UDC 667.613.3

DOI: 10.31650/2786-6696-2022-1-77-84

ANALYSIS OF FACTORS AFFECTING PROPERTIES OF A PRINTED PRODUCT USING A 3D PRINTER

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Abstract. The article provides an analysis of the use of materials to produce construction products developed using additive technologies. The material samples specified in the article have the prospect of becoming advanced in the modern production of construction products. The main factors that affect the properties of printed material using a 3D printer are also determined.

Today, the production of materials for the manufacture of various architectural structures is developing rapidly, becoming more technological, the volume of production is increasing, the accuracy and quality of the production of parts is increasing, and the costs are reduced. The use of a 3D printer is clearly demonstrated in the optimization of the production of architectural structures. In the case of the usual method of production, their cost and complexity are quite high. The introduction of a 3D printer makes it possible to significantly improve the design and structure of products by improving the structure and consumption of materials.

The conducted research revealed a whole range of issues and problems related to the need to improve the 3D printing process, organization, and management of printing of complex construction products, which would allow effective use of the latest additive 3D printing technologies in modern construction.

The properties of the main materials for 3D printing, which are used in the FDM technology of obtaining the product, have been experimentally determined. The procedure for calculating the performance of the extruder and the main problems during printing are determined.

As a result of the conducted research, it is possible to assert that by basic factors which influence on property of the printed material is a percent of the internal filling is a that thickness of wall of good.

Studies have shown that the use of additive technologies in the production of construction products at the current stage will provide an opportunity to combine the latest scientific developments in the fields of engineering, technology, materials science, architecture, design and construction.

Keywords: additive technologies, 3D printing, filament, structure, extruder.

Introduction. In recent years, there is not a single industry that does not use additive technologies (hereinafter – AT). 3D printing technology such as FDM (Fused Deposition Modeling) is especially widely used. This technology is especially actively used in the production of architectural structures, namely: sculptures, pavilions, bridges, urban installations, building models. A new architectural style has almost been formed with the help of 3D printing – "digital grotesque".

Both cheap home 3D printers and high-precision industrial printers are actively used.

This technology is most effectively used when printing products with complex geometry, mesh and channel structure. FDM parts are usually not printed filled to reduce printing time and save material. Instead, the outer perimeter made by several passes is called the shell, and the inner part is filled with a low-density structure, called filling. It is known that the principle of printing parts by FDM technology is to layer-by-layer build-up of molten plastic thread (filament). At the same time, it is quite obvious that with the improvement of technological equipment and the development of design methods, this direction will steadily expand. However, the use of AT in the printing of inexpensive devices with specific tasks, the use of new innovative materials in their manufacture has not yet been fully explored. Thus, the place of FDM technology in the mass production of construction products, their tasks are not fully defined.

Analysis of research and publications. The market of FDM technologies is actively developing, experiments with printing with various types of filament are being conducted, and 3D printer designs, software and 3D printing processes are being intensively improved. According to the international consulting company DELOVOY PROFIL, the annual growth rate of the global market of additive technologies is 19.3%, including FDM technologies, which are the most common today [1]. This technology has many unconditional advantages, but it also has its drawbacks [2].

Layered overlay printing (FDM) is an additive manufacturing process that is implemented using a 3D model in the form of tracks of molten polymer materials that sinter together to create a finished product. FDM products are usually printed without solid filling to reduce printing time and save material. Obtaining the necessary contours of the product layer, their internal filling and ensuring the necessary properties of the product are one of the main tasks when printing on FDM printing technology. Considerable attention is paid to the choice of the optimal technological mode of printing, shrinkage processes during printing, the use of various additional elements [3] and modification of polymers.

In the construction of low-rise buildings, with the help of 3D printing, it is possible to implement almost any ideas, to achieve the best architectural expressiveness of objects [4].

In the modern restoration of architectural heritage, FDM technology is also increasingly used, namely for:

– creation of identical ornaments [5];

– restoration of the lost part of the product [6];

– acceleration of the restoration process [7].

There are printers that are designed only for reproduction of unique objects of historical value [8].

In this regard, there is a rejection of generally accepted concepts in the field of construction, and a focus on additive construction technologies [9].

At the same time, the capabilities of equipment and materials are rapidly evolving towards increasing printing speed with higher print quality and distribution capacity, as well as reducing production costs [10, 11]. Thus, the use of FDM technologies will confidently take its leading place when printing a wide variety of construction products.

The aim of the work is to study the changes in the properties of the material for 3D printing under difficult operating conditions.

Research materials and methodology. The following plastics were the main materials used in the evaluation of products printed using 3D printing.

ABS (acrylonitrile butadiene styrene). The most popular material in 3D printing. It is quite elastic, odorless, and can withstand temperatures up to 100°C. It is supplied in the form of skeins of thread with a diameter of up to 3 mm. The melting point of plastic is 220-260°C. The only significant drawback is vulnerability to direct sunlight.

