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STUDY OF THE INFLUENCE OF FDM 3D PRINTING PARAMETERS ON FORMATION PROCESSES, STRUCTURE AND PROPERTIES OF POLYLACTIDE PRODUCTS

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ABSTRACT

Based on the results of mathematical modeling and theoretical research works, it was established that the most influential factors of 3D printing, affecting the quality and time of end products formation, are extruder die temperature, layers height, speed of printing head movement when forming products, as well as simultaneous fabrication of several products within one cycle. In the work, the modes of the FDM 3D printing process were worked out and the regularities of the influence of the mentioned parameters on the structure and properties of resulted 3D polylactide products were established. The parameters of product formation were experimentally determined, which provide the production of 3D objects with predicted properties: maximum strength (98 % of filament strength), high aesthetic quality (surface smoothness and resolution) and products with minimal investments of time during their production.

KEYWORDS: additive formation, FDM 3D printing technology, polylactide, functional 3D product, filament

INTRODUCTION

Recently, the development of three-dimensional (3D) printing technologies has become explosive [1–3]. Among them, one of the most widespread is the technology of modeling by the deposition method (Fused Deposition Modeling, FDM) [4–6]. On the other hand, in the world (in view of aggravated problem of environmental pollution), the use of biodegradable polymer materials is gaining momentum [7]. Among such materials, a special place belongs to polylactide (PLA) — thermoplastic polyester based on lactic acid, suitable in particular for food packaging [8, 9]. The creation of products from such material, including with the help of 3D printing, is promising for a number of industries. For the research, PLA filament from the MonoFilament Company was chosen [10].

Since FDM 3D printing is a complex process with a great number of parameters that can affect the structure and properties of end products, at the first stage, mathematical modeling of a simplified FDM 3D printing process was carried out in order to reduce the number of experiments to determine its most influential parameters [11].

Thus, taking into account the results of mathematical modeling, which are correlated with the data of literary sources [12, 13], it can be assumed that the basic parameters of the FDM 3D printing process, which affect the quality of end products, include:

- temperature of FDM 3D printing, i.e. extruder die;

- speed of the printing head movement when forming a product;

- layers height (in a certain sense, the volume and mass of the polymer) deposited when forming a product;

- quantity of products formed within one 3D printing cycle.

To experimentally determine the influence of each of these FDM 3D printing parameters on the quality of end products in the work, all samples had the shape of a blade for mechanical research with the cross-sectional dimensions of the thinnest part being 2×4 mm. The total size of the part was 30×6×2 mm. The location of the model relative to the working platform was chosen in a vertical orientation due to the anisotropy of mechanical properties of a formed 3D product along the *X*, *Y*, *Z* axes, since the adhesion strength between the layers can be comparable, but not higher than the strength of the base material.

EFFECT OF 3D PRINTING TEMPERATURE ON THE FORMATION PROCESS AND THE QUALITY OF END POLYMER PRODUCTS

In this part of the work, experimental 3D printing of samples was carried out using commercial PLA filament at five different extruder temperatures — 190, 200, 210, 220 and 230 °C, which are located in the temperature range recommended for similar works by the manufacturing company (190–230 °C). The results of mechanical uniaxial tension tests are presented in Figure 1.

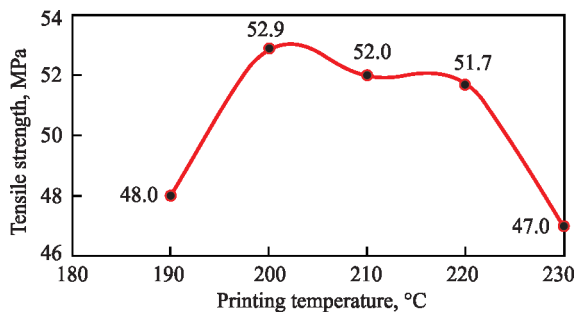


Figure 1. Dependence of mechanical interlayer strength of samples from PLA on temperature of their 3D printing

