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REVEALING THE INFLUENCE OF 3D PRINTING DENSITY ON THE PHYSICAL AND MECHANICAL PROPERTIES OF POLYMER ARTICLES

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This study investigates the process of 3D printing of polymer articles in light industry. The task addressed is to determine the stressed-strained state of 3D-printed articles made of PETG polymer, taking into account the nonlinear (inelastic) physical and mechanical properties of the material and the influence of printing density on its mechanical behavior.

The study's result established that the tensile curve of 3D-printed samples from PETG follows the form of power function that reflects the properties of an inelastic polymer material. Applying the resulting power function relationship between deformations and stress, unlike the linear one, has made it possible to determine the normal stresses that appear in the internal layers of 3D-printed articles in the form of a beam of rectangular cross-section at bending.

Numerical values were derived for parameters of the power function that reflects the dependence of stresses on strain when stretching 3D-printed samples from PETG, manufactured at a print density of 70%, 80%, 90%, and 100%. It was found that with an increase in the density of PETG 3D printing from 60% to 100%, the tensile stresses in the samples increase from 12.3 to 19.6 MPa, while the relative deformation at their rupture decreases from 0.076 to 0.062. The resulting dependences make it possible to determine the required density of 3D printing to ensure the predefined limit load parameters for articles during their application.

Taking into account the nonlinear nature of deformation and the influence of the density of the structure on tensile stresses and relative deformation at the rupture of the polymer material creates opportunities for designing and manufacturing 3D-printed articles in light industry with predictable properties to enable their operability under operational loads

Keywords: 3D printing density, PETG, Ludwick's power function, nonlinear stress-strain dependence

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1. Introduction

In various industries, 3D printing technology is rapidly spreading for the manufacture of articles from polymer materials. In light industry, clothing, footwear, and haberdashery items with polymer elements fabricated by the 3D printing method are successfully manufactured. Such elements are subjected to repeated operational loads; quality of the finished product depends on their physical and mechanical properties. In turn, the physical and mechanical properties of a polymer material are determined by its structure, which is defined by the density of 3D printing and could change when setting up a 3D printer. This must be taken into account when designing and applying articles to ensure their operability, as well as when determining the technological parameters for 3D printing.

Therefore, studies aimed at identifying the patterns of influence of 3D printing density on physical and mechanical properties are important for ensuring that the specified performance indicators of articles are maintained. Results from such studies are needed for setting up 3D printers under industrial conditions.

2. Literature review and problem statement

Work [1] notes that leading manufacturers of sports shoes are already competing with each other in the fastest possible introduction of 3D printing into mass production. Consumers are offered new structures of sneakers with a lattice bottom, which have a modern design, but patterns that influence parameters of such a structure on the physical and mechanical properties of printed articles remain uncertain. Attempts are being made to manufacture shoe insoles and all-polymer shoes on modern high-performance 3D printers [2]. However, manufacturing such large-volume products requires a significant duration of the 3D printing process, which does not always meet the requirements of mass production.

3D printing technology began to be used in light industry in the manufacture of overlays for shoe insoles [2]. Such overlays require additional fixation operations on the surface of the insole and are suitable only for the manufacture of shoes to individual orders.

3D printing in footwear production makes it possible to reduce material waste, increase the dimensional stability of the structure and the level of comfort to meet the needs of individual consumers associated with musculoskeletal disorders [3], which limits their widespread use.

In paper [4], the effect of 3D-printed insoles of different densities on foot pressure during static and dynamic movements was studied. The authors found that depending on the density of the polymer material structure, the distribution of foot pressure on the sole improves, better foot support is provided, and shoe comfort increases. The effect of the density of 3D-printed silicone mesh insoles on their properties was studied in [5]. The results showed that a lower density of the insole reduced peak pressure on the back and front of the foot, as well as increased arch support. However, it is not known whether a similar effect could be achieved in the case of printing the entire sole.

3D-printed outsoles with a lattice structure improve the comfort of sneakers by adapting their shape to the structure of the user's foot [6]. However, issues related to ensuring the performance of the outsoles under repeated operational loads remain unresolved.