PLA (polylactide). The main competitor is ABS with a melting point of 190°C. Eco-friendly.

In addition, PLA plastic decomposes into safe materials over time, which is both a plus and a minus. Less strong than ABS, it loses its properties already at a temperature of 80°C. It is most often used for printing construction products.

PETG (polyethylene glycol terephthalate). This is a classic PET plastic to which glycol is added. Thanks to this, brittleness is eliminated, durability and tensile strength are increased. The material is stronger than ABS or PLA, and at the same time less brittle. It also has minimal shrinkage.

NYLON. Crystallized hard plastic with high tensile strength and wear resistance. Nylon has a high softening temperature and elasticity at low temperatures, withstands sterilization with steam heated to 140°C. This allows you to use it in conditions with temperature differences in a wide range.

To carry out a comparative analysis of the properties of plastic, the same control samples were printed from filling the product with plastic – 50%. Experiments were conducted with various samples of materials under difficult operating conditions, the results of which are listed in the Table 1. The purpose of the analysis was to study changes in material properties under difficult operating conditions.

The properties were evaluated according to eight parameters: tensile strength and load, frost resistance, heat resistance, wear, shrinkage, boiling, exposure to open fire.

Research results. FDM technology allows you to print products on a 3D printer using a wide range of polymer materials with different physical and chemical characteristics and properties. This is the most widespread method of 3D printing in the world, on the basis of which millions of 3D printers work – from the cheapest to industrial 3D printing systems, as it allows for quick and inexpensive printing of various parts during small-scale production [11].

Various polymer materials are used to manufacture products using three-dimensional printing technology (polymer in the form of a thread or rod – filament). At the same time, the filament is fed into the extruder – a device equipped with a mechanical drive for feeding, a heating element for melting the material and a nozzle through which the material is extruded. The extruder contains a thermal barrier with a cooling radiator to ensure the phase transition of plastic from a solid to a liquid phase. In addition, the upper part of the nozzle is connected through a thermal barrier to the feed drive, cooled by a fan to create a sharp temperature gradient necessary to ensure a smooth supply of material. The extruder moves in the horizontal and vertical planes under the control of the microprocessor control board. The nozzle moves along the path specified by the automated design system. The model is built layer by layer, from the bottom up. As a rule, the extruder (also called the "print head") is driven by stepper motors. The most popular coordinate system used by FDM is rectangular, with X, Y, and Z axes.

In this process, there are many factors that affect the quality and accuracy of the product. Obviously, the accuracy of printing a product is determined by the accuracy of a specific 3D printer. However, there are other factors that affect the properties of material printed with a 3D printer. The most common printing problems are poor adhesion of the plastic to the 3D printer table, not enough or too much plastic being extruded, holes or gaps in the top layer of the printout, hairs or webbing, overheating of the plastic, layer misalignment or misalignment, layers separating, and many others are also split.

So, for example, the strength of the material also depends on the modes of FDM printing. The speed of movement of the extruder nozzle together with the thickness of the applied layer affect the adhesion strength of the threads. This is due to the spread of heat from the extruder nozzle to the material [12]. At a high print speed, less heat is transferred at any point of the filament than at a low speed. If you print a small layer at a low speed, the heat dissipation can be very large. This will increase adhesion, but there will be a possibility of defects in the form of plastic overflows. When printing products with a greater layer thickness at high speed, poor adhesion between the layers of plastic may occur due to insufficient heat in the extruder. From here, the problem arises – how to determine the optimal temperature and speed modes of operation of the printer.

The filament, having a low thermal conductivity, does not melt instantly, which requires the presence of a sufficient volume of the heater channel (nozzle) to ensure a continuous supply of material at high printing speeds. In addition, due to the excess pressure of the molten filament in the heater channel, it is impossible to immediately stop the discharge of material from the nozzle.

Which leads to uncontrolled fluidity of the material and deterioration of the appearance of the product.

When the filament is fed quickly, the passage of the short channel takes place in a short period of time, and before it has time to melt, the filament gets stuck in the nozzle. A short melting zone automatically means a low speed. This is acceptable for printing small objects, but starting with a mass of 200 grams, a higher speed is required. Raising the temperature to increase the speed leads to the degradation of the plastic in the finished product.

Three parameters are responsible for the maximum FDM printing speed:

– technical characteristics of the printer, i.e. how fast the print head can move is mainly determined by the design features of the printer and the weight of the moving parts;

– extruder performance – whether the extruder is able to melt enough plastic to provide the required width and height of the layer at a given print speed;

– maximum nozzle capacity – the amount of plastic that can be passed through without clogging the extruder.

