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FORMING THE PROPERTIES OF PARTS OBTAINED BY FDM BY MODIFYING THE SURFACE LAYER USING MECHANICAL AND PHYSICAL-TECHNICAL TREATMENT

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This study focuses on the processes and phenomena related to post-processing of FDM articles in the form of mechanical, thermal (laser), or chemical action, as well as their influence on the set of FDM-printed parts' properties. At present, the lack of a methodological basis for the choice of post-processing methods creates obstacles in the attempt to improve the operational properties of articles and is an important problem in additive engineering.

The paper investigates the post-processing of articles obtained by the method of layer-by-layer arrangement of plastic filament from the point of view of changing their mechanical and physical-technical characteristics due to the formed modified surface layer.

It was noted that post-processing can be performed by mechanical action (blade cutting or abrasive processing), physical-technical, thermal (for example, laser), and chemical (etching, application of adhesive layers). As a result of such actions, a modified layer of a certain thickness is formed on the surface of the article, the structure, and properties of which will differ from the base, and its features can significantly change the operational properties of the article as a whole.

The analysis of various post-processing options was performed on the basis of the functional transformation of the input parameters of the workpiece into the output ones, which made it possible to link the regularities in the formation of stresses, thermal fields, and fields of motion of matter from the parameters of the state of the surfaces, which change in the process of post-processing from the initial to the final one, and which are reflected by combinatorial sets. This approach allows one to avoid duplication of operations or individual transitions, determine the expediency of using certain techniques, increase the reproducibility of the additive process, and ensure the reliability of the finished article as a whole.

The dependence of FDM articles' properties on the state of the surfaces has been established; the corresponding functional dependences have been proposed for determining the thickness of the modified layer formed by certain mechanical or physical-technical influences. It is shown that the use of sharply sharpened tools makes it possible to obtain for PLA R_a = 3.0…3.6 μm, R_z = 20…40 μm during turning, milling, and drilling; for ABS, respectively, Ra = 1.2…1.6 μm, Rz = 5…8 μm, with a modified layer thickness of 0.15–0.65 mm and 0.1–0.25 mm, respectively. Laser exposure modifies the layer at a depth of 0.2…0.5 mm; chemical treatment with ketone vapors forms a layer with a thickness of 0.3…1.1 mm and is determined by the temperature of the saturated vapor, as well as diffusion rate

Keywords: additive manufacturing, mechanical properties, post-processing, mathematical modeling, temperature and stress fields

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1. Introduction

Additive technologies, unlike subs trative processes, are increasingly used in engineering practice as they have undeniable advantages:

– the ability to create set spatial shapes of parts;

– the reproduction of an unlimited number of interconnected surfaces with the formation of faces of the desired profile;

– broad technological capabilities;

– the ability to create thin-shell articles, including those with closed cavities;

– the ability to create gradient structures;

– obtaining set hollow structures and structural elements.

That is why the interest in additive processes, in particular, FDM, SLS, SLA technologies [1], remains unchanged.

The essence of the FDM printing process is known [2] and has been studied in detail [3, 4]: sequential layer-by-layer application of the filament melt by scanning head movements along a calculated trajectory during solidification makes it possible to grow a solid-state model at reasonable productivity. Printers available on the market, both for industrial and consumer use [5], provide printing at speeds up to 600 mm/min with a nozzle from 0.2 mm in diameter: acceleration when bypassing the contour and when changing the direction of the trajectory of movement can reach 16,000 mm/s^2. The layer thickness is variable and can change from 0.08 mm to 0.4 mm; there are technical solutions for printers and control devices for printing with a variable vertical coordinate z [6], which makes it possible to obtain set spatial surfaces, such as aerodynamic profiles.

At the same time, additive items have certain disadvantages, the main of which is that the article ceases to be compact and dense; the quality and strength of the connection of fibers and layers are significantly affected by thermal contact modes and force interaction schemes [7].

The gradual multi-stage reproduction of articles leads to the fact that they are characterized by a certain anisotropy of properties [8], as well as errors in shape and size [9, 10], which in most cases are determined by the conditions and means of reproduction of the item, the quality of the plastic used, the purity of the environment, etc.

Thus, the issue of ensuring the quality and functional properties of finished articles obtained by FDM remains relevant and significant for science and engineering practice. From this point of view, post-processing, aimed at improving the micro- and macro geometric parameters of the article as a whole, appears to be an effective means of combating the shortcomings of the FDM process by modifying the surface layer of the reproduced article by certain controlled influences.

2. Literature review and problem statement

In [10], the authors drew attention to the fact that the process of combining filaments and layers in FDM is not stable, and layer-by-layer deposition leads to a pronounced anisotropy of properties: the limiting values of σ_x σ_y in the main orts, Young's moduli E_x, E_y. E_z, G_x, G_y, G_z and Poisson's ratios ν_x, ν_y, ν_z are different for all types of plastic used. It was shown that the specified mechanical characteristics can vary within quite wide limits, and achieving maximum levels is possible with certain technological techniques. At the same time, the researchers rely on a macro approach to the issues of mechanical properties, without considering how structural defects, the state of the surface layer, etc. affect the mechanical characteristics.

Usually, the deviation of an article's strength values from the filament strength is explained by the fact [11] that the fusion of components occurs at the contact areas between the layers and threads, and [12] provides microphotographs of plastic joints in different sections. The works provide generalized information on the types of inter-turn and inter-layer joints, without a detailed analysis of the phenomena and, as a result, without indicating how different the properties of the finished article formed on a certain oriented laying area can be from the mechanical properties of the filament. The presence of systemic and random factors not only affects the microgeometry of the contact zone [13] but also leads to the formation of a number of defects, a detailed analysis of which is provided by the authors of [14]. The papers provide systematized information on defects, an attempt is made to group defects by several parameters (sizes, spatial shapes, appearance). At the same time, the presented material does not reflect the regularities of defect formation, and the methods of overcoming the sites of their occurrence are of a general theoretical nature.

The above-mentioned shortcoming was partially corrected in [15], in which it was proposed to combine such defects into groups, which would allow them to be considered from the point of view of additional subsequent mechanical processing (post-processing). In addition, in [15] it was shown that there is a cause-and-effect relationship between the conditions of article formation and the parameters of the surface layer and, as a result, the mechanical properties of the article. Therefore, from the analysis of works [14, 15] it can be stated that most defects in FDM arise precisely on the surface or in the surface layer of the part; as a rule, the surface layers differ in properties from the averaged indicators of the volume of the article. In mechanical engineering technology, such a surface layer is called defective. The nature of the occurrence and development of defects, their differences along the cross-section of the workpiece and concentration in the surface layers follows from the peculiarities of the extrusion process itself. Analyzing the extrusion of plastic and its fusion into a finished article, in work [16] it was noted that reducing the thickness of the laying layer (slicing along the z coordinate) leads to an improvement in the density of the article, at the same time, a deterioration in the quality of reproduction of walls and small structural elements with a decrease in the accuracy of dimensions in the filament laying plane is possible since the effect of plastic displacement is manifested. Thus, in some cases, attempts to improve the density of an article lead to a deterioration in the quality of surfaces, which does not make it possible to consider the problem of ensuring the operational properties of additive articles as a task of maximum compression of layers during laying. The study of surface defects formed during printing thin walls, for example, honeycomb spacers [17] proves that improving the quality of shells is achieved by precisely adjusting the extrusion volume and optimizing the motion trajectories. It has also been established that small volumes of extrusion require nozzle cleanliness, which is disturbed by the action of various factors: surface moisture of the filament, structural differences, heterogeneity, fluctuations in the extrusion speed, temperature differences [18], dynamic instabilities of the movement of the working bodies [19]. However, the above works did not provide effective means and techniques for minimizing the number of defects, reducing their impact on the functional properties of the finished additive articles.