It is known that shrinkage of the heated polymer after cooling is stronger, the higher the printing temperature. As is seen from Figure 1, the formation of PLA products at a temperature of 200 °C made it possible to subject thermoplastic polymer material to as little thermal expansion as possible. At the same time, layer-by-layer formation of a product with a preset geometric shape and the highest mechanical interlayer strength $\sigma = 52.9$ MPa at the strength of PLA itself $\sigma = 57.8$ MPa occurred [14]. At a reduced temperature (190 °C), products of a preset geometric shape were formed, but the value of the interlayer strength was $\sigma = 48$ MPa, which is explained by the high viscosity of the PLA melt at this temperature and, accordingly, low adhesive ability. Printing of products with an elevated extruder temperature of 230 °C led to a slight deformation and a low interlayer strength at the level of $\sigma = 47$ MPa due to overheating of samples during their formation.

INFLUENCE OF THE 3D PRINTING SPEED ON THE FORMATION PROCESSES, APPEARANCE, STRUCTURE AND PROPERTIES OF END POLYMER PRODUCTS

Applying the technology of FDM 3D printing from polylactide, the samples with all the constant parameters of product formation were fabricated, which were described above and correspond to the recommendations of the manufacturing company except for the speed of the head movement when forming products. The MonoFilament Company recommends forming

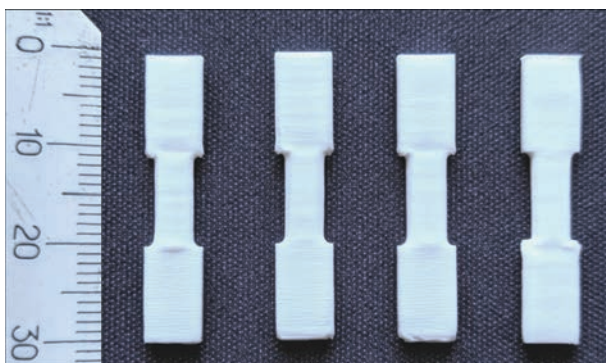


Figure 2. Appearance of the samples Nos 1–4 (from right to left)

products from PLA plastic at a speed of the printing head movement in the range of 30–80 mm/s, while other manufacturers advise to do that at a speed in the range of 40–110 mm/s [10, 15]. In order to reasonably and objectively determine the influence of different speeds (within the recommended limits) on the quality of fabricated products and to find the optimal speed that ensures the fabrication of the highest quality product, the samples were formed with an interval of 30 mm/s from the lowest to the highest recommended limit. The speed of the printing head movement when forming products was 20, 50, 80, 110 mm/s for the samples Nos 1–4, respectively. The time spent on the formation of each blade varied from 14 to 22 min, depending on the chosen speed of forming products.

After conducting the research and processing of the obtained data, it was determined that the speed of products formation within the studied limits and at keeping other printing parameters constant does not significantly affect the appearance (Figure 2). All the formed samples had a preset geometric shape with clear outlines of a part and a visually high density of the deposited layers adhesion.

The dense inner structure of the produced samples and the absence of defects in them that exceed 5 μm are also demonstrated by pictures made while studying the products using a computer tomography and 3D reconstruction of their inner structure (Figure 3). It was established that the inner structure was typical for all samples, despite the different speed of the printing head movement when forming products. For example, Figure 3 shows the structure in the X , Y , and Z planes of the sample, formed at a maximum speed of 110 mm/s.

To study the influence of the speed of the printing head movement when forming samples on the mechanical characteristics of fabricated products, the

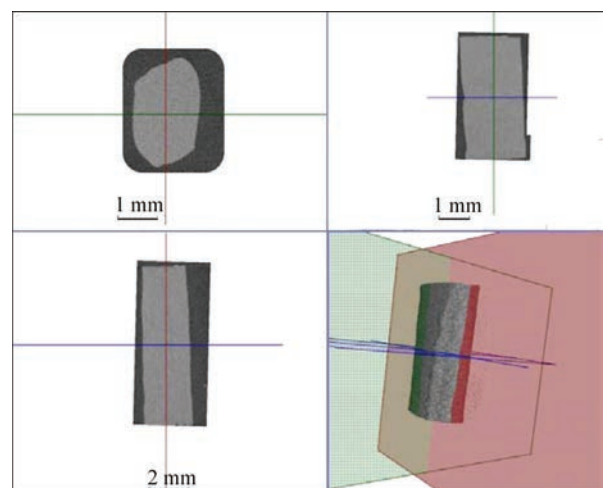


Figure 3. Image of inner structure of the sample No. 4 in different planes, obtained by 3D computer tomography

studies were conducted using the uniaxial tension test of the additively manufactured samples Nos 1–4. The obtained results as for adhesion strength between the layers are shown in Table 1.