In [7], the effect of 3D-printed soles with a cellular structure was investigated; it was found that the cellular structure reduces the pressure on the sole during running. However, the use of the results in production is limited since they relate to a personalized sole.

As a rule, during the loading of polymer parts, various deformations occur, which have different components: flexible, elastic, plastic. This is due to the complex supramolecular structure of both natural [8] and artificial [9] polymer materials. In the case when the material is not elastic, various empirical functions are used to describe its physical and mechanical properties, which must be selected in each specific case, which complicates its further use.

One variant of the universal empirical function for describing the physical and mechanical properties of a polymer material is a power function. This function was used in [10] to approximate the stress-strain curve during the finite element analysis of the tensile process of cast samples made of composite polymer material. The authors found that the calculations of deformation according to different power laws correlate with each other and agree well with the results of experiments on tensile samples. However, it is not known whether a similar approach could be used in the case of 3D printing.

The deformation of composite polymer materials based on epoxy resin can also be described by the power laws of Holloman and Ludwick [11]. In this case, the creep of the material under the action of loads consists of initial, secondary, and tertiary, and its nature changes in time. The presence of areas with different creep characteristics complicates the selection of an empirical function for their approximation.

In [12], the possibility of using power functions to describe the deformation of a composite material based on polyamide with short-fiber filler was considered. It was shown that power, exponential, and linear-exponential functions reasonably describe the tensile curve for samples with different filler contents. However, which function to choose for approximating printed articles with different filling densities of polymer material remains unresolved.

In [13], power functions were selected for analyzing the plastic properties of paper. The authors proposed a system of equations to describe the tensile curve of paper samples, one of which is linear and the second has the form of a power function. As a result of the research, numerical parameters for the equations of this function were determined, which can be used to predict the properties of articles. However, the established parameter values cannot be applied to polymer articles obtained using 3D printing technology.

Power laws are also used to describe the elastic-plastic deformation of metal parts, especially at elevated temperatures [14]. The authors found that the tensile curves of alloyed samples in different temperature ranges correspond to the power laws of Holloman and Ludwick's, which indicates the presence of a plastic component of deformation. However, it is unknown whether these laws could be used to describe the stretching process of printed polymer articles.

As follows from the results of the above studies, the deformation of various materials that have a complex internal structure has a clearly pronounced nonlinear nature and can be described based on the use of power functions. However, the existing nonlinear deformation models have some limitations, namely they reflect the deformation properties of only monolithic homogeneous or composite materials; they are used only under certain conditions, for example, at elevated temperatures. In addition, there are no models that take into account the interlayer anisotropy of printed articles and the influence of 3D printing density parameters on the mechanical properties of the polymer material.

To predict the deformation of products in each specific case, it is necessary to determine the shape and numerical parameters of the power law for the corresponding material. All this allows us to state that, despite the successful use of innovative 3D printing technology in light industry, further improvement of efficiency and quality of footwear articles requires further research in this area.

3. The aim and objectives of the study

The purpose of our study is to identify the influence of 3D printing density on the physical and mechanical properties of polymer articles, namely on the parameters of their tensile curve. This will make it possible to avoid the destruction of the polymer material and ensure the operability of printed articles at the design stage, taking into account operational loads and technological parameters of the 3D printing process.

To achieve the goal, the following tasks were set:

– to establish a law for determining normal stresses in the layers of a 3D printed article in the form of a beam of rectangular cross-section at bending;

– to define numerical parameters for the dependence of stresses on the deformation of the polymer material at different values of 3D printing density.

4. The study materials and methods

The object of our study is the process of 3D printing of polymer articles in light industry. The principal hypothesis of the study assumes that the physical and mechanical properties of the polymer material in 3D-printed articles are determined by the density of 3D-printing.

The following assumptions were adopted in the work:

– the cross-sections o f the products before and after deformation are flat;

– at any point of the product, the material properties are the same;

– the deformations are small compared to the dimensions of the product.

The following simplifications were accepted in the work:

– articles have the shape of a beam of rectangular cross-section;

– during experimental studies, the deformation of the samples in the clamping areas was not taken into account.