Correction of geometric errors of FDM articles, removal of the so-called "sacrificial" elements (supports, heat dissipation devices, stress compensators, etc.) is usually carried out by mechanical post-processing.

In [20], information is provided on the methods of post-processing of polymers, and in [21] information is given on the possibility of obtaining certain parameters of the surface layer by various methods and techniques; however, the researchers did not determine whether the improvement of the quality of the surfaces affects the mechanical properties of the article as a whole.

Paper [22] reports a study on the state of the surfaces of articles after post-processing; however, the researchers focused their attention on the added articles obtained from ABS. The work noted that ABS is prone to the formation of significant residual stresses during laying, as a result of which internal delamination and cracking may occur. Attention is drawn to the fact that mechanical post-processing also ensures the accuracy of the surfaces and their mutual location (with roughness parameters not worse than R_a 2.5 μm, IT qualities not worse than 7...9), forms a defective layer with a thickness of no more than 50...100 μm.

A separate method of post-treatment to be considered is the process of applying surface films, mainly adhesive, to sensitive surfaces, or chemical treatment (etching).

Chemical post-treatment was considered by the authors in several works. In [23] it is noted that a specific type of plastic requires the use of a certain reagent. Along with PLA plastics, acrylonitrile-butadiene-styrene plastics, ABS, [24] are also actively used, which interact quite actively with ketone solvents, so this pair was analyzed to investigate the possibility of changing the surface chemically. In [25], the authors noted the effect of improving the quality of the surface, but the information was given at the level of assumptions. In [26], the improvement of the quality of the surface was also mentioned but only through experimental comparisons of the surface state. For ABS, the result of chemical treatment directly depends on the internal redistribution of the electron density inside the molecule.

Thus, post-processing as a set of techniques to act on the workpiece changes the microgeometry of the surface and the structure of the surface layer. It becomes an effective means of combating the shortcomings of the FDM process by modifying the surface layer and makes it possible to eliminate defects, improve the operational characteristics of an article as a whole.

The lack of a methodological basis for the choice of post-processing methods creates obstacles in attempts to improve the operational properties of articles, in particular, their mechanical characteristics, which is an important problem of modern mechanical engineering.

Thus, there is an unresolved task of substantiating the principles of choosing rational options for post-processing of FDM articles based on predicting the properties of the modified surface layer.

3. The aim and objectives of the study

The purpose of tour study is to devise a principle for selecting post-processing options based on identifying patterns of surface formation and transformations in surface layers during their modification to eliminate defects and improve the quality of the finished article.

To achieve the goal, the following tasks were set:

– to establish the pattern of changes in surface roughness parameters and the conditionality of surface layer modification by mechanical action (cutting or micro cutting);

– to estimate the thickness of the modified layer by laser action;

– to determine the depth of surface modification by chemical post-processing;

– to determine the quality of surfaces under different post-processing options for additive articles and formulating the principle of selecting a rational option based on the conditionality of the mechanical properties of the article by the thickness of the modified layer.

4. The study materials and methods

4. 1. The object and hypothesis of the study

The object of our study is the processes and phenomena in the post-processing of FDM articles in the form of mechanical, thermal (laser), or chemical action, as well as their influence on the set of properties of FDM-printed parts.

The principal hypothesis assumes that the set of functional properties of parts obtained by the FDM-printed method (first of all, mechanical characteristics) is predetermined by regularities in the formation of a modified surface layer under the action of mechanical, thermal, and chemical post-processing.

To simplify the mathematical models, a number of simplifications and assumptions were adopted. It was assumed that the structure of the additive article is homogeneous, without the presence of thin layers and zones of under-extrusion at the points of change in the direction of movement of the extruder.

At the same time, the structure of the article contains defects localized in very small volumes.

The article is characterized by isotropy in the main directions: strength and elongation, as well as other characteristics of the article are the same. Along with this, the structure of the article has regular open cavities.

When considering the mechanical effect, the assumption of a conditionally symmetrical structure of the FDM article and the deterministic action of the cutting wedge on the laid fiber was accepted, which allowed us to simplify the initial model for analytical evaluation of stress fields.

The thermal effect from the laser beam was considered as a concentrated uniform source of heat spreading over the irradiation spot, the diameter of which is determined by the constriction of the beam caustic; the laser is pulsed.

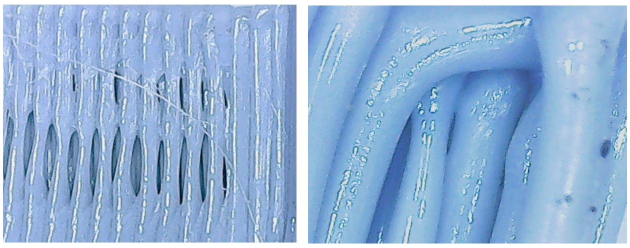
Given the assumption of openness of article cavities, it was believed that the evaporation of volatile liquids could penetrate the surface layer and chemically affect the phenomena of its change; the evaporation itself could be described by the Navier-Stokes equations.

The research methodology is built on the principle: construction of mathematical models to determine the conditions for changing surface layers as a result of a certain action; determination of appropriate modes and methods of influence, assessment of the depth of modification, experimental verification of model results.

4. 2. Methodology for studying the conditionality of the parameters of roughness and thickness of surface layer modification by mechanical action

Articles made by additive processes usually have different density on the outer surfaces and inside, Fig. 1. At the same time, since the contour of the outer surfaces is handled separately from the filling, even full density during printing is accompanied by the formation of cavities, influxes, and incomplete adhesive adhesion both from the outside and on the planes of contact of the contour with the filling. Post-processing, as a rule, changes the state of the surface from the side of direct mechanical or physical-technical impact, thereby reducing the number of defects that negatively affect the mechanical (and operational) properties in general. At the same time, the very action of the means of modifying the surface layer affects its properties, which requires a comprehensive approach to this issue.

The assessment of the level of residual stresses and the depth of their occurrence (which determines the thickness of the modified layer) was carried out on the basis of the following considerations.

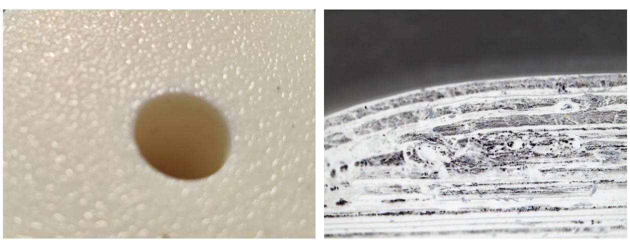


a *b*

Fig. 1. Photograph of article microstructure (*a*), (×100) and the difference in filament packing density in the near-contour zones (*b*), (×400)

The inhomogeneous hollow structure of the added material (Fig. 2), and the presence of a cavity between the turns causes the redistribution of loads during force action. Assessment of the action of the cutting wedge on the surface (or a set of micro-wedges during abrasive treatment) by constructing stress and deformation fields allows us to determine the spread of destruction deep into the material and estimate the formed thickness and, consequently, determine the set of operational properties of the article.