The analysis of the results of mechanical studies showed that the best result $\sigma = 56.9$ MPa, which is close to the table value of the ultimate tensile strength of PLA $\sigma = 57.8$ MPa, was obtained in the case of forming 3D products at a speed of 80 mm/s. The worst result ($\sigma = 39.3$ MPa) was shown by the samples, whose formation occurred at the maximum speed of 110 mm/s. The samples, formed at speeds of the printing head movement of 20 and 50 mm/s, had average values of adhesion strength between the layers and close to each other ($\sigma = 51.7$ and 52.9 MPa, respectively).

Taking into account the fact that at all investigated speeds of the printing head movement during products creation, the samples of a preset geometric shape and visually with an equally high quality were formed, the choice of a mode that satisfies the needs of the consumer/customer depends on additional requirements specified to the future three-dimensional object, namely its mechanical characteristics and the time spent on the formation of each individual part. Objectively, the best printing mode, which allows fabricating products with high mechanical characteristics at relatively low time consumption — 16 min, is the mode of forming the sample No. 3 (Figure 4).

When the speed of the printing head movement during product formation is increased to 110 mm/s, the time for forming a product is slightly reduced (14 min), but at the same time, a negative effect of the speed on the mechanical strength of a produced object is observed.

When the printing head movement is slower (20 and 50 mm/s), the produced samples have average mechanical strength, but the time for forming products increases significantly — up to 22 and 20 min, respectively.

INFLUENCE OF THE METHOD OF ADDITIVE 3D PRODUCT FORMATION ON THE PECULIARITIES OF THEIR MANUFACTURING PROCESS, STRUCTURE AND PROPERTIES

In order to reduce the time spent on the process of creating products with the 3D printer, it is possible to simultaneously print several models within one cycle. The quantity of products that can be formed simultaneously depends on the characteristics of the 3D printer, namely the dimensions of its building area. For the further studies of the influence of simultaneous additive manufacturing of several samples on

Table 1. Strength of fabricated products depending on speed and time of their formation

Number of sample	Speed of movement of printing head during sample formation, mm/s	Time of one sample formation, min	Adhesion strength σ , MPa	Strength of PLA [14]
1	20	22	51.7	57.8
2	50	20	52.9	
3	80	16	56.9	
4	110	14	39.3	

the characteristics of fabricated products, the process mode of forming the sample No. 3 (Table 1) was chosen, with the use of which, the samples of the highest strength ($\sigma = 56.9$ MPa) were produced. As models for building, four similar samples with an identical shape (blades) were chosen, as in the previous research.

After forming the samples, a visual assessment of the fabricated products was carried out and it was established that their shape fully corresponds to the preset digital model, however, the structure of the formed parts is less dense compared to the sample No. 3, which was built separately (one sample per cycle) with the same parameters of forming products. The results of the study with the use of 3D computer tomography of the inner structure of the sample No. 5, whose formation was carried out under the conditions of simultaneous printing of four samples within one cycle, also confirmed a decrease in the density of the adherence of the deposited layers compared to the sample No. 3.

The conducted studies of adhesion strength between the layers of the produced samples using a standardized uniaxial tension test showed a significant decrease in strength ($\sigma = 25$ MPa) compared to single samples ($\sigma = 59.6$ MPa) formed in the same mode (Table 2).