We have used analytical methods in the study that make it possible to identify fundamental relationships between the normal stresses in the product layers at bending and the parameters of the power function, which is proposed for approximating the tensile curve of 3D-printed samples.

5. Results of investigating the influence of 3D printing density on the physical and mechanical properties of articles

5. 1. Establishing a law for determining normal stresses in the layers of a 3D printed article at bending

Some parts of light industry articles have the shape of a plate (sole, heel) or a rod (suitcase handle), etc. Given this, the work considers pure bending of a printed polymer part in the form of a beam of rectangular cross-section [15] (Fig. 1, 2).

The shape of the beam element before and after deformation is shown in Fig. 2.

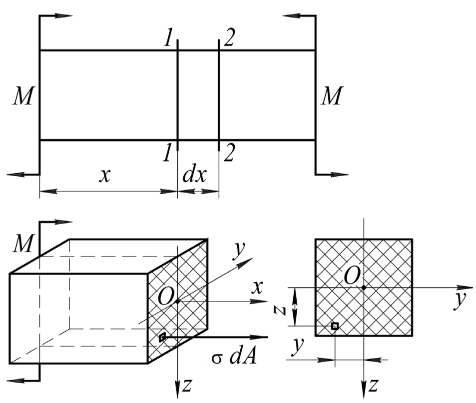

Fig. 1. Beam bending load diagram

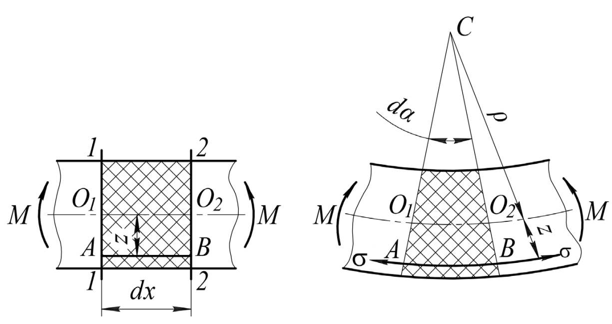

Fig. 2. The shape of the beam element before and after deformation

To describe the material properties of the beam, the Ludwick's power law was used, which reflects the dependence of normal stresses on relative deformation in the form

$$\sigma = K\varepsilon^n, \tag{1}$$

where K is the constant stress, ε is the relative strain, and n is the power exponent.

At bending a beam of rectangular cross-section, the initial length of the fiber AB, which is at a distance z from the neutral axis and stretched under the action of stresses σ

$$dx = \cup O_1O_2 = r \cdot d\alpha, \tag{2}$$

where r is the radius of curvature of the neutral layer.

After deformation, its length

$$\cup AB = \left(r + z\right) \cdot d\alpha. \tag{3}$$

Absolute fiber elongation

$$\Delta l = \left(r + z\right) \cdot d\alpha - r \cdot d\alpha = z \cdot d\alpha. \tag{4}$$

Therefore, the relative elongation

$$\varepsilon = \frac{z \cdot d\alpha}{r \cdot d\alpha} = \frac{z}{r}. \tag{5}$$

Substitution (5) in (1) gives

$$\sigma = K\left(\frac{z}{r}\right)^n. \tag{6}$$

From the conditions of equilibrium, it follows that

$$\int_A \sigma z \mathrm{d}A = M, \tag{7}$$

where M is the bending moment; z is the distance from the neutral plane; dA is the cross-sectional element.

Substituting (6) into (7) gives

$$\frac{K}{r^n}\int_A z^{n+1}\mathrm{d}A = M. \tag{8}$$

The integral in (8) can be denoted as

$$I = \int_A z^{n+1}\mathrm{d}A. \tag{9}$$

Taking into account (8) gives

$$\frac{K}{r^n} = \frac{M}{I}. \tag{10}$$

From (10), radius of curvature of the neutral layer

$$r = \sqrt[n]{\frac{KI}{M}}. \tag{11}$$

Substitution (11) in (6), gives

$$\sigma = \frac{Mz^n}{I}. \tag{12}$$

The integral (8) for a beam of rectangular cross-section (Fig. 3) can be represented as

$$I=\int_A z^{n+1}\mathrm{d}A=\int_{-h/2}^{h/2} z^{n+1}b\mathrm{d}z=\frac{2b}{n+2}\left(\frac{h}{2}\right)^{n+2}. \qquad (13)$$