Limiting the analysis of the interaction of the cutting wedge to the case of a deterministic action on the laid fiber or strip is appropriate for simplifying the initial model for the purpose of analytical or numerical evaluation of the stress and deformation fields. Using the assumption about a conditionally symmetric structure, despite the known heterogeneity and hollowness of the FDM material, makes it possible to establish general patterns of load redistribution.



a *b*

Fig. 2. Photograph of the end face of the workpiece: *a* – before mechanical cutting; *b* – microphotograph of part of the cut surface

To determine the rational conditions for post-processing of the test article, the stress-strain state of the workpiece under the action of a cutting wedge was evaluated. The perpendicular action of the cutting wedge on the surface of a conventional prismatic body will make it possible for us to write the components of the stress tensor as follows:

$$\sigma_{xx}=\frac{2G}{m-2}divU+\frac{1}{2\pi}\times\left(\begin{array}{l}S_x\left(\frac{x}{R^3}-\frac{3x^3}{R^5}+\frac{m-2}{m}\left(-\frac{3x}{R(R+z)^2}-\frac{x^3(3R+z)}{R^3(R+z)^3}\right)\right)+\\+S_y\left(-\frac{y}{R^3}-\frac{3x^2y}{R^5}-\frac{m-2}{m}\left(\frac{y}{R(R+z)^2}-\frac{x^2y(3R+z)}{R^2(R+z)^4}\right)\right)+\\+S_z\left(\frac{z}{R^3}-\frac{3x^2z}{R^5}-\frac{m-2}{m}\left(\frac{1}{R(R+z)}-\frac{x^2(2R+z)}{R^3(R+z)^2}\right)\right)\end{array}\right), \quad (1)$$

$$\sigma_{yy}=\frac{2G}{m-2}divU+\frac{1}{2\pi}\times\left(\begin{array}{l}S_x\left(\frac{x}{R^3}-\frac{3y^2x}{R^5}-\frac{m-2}{m}\left(\frac{x}{R^2(R+z)}-\frac{xy^2(3R+z)}{R^2(R+z)^4}\right)\right)+\\+S_y\left(\frac{y}{R^3}-\frac{3y^3}{R^5}+\frac{m-2}{m}\left(-\frac{3y}{R(R+z)^2}+\frac{y^3(3R+z)}{R^3(R+z)^3}\right)\right)+\\+S_z\left(\frac{z}{R^3}-\frac{3zy^2}{R^5}-\frac{m-2}{m}\left(\frac{1}{R(R+z)}+\frac{y^2(2R+z)}{R^3(R+z)^2}\right)\right)\end{array}\right), \quad (2)$$

$$\sigma_{zz}=\frac{2G}{m-2}divU+\frac{1}{2\pi}\times\left(\begin{array}{l}S_x\left(\frac{x}{R^3}-\frac{3z^2x}{R^5}-\frac{m-2}{m}\frac{x}{R^3}\right)+\\+S_y\left(\frac{y}{R^3}-\frac{3z^2y}{R^5}-\frac{m-2}{m}\frac{y}{R^3}\right)+\\+S_z\left(-\frac{2(m-1)}{m}\frac{z}{R^3}+\frac{2z}{R^3}-\frac{3z^3}{R^5}\right)\end{array}\right), \quad (3)$$

$$\sigma_{xy}=\frac{1}{4\pi}\times\left(\begin{array}{l}S_x\left(-\frac{6x^2y}{R^5}-\frac{m-2}{m}\frac{2y}{R(R+z)^2}\right)+\\+S_y\left(\frac{x}{R^3}+\frac{1}{R^3}-\frac{6xy^2}{R^5}\right)+\\+2S_z\left(-\frac{3xyz}{R^5}+\frac{m-2}{m}\frac{xy(2R+z)}{R^3(R+z)^2}\right)\end{array}\right), \quad (4)$$

$$\sigma_{yz}=\frac{1}{2\pi}\times\left(\begin{array}{l}S_x\left(-\frac{3y^2x}{R^5}-\frac{3xyz}{R^5}\right)+\\+S_y\left(\frac{m-2}{m}\left(\frac{2}{R(R+z)}+\frac{yz(2R+z)}{R^3(R+z)^2}-\frac{x^2(2R+z)}{R^3(R+z)^2}\right)\right)+\\+S_z\left(-\frac{6z^2y}{R^5}+\left(1+\frac{3(m-2)}{m}\right)\frac{y}{R^3}\right)\end{array}\right), \quad (5)$$

$$\sigma_{zx}=\frac{1}{4\pi}\times\left(\begin{array}{l}S_x\left(-\frac{3zx^2}{R^5}-\frac{3z^2x}{R^5}-\frac{m-2}{m}\left(\frac{x^2(2R+z)}{R^3(R+z)^2}+\frac{x^3(2R+z)}{R^3(R+z)^3}\right)\right)-\\-S_y\frac{6xyz}{R^5}+Sz\left(\left(1+\frac{m-2}{m}\right)\frac{x}{R^3}-\frac{6xz^2}{R^5}\right)\end{array}\right), \quad (6)$$

where R is the unit direction vector; m is Poisson's number; S_x, S_y, S_z are the projections of the concentrated force onto the XYZ axes acting inside the half-space.

For a conditionally symmetric structure formed by laying out the filament, we obtain:

$$\sigma_{yx}=\frac{1}{4\pi}\times\left(\begin{array}{l}S_x\left(\frac{6x^2y}{R^5}-\frac{m-2}{m}\frac{2y}{R(R+z)^2}\right)+\\-S_y\left(\frac{x}{R^3}+\frac{1}{R^3}-\frac{6xy^2}{R^5}\right)+\\+2S_z\left(\frac{3xyz}{R^5}-\frac{m-2}{m}\frac{xy(2R+z)}{R^3(R+z)^2}\right)\end{array}\right) \quad (7)$$

$$\sigma_{zy}=\frac{1}{2\pi}\times\left(\begin{matrix} S_x\left(\frac{3y^2x}{R^5}+\frac{3xyz}{R^5}\right)- \\ -S_y\left(\frac{m-2}{m}\left(\begin{matrix}\frac{2}{R(R+z)}+\frac{yz(2R+z)}{R^3(R+z)^2}- \\ -\frac{x^2(2R+z)}{R^3(R+z)^2}\end{matrix}\right)\right) \\ +S_z\left(\frac{6z^2y}{R^5}-\left(1+\frac{3(m-2)}{m}\right)\frac{y}{R^3}\right)\end{matrix}\right)+ \quad (8)$$

$$\sigma_{xz}=\frac{1}{4\pi}\times\left(\begin{matrix} S_x\left(\begin{matrix}\frac{3zx^2}{R^5}+\frac{3z^2x}{R^5}+ \\ +\frac{m-2}{m}\left(-\frac{x^2(2R+z)}{R^3(R+z)^2}+\frac{x^3(2R+z)}{R^3(R+z)^3}\right)\end{matrix}\right)+ \\ +S_y\frac{6xyz}{R^5}-S_z\left(\left(1+\frac{m-2}{m}\right)\frac{x}{R^3}-\frac{6xz^2}{R^5}\right)\end{matrix}\right) \quad (9)$$

To obtain patterns of stress redistribution between layers, threads, and other structural components of the workpiece, the conditions of contact of the cutting wedge with the machining surface were determined. The contact diagram is shown in Fig. 3.