This is explained by the fact that when forming four parts in parallel, when the extruder die passes

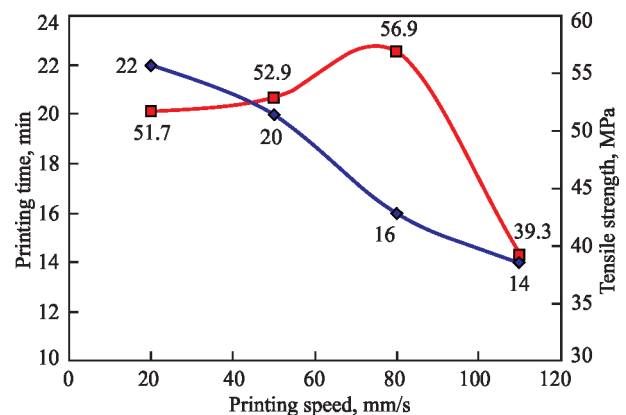


Figure 4. Dependence of time for sample formation and interlayer strength of formed 3D products on speed of their formation

Table 2. Strength of 3D products and time of their fabrication depending on the method of their formation

Time of 3D printing and mechanical properties of produced samples	Sample No. 3 (1 pc)	Sample No. 5 (4 pcs within one cycle)
Time of one sample formation, min	16	8
Interlayer strength σ , MPa	56.9	25
Strength of PLA filament, MPa [4]	51	
Strength of PLA, MPA [2]	57.8	

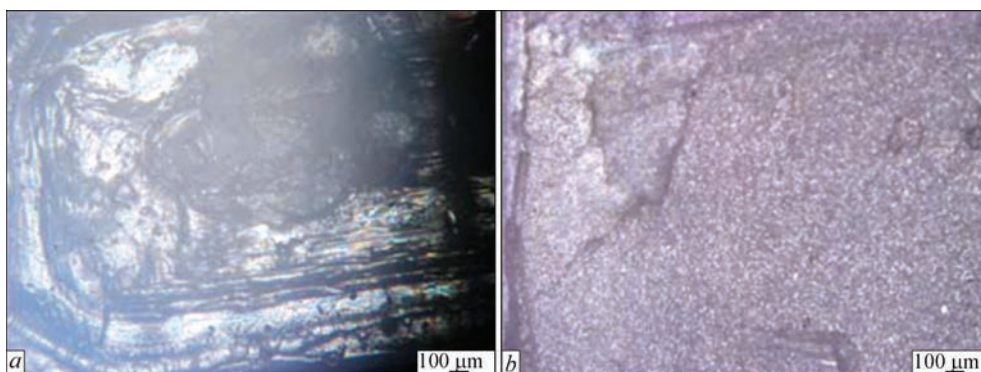
from one model to another, the temperature and ductility of the upper layers of a product decrease, which is predetermined by an increase in the cooling time, and the following layers of the fused material lie on the base, which had already time to partially solidify. This leads to a decrease in the adhesion and deterioration of the contact mechanical adhesion between the layers of a printed product and, as a result, a decrease in strength. On the other hand, it provides control of the mechanical properties of a product when it is formed by 3D printing and allows obtaining the specified strength in the desired areas of a part. For example, to create a predetermined local area with weakened mechanical properties in a product, along which the fracture of a part will occur when a force loading is applied to it, printing should be carried out in the appropriate mode — with pauses at the height of those layers, the adhesion between which should be predicted to be low. The program for reformatting a 3D model into a control code for 3D printer provides for changing the parameters of products formation according to the height of the model (for example, the speed of the printing head movement when forming products), including performing 3D printing with pauses. In the case of the mode of forming products of four samples within one cycle considered above, the pause between the deposition of the n^{th} and $n+1$ layers for each sample was the same, since the models on the platform were placed on the outer corners of the square, and was ~ 10 s for a wider area of the blade and ~ 8 s for its narrow part.

On the other hand, if the use of a product does not involve its operation under the conditions of significant loads, then the formation of simultaneously several parts by 3D printing allows a significant reduction in the time for the process of their manufacturing. Thus, under the conditions of the same 3D printing parameters, 16 min were spent to create one sample, the formation of which took place separately, and 8 min for a one sample, the formation of which was carried out simultaneously with three other within one cycle (see Table 2).