Substitution (13) in (12) gives

$$\sigma=\frac{Mz^n}{\frac{2b}{n+2}\left(\frac{h}{2}\right)^{n+2}}. \qquad (14)$$

Substitution (13) in (11) gives

$$r=\sqrt[n]{\frac{K\frac{2b}{n+2}\left(\frac{h}{2}\right)^{n+2}}{M}}. \qquad (15)$$

As one can seen from formulae (14) and (15), the parameters of the power law (1) K and n affect the values of maximum stresses and the radius of curvature of the neutral layer when bending a polymer part in the form of a beam.

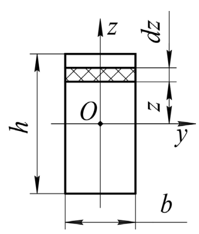

Fig. 3. Beam cross-sectional diagram

To determine parameters for the power law (1), it is necessary to logarithmize its left-hand and right-hand sides [16]

$$\log\sigma=\log\left(K\varepsilon^n\right). \qquad (16)$$

Expression (16) can be converted to the form

$$\log\sigma=\log K+n\log\varepsilon. \qquad (17)$$

Therefore, from experimental dependence (17), it is possible to determine parameters K and n.

5. 2. Establishing numerical parameters for the dependence of stresses on the deformation of a polymer material at different values of 3D printing density

To determine parameters K and n for the power law of deformation of the polymer material in 3D printed parts, experiments were conducted on stretching to rupture of PETG samples (Fig. 4) using a modernized rupture machine 2167 P-50 (Fig. 5).

The relative deformation was calculated from formula $\varepsilon=\Delta l/l$, where Δl is the absolute deformation, mm; $l=85$ mm is the length of the sample. The magnitude of stresses was calculated from formula $\sigma=F/S$, where F is the force applied to the sample, N; $S=4\times10^{-3}\times10\times10^{-3}=40\times10^{-6}$ m^2 is the cross-sectional area of the sample.

Fig. 4. General view of a printed PETG-based sample after breaking

Fig. 5. Modernized rupture machine 2167 P-50

In order to determine parameters K and n, the dependence of the decimal logarithm of stresses on the decimal logarithm of relative deformation during stretching of PETG samples at 60% print density was constructed, which was fitted to a linear regression equation in the form

$$\log\sigma=7.793+0.47\log\varepsilon. \qquad (18)$$

As a result of our experiments, it was found that the tensile stress for PETG samples at 60% print density is $\sigma_r=12.3$ MPa; the relative strain at rupture is $\varepsilon_r=0.076$.

Fig. 6 shows the graphical dependence for PETG samples at 60% print density, calculated from equation (18).

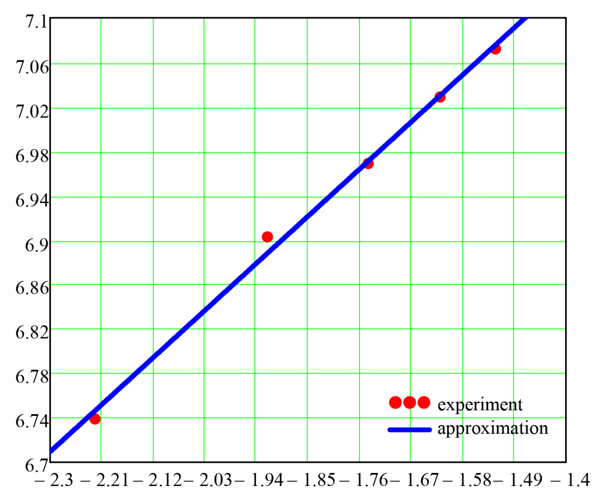

Fig. 6. Dependence of the decimal logarithm of stresses on the decimal logarithm of relative deformation when stretching PETG samples at 60% print density

From equation (18) it follows that for PETG samples at 60% print density, $n=0.471$. In addition, $\log K=7.793$, which implies $K=62.1$ MPa.