The maximum productivity of the nozzle is the main factor influencing the overall productivity of the entire extruder, which affects the maximum printing speed of the layer. The standard E3D V6 extruder melts less plastic than the E3D Volcano extruder. But, as a rule, there are no problems in this case, because on standard nozzles with a diameter of 0.2 to 0.6 mm, the main reason for limiting the maximum printing speed is the productivity of the nozzle. A linear extrusion speed of mm/s is often used when calculating the productivity of the printer. This seems logical – the faster the melt is squeezed, the faster the head can move. To measure the speed, for example, the filament is squeezed into the atmosphere, the length is measured, and the printing speed is calculated. However, this method does not give an accurate idea of the printer's performance. Under certain conditions, the thread expands when leaving the nozzle due to the high viscosity of the melt. This greatly distorts the actual diameter of the thread. In some printers at very high speeds, the diameter of the thread can be three times the diameter of the nozzle from which it was squeezed. Also, the filament thread can stretch under its own weight if it has been squeezed out hot enough. It can also be glued, bent or extruded on the desktop with some smearing, although this is necessary for a good connection of filament threads in a monolithic product. In this case, the productivity W mm^3/s is calculated by formula (1), multiplying the speed of movement of the head by the width of the extruded thread and the height of the layer. The exact calculation in this case is quite problematic, because the edges of the wall have a curved shape [7].

$$W=V\cdot A\cdot H, \tag{1}$$

where V – the speed of movement of the head, mm/s;

A – width of the extruded thread, mm;

H – height of the layer (head height above the table), mm.

Obviously, the most accurate and unambiguous will be the expression of the extrusion rate in mm/s or mg/s. Because plastic has a different specific gravity (for example, the specific gravity of polyamide 1140 kg/m^3 and ABS 1050 kg/m^3), it is better to use mm^3/s (cm^3/s) to assess the performance of the printer. However, it is still necessary to indicate with which nozzle this result was achieved. With equal nozzle performance, significant differences in linear velocity values can be obtained by weight and volume of extruded molten plastic.

For example, if the printer has an extrusion speed of 100 mm/s, there will be significant differences in performance with different nozzle diameters. The calculation of printer performance is clearly seen from formula (2):

$$V= (L\,\pi\, D^2/4)\,/\,\rho, \tag{2}$$

where ρ is the filling density of the product.

The formula shows that with increasing the diameter of the printer nozzle twice, at the same extrusion speed, the print speed will quadruple.

Another factor that affects the properties of the printed product is the diameter (or width) of the extruded filament. The melt is extruded in the form of a cylinder from the nozzle of the head, but to fasten the layers together, the height of the head above the product is taken slightly less than the diameter of the nozzle. The filament is slightly smeared and expanded. In practice, the thickness of the layer is chosen 1.5-2 times smaller than the diameter of the nozzle.

One of the problems is the low resolution and accuracy of printing, and the more accurate the print (smaller the diameter of the nozzle), the lower the print speed. Several factors affect print resolution and accuracy. Namely, uneven walls and shrinkage of plastic after printing and deformation during printing, which significantly complicates the exact size and as a result of warping large parts, and most importantly – the diameter of the nozzle determines the size of the smallest details to be printed.

However, the most significant factor that affects the properties of the product, of course, is the material and quality of the filament [8]. To conduct a comparative analysis of the properties of plastic, experiments were conducted with different samples of the most popular materials. The purpose of the analysis was to study changes in the properties of the material in difficult operating conditions. The main characteristics of the most used materials are given in Table 1.

Table 1 – The main characteristics of materials for 3D printing

Type of plastic	Indicators				
	t °, s softening / operation	Strength on the break MPa	Strength for bending MPa	Printing accuracy %	Density, kg/m^3
ABS	100/ -40 +80	22	41	1	1050
PLA	50/ -20 +40	57.8	55.3	0.1	1230
PETG	80/ -40 +70	36.5	76.1	0.1	1270
NYLON	120 -30 +120	83	70	3	1140

Evaluation of the properties of materials was performed according to the following parameters:

1. Tensile strength (kg). A filament with a diameter of 1.75 mm was taken from the corresponding 4 materials and the tensile strength was checked with the help of a dynamometer.
2. Load strength (kg). A single load of 1500 kg was applied on samples of cubic products (with a side of 30 mm).
3. Frost resistance (C°). Strips of products were placed in a freezer with a temperature of -20 ° C. Then, after 5 minutes, their flexibility was tested.
4. Heat resistance (C°). Samples of materials in the form of strips were placed in a furnace with a gradual increase in temperature, in the process the strips were deformed depending on the material of execution, at certain temperatures.
5. Wear (mm). The wheels of the respective products were placed on the axle and rotated on a coarse abrasive belt at a speed of 20 m/s, each of the wheels overcame a distance of 5500 m. After that, measurements of the diameter of the products were made.
6. Shrinkage (mm). After production with a 3D printer, wheels with an initial diameter of 25 mm were cooled and diameter reduction measurements were performed.
7. Boiling. The products were boiled in water for 10 minutes. After that the samples of products were compared with similar samples that were not subjected to heat treatment.
8. Influence of open fire. The nozzle of a construction hair dryer with a temperature of 420 ° C was sent to the products for some time.