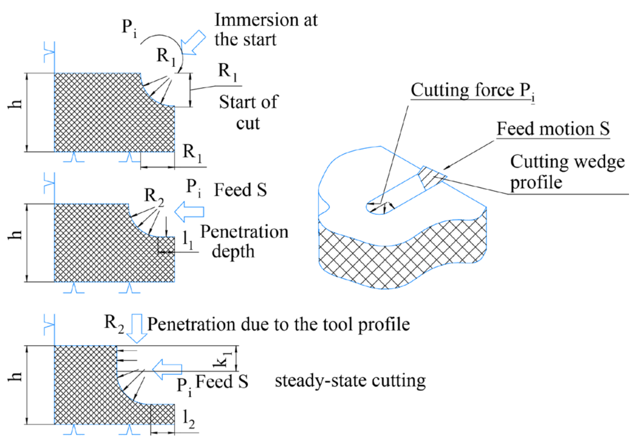


Fig. 3. Model of the action of the cutting wedge on a machined workpiece

Dependences (1) to (6) and (7) to (9) for determining the stresses in the cross-sections and on the contact planes between the threads and layers of the laid filament were compared with the limit values inherent in a particular material, which allows for the modeling to estimate.

The conditions of the loads on the working surfaces from the cutting edges of the tool were determined by the cutting scheme and the design of the workpiece, which are specified in the modeling.

By changing the force load during cutting, the speed of movement of the cutting wedge along the direction of the main movement, the spread of the zone of probable destruction from the contact surface was established at the time when $\sigma_{ij} \geq [\sigma]$. According to the latter condition, the thickness T_d^m, from the surface, which became the partition between the workpiece body and the separated chip, was estimated.

Micro geometric parameters (in particular, R_a, μm) of the surface were estimated according to the profile of the envelope of the zones of the formed destructive stresses in the body, taking into account its layered and hollow structure, as well as under the condition of forming grooves in the compact material by a wedge cut having certain geometric parameters [26].

4. 3. Assessment of the thickness of the surface layer modification by thermal influence

A point heat source was used for thermal modification of the surface: local heating did not lead to significant temperature deformations of the article as a whole, and the possibility of partial melting and subsequent vitrification and crystallization of the plastic on the surface significantly changed its structure, eliminating individual defects. In this case, it was assumed that an ultra-high concentration of heat is capable of destroying the sample and not modifying the surface layer.

A pulsed Nd:YaG laser was chosen as the heat source. It enabled maintaining the pulse repetition frequency up to 250 Hz, provided pulse energy up to 640 J (max). The diameter of the radiation spot was 0.2...0.5 mm. To determine the speed of the beam movement along the surface under the condition of melting only the surface layer with prior evaporation of the material, thermal fields were simulated by numerical methods.

It was assumed that the action of a solid-state laser beam for some time creates local heating of the irradiation zone. The density of absorbed energy is determined from the following dependence

$$q(x)=q_0\exp^{\left(-x^2/r^2\right)}, \quad (10)$$

where q_0 is the radiation power density at the center of the focusing spot; r is the radius of the beam taking into account the distribution of radiation density according to Gauss's law [27].

The differential equation of heat conduction in a stationary medium, which does not assume convection or radiation, takes the form

$$\frac{\partial^2 T}{\partial x^2}+\frac{\partial^2 T}{\partial y^2}+\frac{\partial^2 T}{\partial z^2}+q=\frac{1}{\alpha}\frac{\partial T}{\partial t}. \quad (11)$$

That is, for a certain body, the following change in temperature

$$dT(x,y,z,t)=\frac{\delta q}{\rho C\left(4\pi\alpha\left(t-t'\right)\right)^{3/2}}\times \times\exp\left[-\frac{\left(x-x'\right)^2+\left(y-y'\right)^2+\left(z-z'\right)^2}{4\alpha\left(t-t'\right)}\right]. \quad (12)$$

This expression describes the distribution of thermal energy (thermal process) and is the fundamental solution of the heat conduction equation (or Fourier equation).

It corresponds to the case when:

– heat δ_q instantaneously arrives at a certain point on the surface with coordinates (x', y', z') at time t';

– the temperature (or temperature change) at any other point (x, y, z) at a later time t is calculated.

This expression is the Green's function for the heat conduction equation and allows us to determine the temperature field generated by a point instantaneous heat source.

It uses the following physical parameters of the material: C – heat capacity (specific or volumetric); ρ – density; K – thermal conductivity (thermal conductivity coefficient); α – thermal diffusivity coefficient (or diffusivity).

In a limited body, the temperature change is determined from the following dependence

$$dT\left(x,y,z,t\right)=\frac{\delta q}{\rho C\left(4\pi\alpha\left(t-t`\right)\right)^{3/2}}\times$$
$$\times\exp\left[-\frac{\left(x-x`\right)^2+\left(y-y`\right)^2+\left(z-z`\right)^2}{4\alpha\left(t-t`\right)}\right]\times$$
$$\times\left[\exp\left[-\frac{\left(z+z`\right)^2}{4\alpha\left(t-t`\right)}\right]+\exp\left[-\frac{\left(z-z`\right)^2}{4\alpha\left(t-t`\right)}\right]\right]. \qquad (13)$$

The options for performing laser irradiation of the surface during modeling correspond to Fig. 4. In the first case, the area with horizontally arranged fibers is irradiated, Fig. 4, *a*; in the second, its end part, Fig. 4, *b*.

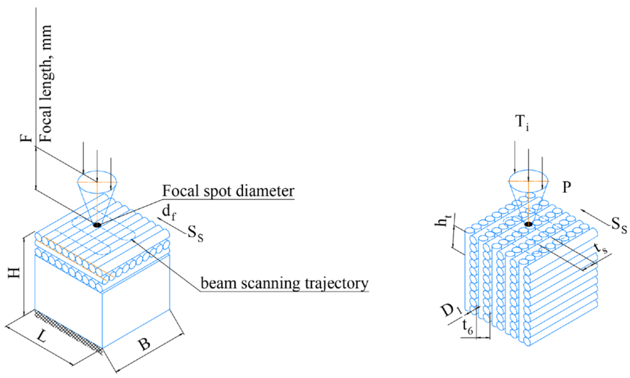


Fig. 4. Scheme of irradiation of the surface area: *a* – in the plane of fiber placement; *b* – when the ends of the workpiece are open

The temperature distribution when a body is irradiated by a circular source (which corresponds to the constriction of caustic in the focal plane) is described as follows:

$$dT\left(X,Y,Z,t\right)=\frac{2Pdt`}{8\rho C\pi\sigma^2\left(\pi\alpha\left(t-t`\right)\right)^{3/2}}\times$$
$$\times\exp\left[-\frac{Z^2}{4\alpha\left(t-t`\right)}\right]\int_{-\sigma}^{\sigma}\exp\left[-\frac{\left(X^2+x`\right)^2}{4\alpha\left(t-t`\right)}\right]dx`\times$$
$$\times\int_{-\sqrt{\sigma^2-x`^2}}^{\sqrt{\sigma^2-x`^2}}\exp\left[-\frac{\left(Y^2+y`\right)^2}{4\alpha\left(t-t`\right)}\right]dy`. \qquad (14)$$

The process of heat conduction in the volume of the workpiece material, which is limited by region Ω, with the surface $\partial\Omega$, according to [25]: scalar temperature field: $T=T(P,t)$, vector heat flux field: $q=q(P,t)$, $P=\{(x,y,z)\}\in\Omega$, scalar field with specific thermal energy: $e=e(T)$.

