapid Prototyping, and Direct Digital Manufacturing. Springer, 498. doi: https://doi.org/10.1007/978-1-4939-2113-3
19. Shishkovsky, I. V. (Ed.) (2016). New Trends in 3D Printing. IntechOpen, 270. doi: https://doi.org/10.5772/61398
20. Horbachuk, V. M., Kushlyk-Dyvulska, O. I. (2023). Teoriya ymovirnostei ta matematychna statystyka. Kyiv: KPI im. Ihoria Sikorskoho, 351. Available at: https://ela.kpi.ua/handle/123456789/52357