After uniaxial tension tests, the structure of the samples at the points of fracture was evaluated. Thus, on the microphotographs of the fracture plane of the sample No. 5 (Figure 5, *a*), the trajectory of the printing extruder head movement at the moment of depositing the previous layer material can be clearly traced — it starts from the lower right corner and further follows clockwise in a spiral to the center, which indicates that the fracture of a part occurred along the interlayer region. For comparison, the photomicrograph of the location of the fracture of the blade, the creation of which was carried out using the same printing parameters, only separately one by one, shows that its fracture occurred not between the layers, but in the plane of the layer (Figure 5, *b*), which indicates a higher adhesion between the layers in a formed 3D product.

INFLUENCE OF THE LAYER HEIGHT OF 3D PRODUCTS ON THE PECULIARITIES OF THEIR FORMATION, APPEARANCE, STRUCTURE AND PROPERTIES

Depending on the application of one or another FDM 3D printer and thermoplastic material, as well as the specified tasks (production of 3D parts with high accuracy and detailing, quick printing of end products of large sizes, etc.), it is possible to create volumetric products with surfaces of different quality. In this work, the selection of the parameters of the layer height of a 3D product, which directly affect the qual-

**Figure 5.** Morphology of the samples in places of fracture after the tests on uniaxial tension of the sample No. 5 (*a*) and the sample No. 3 (*b*)

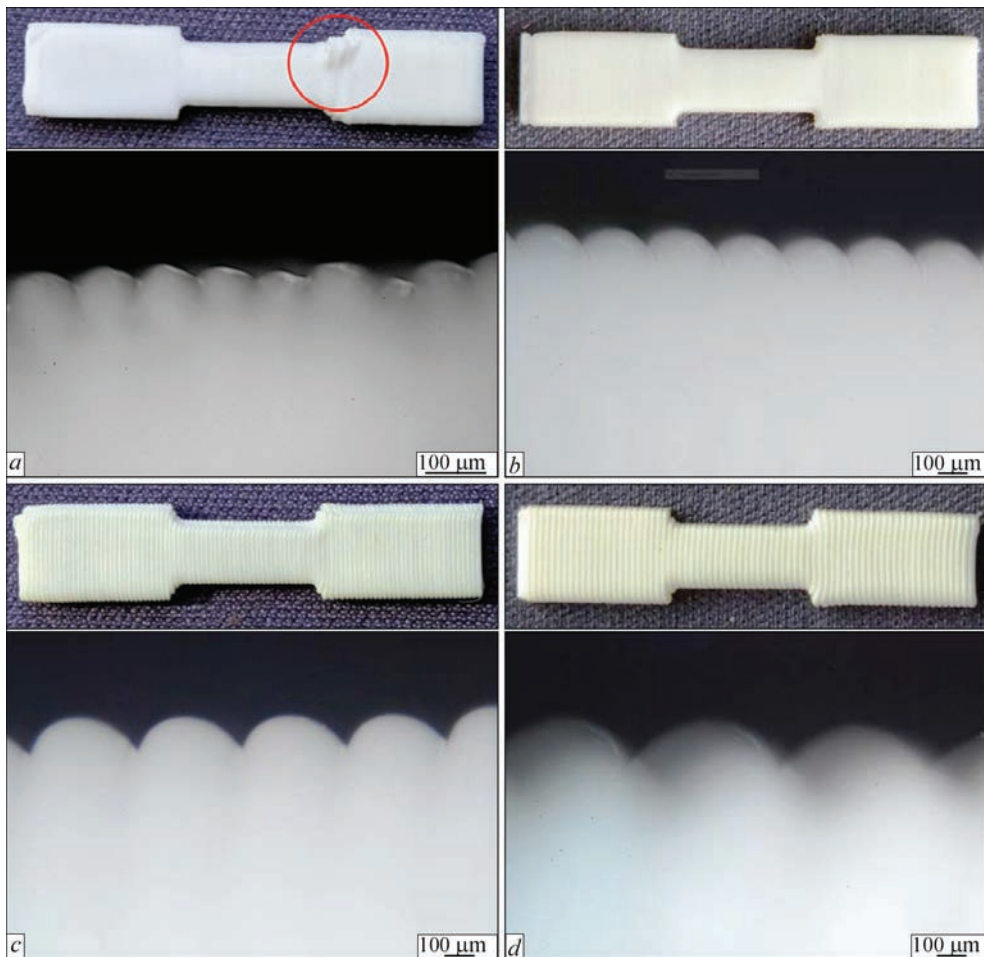


Figure 6. Photos and morphology of the samples of different quality: the sample No. 6 with the layer thickness of 0.08 mm (*a*); the sample No. 7 with the layer thickness of 0.20 mm (*b*); the sample No. 8 with the layer thickness 0.30 mm (*c*); the sample No. 9 with the layers thickness of 0.40 mm (*d*)