The test results of the respective materials are presented in Table. 2.

Table 2 – Impact of tests on materials

Type of plastic	Experiments							
	Tensile strength (kPa)	Load capacity (1500 kg)	Frost resistance	Heat resistance (C°)	Wear (мм)	Shrinkage (initial size 25 mm)	Boiling	Influence of open fire
ABS	608	unchanged	lost flexibility	1115	0.19	24.73	size increase, color change	ignition occurred
PLA	784	unchanged	unchanged	661	0.12	24.55	size increase	no ignition occurred
PETG	686	unchanged	unchanged	776	destroyed	24.8	structure completely destroyed	no ignition occurred
NYLON	666	unchanged	unchanged	1145	0.08	24.59	unchanged	no ignition occurred

Analysis of the results shows that there is no absolutely ideal material for 3D printing. Each material has both negative and positive characteristics. The choice of material for printing the product will depend on the purpose of the product and its operating conditions. It is necessary to develop a technique for selecting composite material for printing depending on the requirements of the technical task. This will resolve the contradiction in the choice of material used for printing construction products. This is because the choice of filament is limited by the technical characteristics specified in the passports of the installations, the requirements for the product and the required quality of the resulting product. Moreover, one type of filament from the same producer, but of different grades or lots, can differ significantly in physical and mechanical properties. The development of such a technique is our direction of further research.

Inside the product, the 3D printer prints a stiffening grid that distributes the load on the structure of the detail. The filling of the product can vary from 0% to 100%, depending on the technical conditions and the nature of the product. Partial filling of the structure allows you to significantly reduce the price of the product and printing time. This factor has a very significant effect on the strength and weight of the product. The strength of the entire structure decreases when the structure of the product is partially filled. However, to increase the strength is possible by increasing the wall thickness of the product. By increasing the wall thickness, for example up to 1.2 mm, it is possible to increase the overall strength of the product.

Conclusions. The mastering of additive technologies will entail the adjustment of construction product design principles, the development of printing technologies, the study and use of new and promising materials, and the emergence of technologies related to 3D printing. The research provided an opportunity to analyze the factors that affect the properties of a printed product using a 3D printer. As a result of the study, it was found that the main factors are: the percentage of internal filling and the thickness of the wall of the product. However, the conducted research does not exhaust the entire raised problem, and therefore the study of the factors that affect the properties of the printed building product remains relevant and requires further research.

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АНАЛІЗ ФАКТОРІВ, ЯКІ ВПЛИВАЮТЬ НА ВЛАСТИВОСТІ НАДРУКОВАНОГО ВИРОБУ ЗА ДОПОМОГОЮ 3D-ПРИНТЕРА

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Анотація. У статті наведено аналіз застосування матеріалів для виробництва будівельних виробів розроблених з використанням адитивних технологій. Зазначені в статті зразки матеріалів мають стати найбільш поширеними під час виробництва будівельних споруджень. Визначені також основні фактори, які впливають на властивості надрукованого матеріалу за допомогою 3D-принтера.

На сьогоднішній день виробництво матеріалів для виготовлення різних будівельних споруджень швидко розвивається, стає більш технологічним, збільшуються обсяги виготовлення, підвищується точність та якість виготовлення деталей, при знижені витрат. Використання 3D-принтера дозволяє вдало проводити оптимізацію виробництва будівельних споруджень. У випадку звичайного способу виробництва їх вартість і складність досить висока. Впровадження 3D-принтера дає змогу суттєво покращити дизайн та структуру виробів за допомогою удосконалення технології та витрат матеріалів.

Проведені дослідження відкрили цілий пласт питань та проблем, пов'язаних із необхідністю вдосконалення процесу 3D друку, організації та управління друку складних будівельних виробів, які б дозволили ефективно використовувати новітні адитивні технології 3D-друку в сучасному будівництві.

Експериментально встановлені властивості основних матеріалів для 3D друку, які використовуються при FDM технології отримання виробу. Визначений порядок розрахунку продуктивності екструдера та основні проблеми під час друку.

Дослідження показали, що використання адитивних технологій у виробництві будівельних виробів вже на сучасному етапі надасть можливість об'єднати новітні наукові розробки в галузях техніки, технології, матеріалознавства, архітектури, дизайну для коригування принципів конструювання, відпрацювання технологій друку, використання нових стратегій побудови сучасних будівель, появі нових, суміжних з 3D-друком технологій.

Ключові слова: адитивні технології, 3D друк, філамент, структура, екструдер.

Стаття надійшла до редакції 12.07.2022