The boundary conditions on the external surfaces at $\tau>0$ were determined as follows

$$\begin{cases}\Gamma_1:-\lambda\dfrac{\partial t}{\partial n}=q_r;\ \Gamma_2:\dfrac{\partial t}{\partial n}=0;\\ \Gamma_3:-\lambda\dfrac{\partial t}{\partial n}=\alpha\left(t-t_{medium}\right).\end{cases}$$

Conditions at the contact boundary Γ_4 at $\tau>0$:

$$\begin{cases}t\big|_{\partial_4^-}=t\big|_{\partial_4^+},\\ -\lambda_-\dfrac{\partial t}{\partial n}\Big|_{\partial_4^-}=\lambda_+\dfrac{\partial T}{\partial}\Big|_{\partial_4^+},\end{cases}$$

$$\begin{cases}t<t_m-\dfrac{\Delta t}{2},\lambda_1\left(t\right)=\lambda_s;\left[c_p\left(t\right)\rho\left(t\right)\right]_1=c_{ps}\rho_s;\\ t_m-\dfrac{\Delta t}{2}\le t\le t_m+\dfrac{\Delta t}{2},\lambda_1\left(t\right)=\lambda_s+\dfrac{\lambda_m-\lambda_s}{\Delta t}\left(t-t_m+\dfrac{\Delta t}{2}\right);\\ \left[c_p\left(t\right)\rho\left(t\right)\right]_1=c_{ps}\rho_s+\dfrac{c_{pm}\rho_m-c_{ps}\rho_s}{\Delta t}\left(t-t_m+\dfrac{\Delta t}{2}\right)+\dfrac{L_f}{\Delta t};\\ t>t_m+\dfrac{\Delta t}{2},\lambda_1\left(t\right)=\lambda_m;\left[c_p\left(t\right)\rho\left(t\right)\right]_1=c_{pm}\rho_m,\end{cases} \qquad (15)$$

where n is the normal to the surface; q_r is the power density; α is the heat transfer coefficient; Γ_1 is the irradiated surface, Γ_2 is the surface of axial symmetry, Γ_3 is the surface in contact with the external environment, Γ_4 is the contact boundary of the binder and the matrix.

The final temperature is obtained by integrating over time from 0 to t.

The temperature at a point with coordinates (x, y, z), provided that the laser beam moves along the surface with a speed v, and provided that heat losses from the surface are neglected, is defined as

$$\bar{T}=\frac{16}{\sqrt{\pi}}\int_0^{\infty}\frac{1}{\sqrt{\left(c'^2+t'^2\right)\left(b'^2+t'^2\right)}}\exp\left[-\frac{\left(2\bar{x}'^2+\bar{\upsilon}'t'\right)^2}{4\left(\bar{c}'^2+\bar{t}^2\right)}-\frac{\bar{y}^2}{\bar{b}^2+\bar{t}^2}-\frac{\bar{z}^2}{\bar{t}^2}\right]dt, \qquad (16)$$

where $\bar{T}=16\sqrt{\pi KrT}/PA_0$; $\bar{\upsilon}=\upsilon_r/2a$; $\bar{x}'=x/r$; $\bar{y}'=y/r$; $\bar{z}'=z/r$; $\bar{c}'=c/r$; $\bar{b}'=b/r$; $r^2=cb$; A_0 is the reflectivity of the workpiece material; P is the laser radiation power; b, c are the parameters of the laser radiation power density distribution (according to Gauss's law).

The thermomechanical behavior of the material is described by relations: $\varepsilon=\varepsilon^e+\varepsilon^\theta$; $e^\theta=\alpha(\theta-\theta_0)I$; $s=2Ge$, $tr\sigma=3K_v tr(\varepsilon-\varepsilon^\theta)$. Here ε^e and ε^θ are the elastic and thermal components of deformation, s and e are the deviators of the stress and strain tensors; G and K_v are the shear modulus and bulk modulus; tr is the tensor trace; I is the unit tensor.

During simulation with varying the laser energy parameters and the speed of movement along the trajectory, the temperature field was established in the model environment, and under the condition $T_{x,y,z}<T_{cp}$, where T_{cp} is the glass transition temperature of the plastic, the modification depth was determined, which was subsequently compared with experimental data.

4. 4. Determining the depth of chemical modification of the surface layer

The task of processing the workpiece with vapors of volatile active liquids (mainly solvents – ketones) was reduced to determining the conditions for vapor flow around the layered structure of the article under the condition of a small pressure difference.

The presence of the reagent at a particular point on the surface determined the intensity of the reactions that determined the change in the surface state, roughness and conditions for the development of defects (according to (5)). It is assumed that the activity of the reactions is determined by the conditions of the vapors being located over a specific area of the surface and the movement of vapors through the loose structure of the article material.

Due to the formed common electron density, the formation of dense, water- and air-tight articles is ensured, which are isotropic and have equal strength in all directions. The use of steam treatment with a ketone compound – acetone – contributes to the delocalization of the total electron density, the formation of a system of conjugated double bonds due to the ability of the acetone molecule to undergo keto-enol tautomerism

$$CH_3-\underset{\underset{O}{||}}{C}-CH3 \leftrightarrow CH_2=\underset{\underset{OH}{|}}{CH}-CH_3 \quad (17)$$

In this case, the localization of the electron density is disturbed, which describes the distribution of electrons around atoms or molecules, indicating the probability of finding an electron at a certain point in space. It is obvious that the permeability of acetone vapors will directly determine the localization and intensity of the chemical interaction; accordingly, it can be expected that a modified layer will form on the surface, the thickness of which will be determined by the ability of vapors to penetrate deep into the material.

The calculation of flows through the layered structure was performed on the basis of non-stationary three-dimensional Navier-Stokes equations.