Fig. 7 shows the results of experiments and calculations based on equation (1) as a result of substituting the numerical values of parameters K and n.

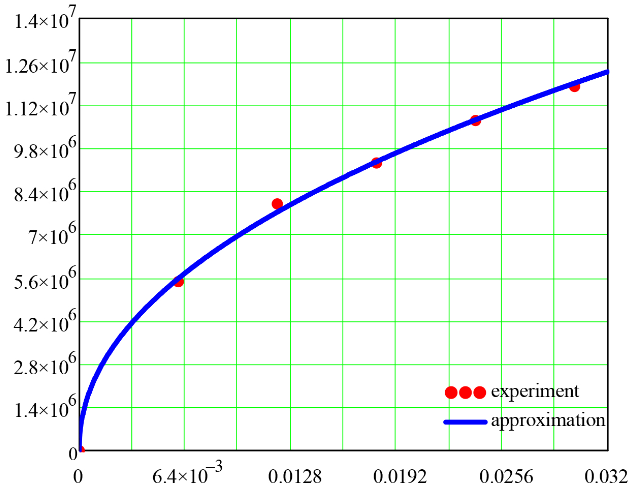

Fig. 7. Experimental and theoretical dependence of stresses on relative deformation when stretching PETG samples at 60% print density: 1 – experiment; 2 – calculation results

As one can see from Fig. 7, the stress-strain curve at the initial stage of stretching of printed PETG samples at 60% print density can be satisfactorily approximated by the Ludwick's power law (1).

To determine the effect of filling printed articles with polymer material, experimental studies on the stretching process of PETG samples obtained at print densities of 70%, 80%, 90%, and 100% were conducted. As a result of processing the research results, the values for tensile stresses σ_r, relative strain at rupture ε_r, as well as parameters K and n, were derived, which are given in Table 1.

The table demonstrates that with increasing print density, parameter K increases, and parameter n decreases, which indicates a more rapid increase in stresses in the initial period of deformation.

Fig. 8, 9 show the dependences of tensile strength and tensile relative deformation on print density.

Table 1

Parameters for tensile curves of printed samples

Print density ρ, %	K, MPa	n	σ_r, MPa	ε_r
60	62.1	0.471	12.3	0.076
70	73.2	0.468	14.5	0.071
80	78.0	0.445	16.3	0.068
90	79.2	0.418	18.1	0.065
100	83.8	0.407	19.6	0.062

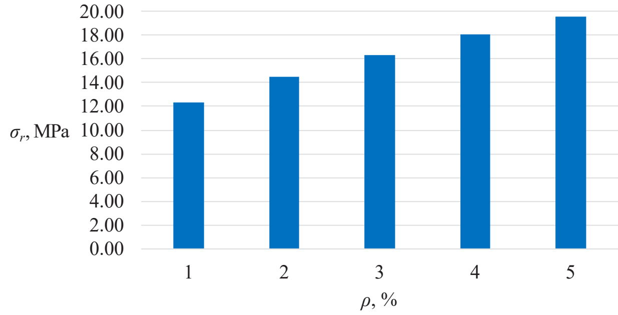

Fig. 8. Dependence of tensile strength on print density

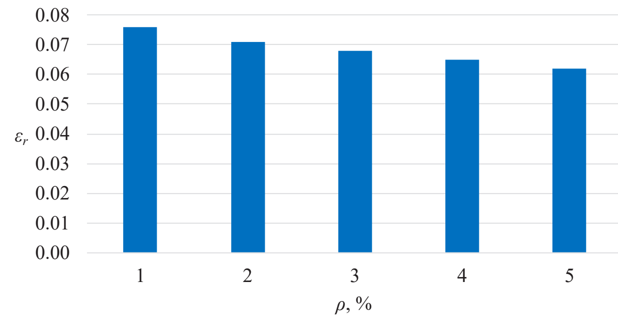

Fig. 9. Dependence of breaking relative deformation on print density

From Fig. 8, 9 one can see that with increasing printing density, the tensile stress increases while the tensile relative strain decreases.