ity of produced samples, was based on the extreme admissible values (within the recommended limits) for the CreatorPro 3D printer and PLA filament. Without changing other printing parameters, except for the layer height, which was 0.08, 0.10, 0.20, 0.30 and 0.40 mm for the samples Nos 6–9, respectively, a study of the influence of the selected parameter on the appearance, structure and properties of fabricated products was carried out.

Figure 6 shows photos of the appearance and microstructure of the samples Nos 6 (*a*), 7 (*b*), 8 (*c*) and 9 (*d*), formed by the FDM 3D printing technology in accordance with the printing parameters. The fabricated blades generally have a preset geometric shape with sharp edges and clear outlines of a part. Since the products are formed in layers, it is obvious that the smaller the height of the layer, the less noticeable the transition between them and accordingly, the surface of an object is smoother, and its parts are more expressive. The samples, whose formation was carried out according to the specified thickness of each layer of 0.40 and 0.30 mm (Figure 6, *c*, *d*), have a lower resolution compared to the samples with a fixed

height of each layer of 0.08 and 0.20 mm (Figure 6, *a*, *b*). The latter have much smaller visible layer lines and a smoother surface. However, at the minimum possible layer height, some inaccuracies — printing artifacts may be present (Figure 6, *a*). In this case, such inaccuracies may appear around the complex elements as, for example, in a printed sample, when its formation was carried out on the expansion of a part — transition from the narrowest part of a product to the wide one. With such a transition, additive overhang forming takes place, when each previous plane of a formed part is smaller in relation to the next one, which should be formed on its basis, and the more difficult it is to form a quality product in such conditions, the thinner the layers height of a future part. This error may be eliminated by building support structures (including soluble ones) under the overhanging elements of a part.

In this study, it was established that the time spent on the formation of one sample with a height of 0.08 mm layers of the printed products was 29 min. At the same time, printing of a sample identical in shape and sizes with the layer thickness of 0.40 mm made

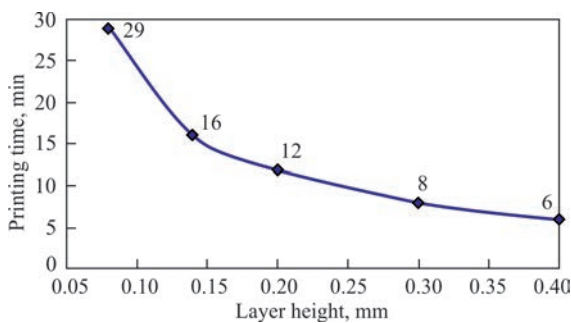


Figure 7. Dependence of time for 3D printing of samples on height of their layers

it possible to reduce the time spent on its creation to 6 min (Table 3).

In a situation where a logical inversely proportional dependence between the layer height — vertical resolution of a part and the time spent on printing the model is clearly visible (Figure 7), the dependence between the resolution and the strength of a part does not look so clear, since the conducted experiments showed that both at the minimum as well as at the maximum specified layer height for this material and the printer, the formed products had a visually high enough quality and density of layers.

It is obvious that the better the layers of a product adhere and wet each other during 3D forming, the higher the strength of a printed part will be. The problem is what layer height, if other settings being equal, will create conditions for forming layers with the highest adhesion between them.