The system of equations includes the equation of continuity of flow through a plane, the equation of conservation of momentum, conservation of energy, the equation of transfer of flow disturbances and the concentration of gases (chemical substances)

$$\frac{\partial \rho}{\partial t}+\nabla\left(\rho\vec{v}\right)=S_m, \quad (18)$$

S_m – mass added to the continuous phase (chamber atmosphere) due to the evaporation of ketones

$$\frac{\partial}{\partial}\left(\rho\vec{v}\right)+\nabla\left(\rho\vec{v}\vec{u}\right)=-\nabla p+\nabla\left(\overline{\overline{\tau}}\right)+\rho\vec{g}+\vec{F}, \quad (19)$$

where p is the static pressure in the chamber; $\overline{\overline{\tau}}$ is the stress tensor; $\vec{F}$ is the external force arising from the interaction with the added (penetrated) body (when it is impregnated with ketone vapors); the stress tensor is

$$\overline{\overline{\tau}}=\mu\left(\left(\nabla\vec{v}+\nabla\vec{u}\right)-\frac{2}{3}\nabla\vec{v}l\right), \quad (20)$$

μ – molecular viscosity; l – unit tensor.

The compressibility of the moving flow in front of the obstacle in the form of the workpiece being processed is taken into account as $\frac{\rho_0}{\rho}=\exp\left\{\frac{\int_T^{T_0}\left(c_p/T\right)dT}{R}\right\}$, p_0 – total pressure in the chamber; T_0 – temperature in front of the surface. The energy conservation equation takes the form

$$\frac{\partial}{\partial t}\left\{\rho\left(e+\frac{v^2}{2}\right)\right\}+\nabla\left\{\rho\vec{v}\left(h+\frac{v^2}{2}\right)\right\}=$$
$$=\nabla\left\{k_{ef}\nabla T-\sum_j h_j\vec{J}_J+\tau_{ef}\vec{v}\right\}+S_h, \quad (21)$$

where k_{ef} is the effective thermal conductivity taking into account the mixing of the flow J_l is the diffusion chemical flow.

To determine the contact plane, the conditions for the flow of ketone vapors around article components, a geometric model of a part of this article was built, Fig. 5. This model, which was originally used to analyze the mechanics of carbon-carbon composites [28] under the influence of multiphase flow, was adapted for the problem of predicting impregnation with volatile substances. Taking into account the specific layer thicknesses and the filament laying step (*dx, dy, dz, hz, by*), it was used to analyze the flow conditions during chemical treatment.

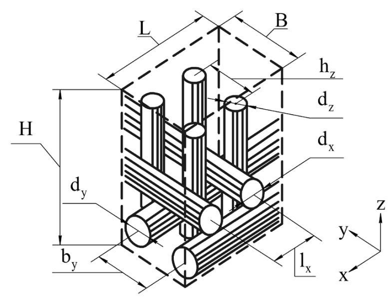


Fig. 5. Structure of the analyzed body

Typically, impregnation is performed in steam baths for a long time τ. The modification condition is the distribution of chemical compounds of a given concentration (up to 50%) deep from open surfaces.

The thickness of the modified layer T_d^h was determined by the conditional impregnation boundary excluding the average roughness value R_a, μm, formed during article laying operations. Since the roughness of the side surfaces and the laying surface is different, T_d^h will be different.

4. 5. Methodology for determining the rational sequence of post-processing

In the process of post-processing, the surface layer is modified to different depths with a simultaneous change in the state of the surface layer.

One of the important results of the modification is the thickness of the modified layer, which is determined by the types of technological influence and depends on the processing modes. From this point of view, it can be assumed that post-processing is aimed not only at improving the geometric accuracy of the part as a whole but also at changing the surface state and forming the modified layer. Then the issue of finding the principles of choosing a process, or their combination, to achieve the required operational properties with minimal material and time costs can be solved on the basis of morphological analysis of options for achieving operational properties, provided that the conditionality of functional properties by individual article characteristics is known.

Let the final operational properties of article (G) be determined by the parameters and structure of the surface layer, the thickness of which (T_d) depends on the selected post-processing methods and its execution modes. Then, having established the regularities of formation during post-processing of stress fields, thermal fields and fields of fluid (vapor) motion on the surfaces and in the structure of the additively manufactured workpiece, we can associate the depth of modification with them and obtain a tool for predicting the initial quality indicators and, accordingly, rationally choose one or another influence from the set of possible ones.

Establishing dependences between input parameters (R) and initial properties (G) through functional transformation by post-processing methods (D_j) will make it possible:

– to identify rational sequences of technological influences (operations);

– to minimize duplication of actions, reducing material and time costs;

– to increase the reliability and predictability of the final article by reducing the number of defects and slowing down their development during operation.

A typical sequence of stages for fabricating articles using additive technologies, including the post-processing provided, is usually implemented in the case when the requirements for the surfaces of the created object are strict, and there are no restrictions on economic feasibility in an acceptable approximation.

Then the post-processing will be aimed at:

– correction of certain geometric defects of the executed dimensions and mutual arrangement of surfaces (p_1);

– formation of surfaces that were not obtained using additive processes (p_2);

– removal of compensating elements, supports, "sacrificial" parts and ballast means (p_3);

– ensuring the required microgeometry of the surface (p_4);

– ensuring the structure of the near-surface layer, its density (p_5);

– removal of residual stresses (p_6);

– ensuring the closedness of the structure of article elements (p_7);

– obtaining a certain anisotropy (in some cases, its reduction to an ortho- or even isotropic state) (p_8);

– ensuring the properties of the surface layer (p_9).

After reproduction, the parts are subjected to mechanical action (cutting or grinding), Fig. 6, *a*, physical-technical treatment, Fig. 6, *b*, or chemical, Fig. 6, *c*.

When machining the workpiece with a milling cutter, Fig. 6, *a*, although the surface layer is removed and the mutual arrangement of the surfaces is ensured, the defects are not eliminated. This is explained by the fact that the material (with a void content of 1.5–5%) perceives mechanical stress during cutting, which can destroy the loose parts of the structure of the printed article, especially if it is not sufficiently dense.

A type of mechanical treatment is grinding, in which the micro cutting process is accompanied by significant heat release; therefore, simultaneously with the manifestation of mechanical stress, the processed body is subjected to significant thermal effects.

Laser scanned heating of the workpiece surface makes it possible to change the state and structure of the surface layer due to intense local heating with the transfer of the heating zone, Fig. 6, *b*, as a result of which it is possible to achieve complete or partial remelting of the surface layer. In this case, the workpiece $L \times B \times H$ is subjected to a high-intensity irradiation spot focused to a diameter d on one face of the workpiece during scanning motion at a speed v. The scanning step t is set based on the condition of overlapping of the tracks that have been subjected to thermal influence. Usually, this way it is possible to eliminate surface defects in the form of delamination, the emergence of threads to the surface, over- or under-extrusion.

Chemical treatment of the workpiece, for example, in a chamber above a bath with a ketone liquid (acetone), makes it possible to obtain a chemical effect on the entire outer surface (for a prismatic body $L \times B \times H$) practically on all six faces, excluding the point of attachment of the workpiece; a type of such treatment consists in applying an adhesive reagent in strips or by immersion; as a result, an adhesive layer with a thickness T_k is formed. This forms a sufficiently dense and closed surface structure (in the form of a film), which, provided that it has high wetting ability, ensures the tightness of the article and its ability to resist the development of microdefects from cyclic loads.