6. Results of investigating the influence of 3D printing density on the physical and mechanical properties of articles: discussion and summary

Our results are represented at the analytical level for the nonlinear stressed state of a beam of rectangular cross-section in formula (14), which demonstrates the fundamental dependence of normal stresses in the layers of the beam at bending on the parameters of the power function proposed to approximate the tensile curve of 3D-printed samples.

When stretching 3D-printed polymer samples, the evolution of significant deformations is observed while maintaining maximum stresses and the absence of the formation of the so-called neck at the site of fracture of the samples (Fig. 4), which indicates the gradual destruction of the elements of the material structure under the action of the applied load. Therefore, of the greatest interest is the initial section of the tensile curve, which corresponds to the state of the sample in which the destruction of the internal structure has not yet begun.

The nonlinear nature of the relationship between stresses and strains of 3D-printed articles is explained by their complex internal structure, which is formed during the 3D-printing process. That is why the relationship between the decimal logarithms of stresses and strains according to formula (18) is linear, which allowed us to determine the numerical values for parameters K and n.

The initial section of the tensile curve of polymer samples obtained by the 3D-printing method is reasonably fitted to the Ludwick's power law whose parameters depend on the print density.

In comparison with the results reported in [10–14], a wider use of the determined parameters of the tensile curve is proposed when establishing regularities in the bending process of articles.

Unlike existing methods for determining stresses in beams [15], which use a linear approximation of the relationship between stresses and deformations, the use of a power dependence has made it possible to take into account the influence of the density of 3D printing on the magnitude of normal stresses in the product layers.

Our research results make it possible to justify the use of Ludwick's law to describe the deformation properties of printed parts in Fig. 7, 8, which expands the existing scientific ideas about their deformation. The established numerical values for the power function make it possible to more accurately predict the behavior of a polymer material under the action of operational loads.

Our numerical values for parameters of the tensile curve, as well as values of the tensile stresses and relative deformation at rupture of 3D-printed samples depending on the density of 3D printing, could be used in the design, manufacture, and operation of light industry articles in order to ensure their operability within the limits of existing loads.

The limitation of our results is that the experimental determination of the influence of 3D-printing density on the parameters of the tensile curve was carried out only for one material – PETG, and at selected density values in the range from 60% to 100% (Table 1, Fig. 8, 9) which does not make it possible to generalize them for other materials and experimental conditions. In this regard, the priority areas of further research are confirmation of the obtained patterns for other polymer materials, other article geometry, and other printing temperatures.

The disadvantage of the study is that it considers only one type of load – pure bending, while during operation light industry articles are also subjected to other, more complex types of loads. To eliminate this drawback, it is necessary to consider in further work all possible types of loading of printed articles that arise during operation.

A promising direction for further research is the construction of analytical dependences to describe the stressed-strained state of 3D printed articles under different types of loads (static, cyclic, temperature), checking their adequacy for different polymer materials and printing modes, as well as expanding the model to multilayer and composite structures.

7. Conclusions

1. A law has been established for determining the normal stresses in the layers of a 3D-printed article in the form of a beam of rectangular cross-section at bending. In contrast to known approaches, the nonlinear nature of the dependence of stresses on deformations, which can be described by the Ludwick's power law, has been taken into account.

2. Numerical values for parameters of the nonlinear dependence of stresses on deformation of a polymer material at different values of 3D-printing density have been established. It has been found that with an increase in the density of PETG 3D-printing from 60% to 100%, parameter K increases from 62.1 to 83.8 MPa while parameter n decreases from 0.471 to 0.407. The revealed patterns are explained by the influence of the microstructure of layers and the interlayer adhesion on the mechanical behavior of 3D-printed articles.

Conflicts of interest

The authors declare that they have no conflicts of interest in relation to the current study, including financial, personal, authorship, or any other, that could affect the study, as well as the results reported in this paper.

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Data availability

All data are available, either in numerical or graphical form, in the main text of the manuscript.

Use of artificial intelligence

The authors confirm that they did not use artificial intelligence technologies when creating the current work.

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