Since the possibility of specifying the minimum and maximum possible value of the layer height for each specific filament in the software settings is limited by the diameter of the extruder die of the 3D printer, it is worth taking into account its influence on the conditions of product formation, structure and properties of fabricated products. Thus, during 3D forming of polylactide samples with a minimum admissible

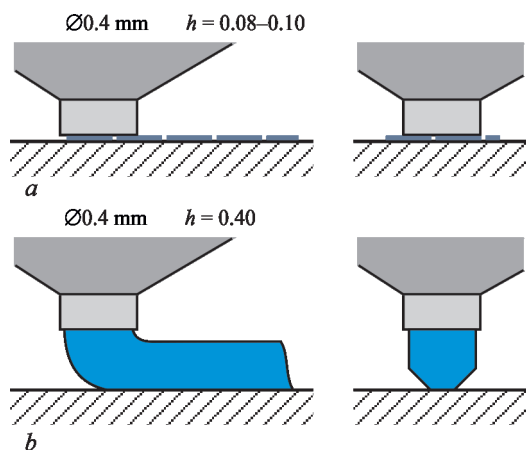


Figure 8. Schematic image of the process of depositing layers of fused polymer when forming 3D models with a different layer height with a diameter of 0.4 mm: $h = 0.08\text{--}0.10$ mm (a), $h = 0.40$ mm (b)

Table 3. Time for printing fabricated products depending on layer thickness of 3D models

Number of sample	Layer height, mm	Time of one sample formation, min
6	0.08	29
7	0.20	12
8	0.30	8
9	0.40	6

layer height of 0.08–0.10 mm in the 3D printer with an extruder die of 0.4 mm diameter, the fused polymer squeezing through the die during product formation will be flattened, taking an oval shape of a preset height. This process is shown schematically in Figure 8, a. Adhesion of such layers will obviously be much higher than the layers with a height, for example, of 0.4 mm (Figure 8, b) due to the different area of contacting surfaces of the layers. Since the polymer melt at the moment of discharge from the extruder die with a diameter of 0.4 mm is flattened the less, the closer the specified layer height to 4 mm, and their shape at the same time is closer to cylindrical, then due to overlapping of layers of such a shape during forming a 3D product, a reduction in the contact surface between them occurs.

Therefore, the closer the value of the layer height of the future 3D object is set to the diameter of the extruder die in the software settings, the more rounded the shape of the layers will be in a formed product. This, in turn, leads to weakening of interlayer bonds.

To determine the dependence and more fully assess the effect on the mechanical strength of the layer height of formed 3D products with an extruder die diameter of 0.4 mm, mechanical tests on uniaxial tension of the samples Nos 6–9 were conducted. The analysis also used data from the sample No. 3, the formation of which was carried out under the identical conditions. The only difference was the investigated parameter — the layer height, which was 0.14 mm (Table 4).

It is seen that the highest values of the interlayer strength ($\sigma = 56.9$ MPa) were obtained in the printing mode No. 3 with a layer height of 0.14 mm. The same results were obtained for the samples Nos 7 and 9. I.e., with a preset minimum height of 0.08 mm, the val-

Table 4. Interlayer strength and time of product formation depending on thickness of their layers

Number of sample	Layer height, mm	Interlayer strength σ , MPa
7	0.08	47
8	0.30	42.5
9	0.20	47
10	0.40	39.6
3	0.14	56.9

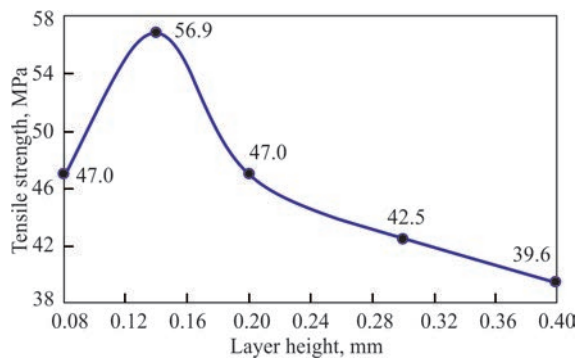


Figure 9. Dependence of interlayer strength of 3D products on height of their layers

ue of the interlayer mechanical strength of products was at a level with products that had a layer height of 0.2 mm. However, in general, a tendency of a decrease in the interlayer strength of fabricated products with an increase in the value of height of their layers is observed. To visualize the obtained results, a diagram of the dependence of the interlayer strength on the layer height of 3D models was built (Figure 9).