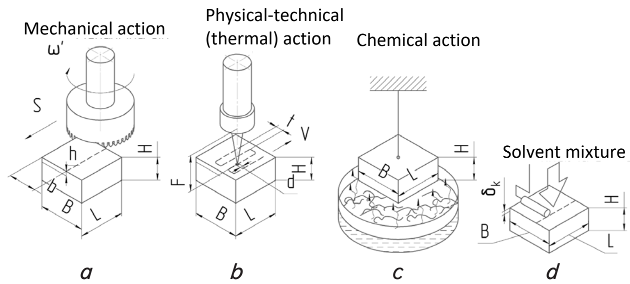


Fig. 6. Post-processing options: *a* — mechanical; *b* — physical-technical; *c* — chemical methods; *d* — application of films (adhesive)

The corresponding post-processing methods are designated as follows: D_m^i – mechanical cutting (D_m^1 – turning, D_m^2 – milling, D_m^3 – drilling, etc.); D_a – abrasive treatment; D_f – physical-technical treatment; D_h – chemical treatment. Then, ensuring the set of properties of the finished article described by array G will correspond to the transformation of the initial parameters of part R by corresponding methods D_j, which have a manifestation through corresponding components P_k

$$R \cap D\left(P_k\right) \rightarrow G. \tag{22}$$

Here, for each D_i, the set of components P_k will be its own, determined by the mechanisms and features of their occurrence during post-processing. For example, D_m^i will be determined as follows

$$D_m^i \subset \left(P_1, P_3, P_4, P_9\right). \tag{23}$$

Other post-processing methods:

$$D_a \subset \left(P_1, P_2, P_3, P_4, P_9\right), \tag{24}$$

$$D_f \subset \left(P_4, P_5, P_6, P_7, P_9\right), \tag{25}$$

$$D_h \subset \left(P_4, P_5, P_7, P_8, P_9\right). \tag{26}$$

From the above expressions it follows that achieving the required article quality (forming initial indicators) is possible by several post-processing methods:

– D_{mi} (mechanical impact) is aimed mainly at correcting the shape;

– D_f and D_h (other types of impact, probably physical and thermal) are aimed at changing the state of surface properties.

Thus, the full range of quality indicators is provided by the condition

$$G \subset \sum_{i=1}^{4} R \cap D_i\left(P_k\right). \tag{27}$$

The thickness of the modified surface layer for different types of impact is denoted as follows: T_d^m – for mechanical cutting; T_d^t – for laser impact; T_d^h – the action of chemical reagents. Then the dependence of values of the initial parameters **G** as certain transformations of input values **R**, will take the form

$$\mathbf{G} = \sum_{i=1}^{4} \mathbf{R} \cap \left(kT_d^m\right)_{D_{(pk)}}, \quad (28)$$

k – proportionality coefficient inherent in a specific technique D_j to achieve properties P_j depending on the thickness of the modified layer T_d.

With different types of processing, thickness T_d is determined by the processing modes (how much this or that effect is "sparing" and local for the structure and material of the article), i.e., the characteristics of D_m^i – mechanical cutting (D_m^1 – turning, D_m^2 – milling, D_m^3 – drilling, etc.); D_a – abrasive processing; D_f – physical-technical processing; D_h – chemical processing. This requires a detailed analysis of the phenomena occurring as a result of the action of post-processing factors.

At the same time, (28) reflects the main principle of choosing a post-processing method: achieving **G** for different options allows us to determine $D_{(pk)}$ as an action or a set of actions, estimated by material P_{mi} or time costs Q_{mi} of forming a certain thickness of the modified layer T_d

$$P_{mi} = f\left(C_m\right); \; W_{mi} = f\left(\tau_m\right). \quad (29)$$

Thus, expression (29) is an optimization criterion for choosing a rational method of post-processing. It makes it possible to quantitatively assess the technological impact from the standpoint of economic feasibility, ensuring the achievement of the required operational properties with minimal material or time costs.

The modeling was carried out in the SOLID Works environment. The results were compared with experimental data.

For full-scale experiments, a number of test articles were manufactured on the CREALITY K1C printer.

During printing, a 0.4 mm nozzle was used, the laying temperature was $T_e = 220$°C, and the layer thickness was 0.12…0.25 mm. This allowed us to obtain a fairly dense structure, which is determined quite accurately (1). The samples were made from Creality PLA and Creality ABS filaments under modes that ensured optimal process performance. For post-processing, desktop equipment with a Procraft CNC was used: a lathe with a Procraft VMM800 CNC; milling and drilling machine Procraft VMM1100; grinding machine Sturmax BGM6055DB.

The tools used had a working edge of P6M5, T15K6; grinding was performed with a wheel with an abrasive – white electro corundum 25A, fractionation 25/50 microns; for chemical treatment, a solvent was used – technical acetone Aceton+ (TM "Khimrezerv", combined with toluene).

The accuracy of the shape was assessed on a coordinate measuring machine MITUTOYO A-1, and the profile characteristics – on a profilometer-profilograph of the SURFCOM series manufactured by ACCRETECH (Japan), the type of HANDISURF.

The assignment of cutting modes (speed of main movement v_r, feed s, cutting depth t_p; speed of sliding of the abrasive on the surface v_a was carried out based on the recommendations from [29], as well as the peculiarities of the behavior of compacted materials on a polymer base [30] so that the modeling conditions were relevant to the conditions of real processing. For abrasive processing, the force effect was combined with the thermal effect. In this case, the duration of abrasive cutting was limited by an increase in the surface temperature to $T_p = 120$°C, which for the analyzed plastics slightly exceeds the glass transition temperature.

Experimental variants of mechanical processing included:

– turning (through-thrust cutter T15K6) at 570 rpm, feed 0.14 mm/rev, cutting depth 0.2 mm;

– milling (end mill, 4 inserts T15K6) at 71 mm/min feed, 800 rpm, cutting depth 0.2 mm;

– drilling (drill bit $D = 8.0$ mm P6M5) at 570 rpm and feed rate 5 mm/s;

– grinding (white electro corundum 25A, wheel diameter 250 mm) at a rotation speed of 3000 rpm and feed rate 30 mm/s.

The processing was performed with a cutting tool with pointed wedge angles $\gamma = 5…12°$, $\alpha = 10…15°$, $\varphi = 30…45°$, ensuring the minimum possible temperature in the zone of formation of new interface surfaces. Cutting modes were assigned according to recommendations, similar to the processing of polymeric materials, including layered polymeric composites, with a limitation of the force effect and taking into account a certain anisotropy of properties.

Laser scanning (spot speed and track overlap) was performed based on recommendations from [31].

The depth of modification of surface layers was determined based on microelectronic examination of sections of test samples made on the "Microtome MR 3000".

After post-processing, the obtained articles were subjected to metrological analysis and surface roughness was determined by parameters *Rz, Ra*, μm. For a comprehensive assessment of the modification, a contact profilometer with a typical accuracy of up to 0.01 μm was used. Separately, the presence of defects on the controlled surfaces, as well as the condition of the bonding layers, was determined using a REM-105-I electron microscope.