In conclusion, it can be noted that such a parameter as the layer height has a significant impact on the strength of fabricated 3D products and the time spent on their formation, and therefore affects the economic indicator of the 3D printing process and resolution of the surface of a three-dimensional part.

If it is necessary to create a product with the minimum possible layering of the surface and the maximum possible detailing, its formation should be carried out according to the specified minimum height of layers, which is possible when forming a part with the 3D printer extruder die of the appropriate diameter. However, it is necessary to take into account the fact that this leads to a significant increase in the time for creating products. In addition, at the minimum thickness of the layers, there is a higher probability of obtaining artifacts on the surface of a product. In order to achieve an even greater minimization of the layered structure on the surface of 3D products, which is obtained during 3D printing using the FDM technology, it is necessary to use a die of a smaller diameter, perform the following surface treatment of finished 3D products, or use another 3D printing technology, for example, SLA, DLP, which allow creating models with higher resolution.

To systematize and summarize the obtained data according to the results of the carried out studies of the impact of the layer height on the time of products formation and their strength, a combining diagram was built (Figure 10). According to its analysis, the optimal height range of 3D products was determined, which should be kept to provide the additive formation of models with the interlayer strength

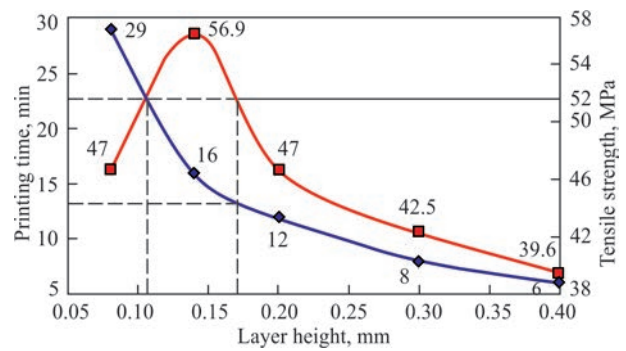


Figure 10. Dependence of time for 3D printing of products and interlayer strength of formed products on height of their layers

at a level of 90 % of the strength of a consumable. Taking into account that the mechanical strength of polylactide according to the data of literary sources is $\sigma = 57.8$ MPa [14], then at the level of $\sigma = 52$ MPa, which is 90 % of the filament strength, along the axis of the “Tensile strength, MPa” diagram, a straight line was drawn. After that, perpendiculars were lowered from the points of its intersection with the distribution curve to the “Layer height, mm” axis. Therefore, it follows from the diagram that at the layer thickness of 0.108–0.173 mm, formation of 3D objects occurs with the interlayer strength at a level of 90 % of the strength of the source material and at the average time consumption for printing of one part (13.5–23 min).

CONCLUSIONS

1. A study of the influence of the FDM 3D printing process on the structure and properties of polymer filament material — polylactide was conducted. It is shown that the process of 3D printing (its basic parameters: extruder die temperature; height of layers deposited during formation of a product; speed of printing head movement during formation of a product and quantity of products formed in a one 3D printing cycle) significantly affects the appearance, structure, mechanical properties and the time spent on product formation.

2. A rational mode of additive formation of products was determined, which provides fabrication of parts of a preset geometric shape with the interlayer strength $\sigma = 56.9$ MPa close to the strength of the base material $\sigma = 57.8$ MPa and small time consumption (14 min) on the formation of a one part.

3. The mode of formation of 3D polylactide products was determined, which provides the ability to control the indices of mechanical properties of products during their additive manufacturing and obtain an early projected strength in the desired places of a part, for example, create local areas with weakened mechanical properties, along which the fracture will take place.

4. The modes of the process of volumetric product formation were determined that allow producing parts of a preset geometric shape within the shortest possible period of time (6 and 8 min). The time and, as a consequence, the costs on product formation are reduced at the expense of:

- simultaneous fabrication of several products within one cycle,
- formation of parts with the layer height as larger as possible for the studied material, 3D printer and recommended limits.

5. The modes of 3D printing process were determined, which allow creating products with the maximum possible detailing (along Z axis) due to software presetting of the minimum possible thickness of a product in 3D printing of the used thermoplastic material and 3D printer.

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CONFLICT OF INTEREST

The Authors declare no conflict of interest

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