5. Results of determining the parameters of roughness and thickness of the modified layer and development of the principle of selection of post-processing options

5. 1. Determining the level of surface roughness and thickness of modification of surface layers during cutting and micro cutting of added parts

When modeling, the mechanical effect was created in the form of a contact problem of the interaction of a wedge-shaped absolutely rigid body (indenter) with a deformable loose medium, the characteristic dimensions of which in the main axes many times exceed the size of the contact zone, Fig. 3. This gave grounds to consider the workpiece as half-space, which simplifies the statement of the contact problem. The rigid indenter – the cutting wedge – was made with angles $\gamma = 10°$, $\alpha = 15°$, $\varphi = 45°$ and had a radius at the apex of 0.2 mm. The main movement was carried out along and across the fibers, the cutting forces were determined by known ratios and were: $P_z = 38.5$ H, $P_y = 14.8$ H, $P_x = 8.5$ H. The material properties were obtained from the software environment libraries and are given in Table 1.

The key assumptions in the modeling were as follows:

– the workpiece has a regular structure of symmetrically arranged fibers, the structure of the workpiece corresponds to Fig. 5, the average fiber diameter $d_{v=} 0.35…0.4$ mm;

– the strength of the joints corresponds to the permissible stresses for this material taking into account the attenuation coefficient $\sigma_{ij} \geq [\sigma] / k$;

– all sections of the joints have the same strength, and there are no internal defects.

Table 1

Basic physical and mechanical properties of PLA and ABS materials (according to [29])

Parameter	PLA	ABS
Melting point T_{pl}, °C	173–178	220–260
Softening temperature T_r, °C	50	80–108
Hardness (according to Rockwell)	R70–R90	R90–R116
Relative elongation at break δ, %	3.8	5–7
Bending strength σ_i, MPa	55.3	75
Tensile strength σ_n, MPa	57.8	55
Modulus of elasticity under tensile stress, E_x, GPa	3.3	2.5
Modulus of elasticity at bending E_m, GPa	2.3	3.0
Glass transition temperature T_{cp}, °C	60–65	95–110
Density ρ, g/cm^3	1.23–1.25	1.02–1.06

The conditions for fixing the workpiece and applying force during mechanical impact corresponded to the location on a rigid base, with full fixation in the plane of the table and in the vertical coordinate.

The results of modeling the stages of the development of the cutting groove during mechanical impact are illustrated in Fig. 7, *a* (force load of the wedge across the fibers) and Fig. 7, *b* (force load of the wedge along the fibers).

From the above illustrations, it was established that the stress fields that determine the modification of the surface layer cover a depth of up to 4 layers when cutting along the fibers, and up to 5 layers when cutting across them. For this problem statement, the stress state changes at a depth of up to 1.3...1.5 mm. However, the condition $\sigma_{ij} \geq [\sigma]/k$ is satisfied exclusively within one fiber, which is located directly at the point of action of the cutter tip. Therefore, $T_d^m \approx d_v$.

According to the constructed envelope and taking into account the recommendations from [32], the roughness parameter was also calculated, which for the adopted modeling conditions is $Rz = 20...40$ μm.

During the modeling of mechanical interaction, it was noted that cutting satisfactorily removes the surface layer, forming a new surface of a certain roughness, on which there are no defects. However, new defects in the form of cavities, delamination and chipping may appear during the cutting process.

The differences in the interaction mechanism when removing the top layer are significant since they are due to the anisotropy of article properties that occurs during the layer-by-layer deposition process. The simulation results clearly show that the stress fields that determine the modification of the surface layer cover different depths depending on the cutting orientation relative to the fibers: up to 2 layers when cutting along the fibers and up to 3 layers when cutting across the fibers. This confirms that the mechanism of interaction of the cutting wedge is different for different directions of processing the top layer.

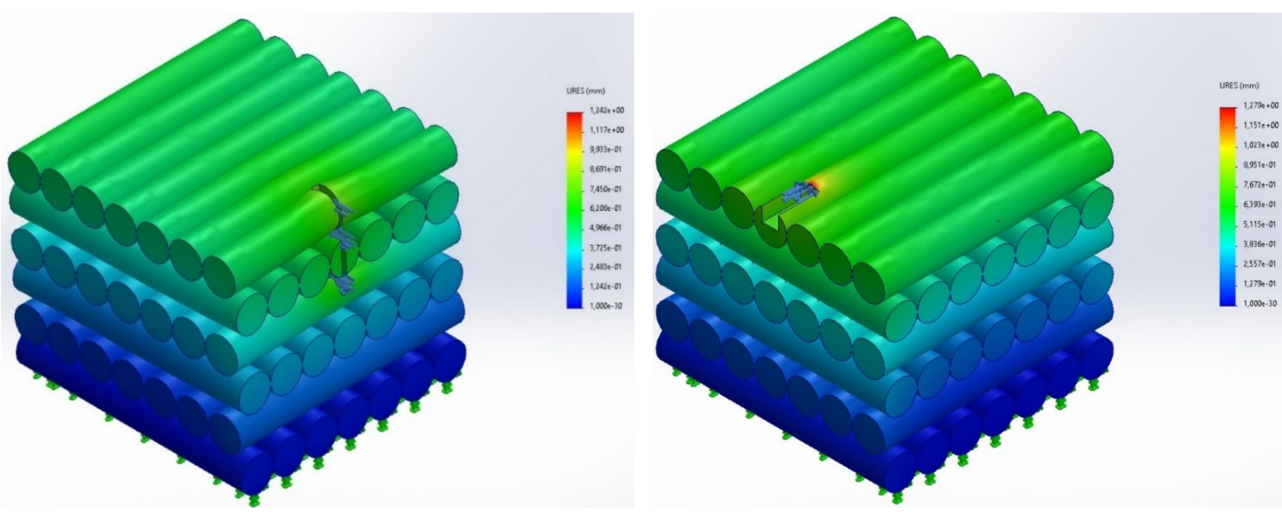
The articles turned out to be quite sensitive to the accuracy of the cutting mode assignment. Thus, it was established that when turning with an increase in the cutting speed $v_r > 45$ m/min with a removal thickness of more than $t_p = 1.0...1.5$ mm and a feed $s = 0.5...0.6$ mm/rev, an increase in stresses is observed on the interturn and interlayer planes, which increase to $\sigma = 32....48$ MPa; such stresses are already comparable to the tensile strength at these points, $[\sigma]$, so we can expect a violation of the density of the finished article and a sharp increase in the thick ness of the destruction.

Reducing the removal thickness to $t_p = 0.3...0.7$ mm helps reduce this factor. In addition, cutting with a smaller thickness, as well as with a smaller feed (less than $s = 0.15...0.2$ mm) leads to an improvement in the quality of the workpiece and a decrease in the thickness of the surface layer, which can be destroyed.

It was found that for rigid articles with linear dimensions of 50...150 mm, the shape errors for PLA plastic do not exceed 0.5...0.9 mm; for ABS, such errors are already 1.2...1.8 mm and manifest themselves in delamination, swelling, etc.; for less rigid articles, the shape errors can reach 1.5...2.5 mm.

The use of sharply sharpened tools makes it possible to obtain a fairly high-quality surface layer on PLA material: $R_a = 3.0...3.6$ μm, $R_z = 20...40$ μm when turning, milling, and drilling; on ABS materials, respectively, $R_a = 1.2...1.6$ μm, $R_z = 5...8$ μm; cutting speed – 35...50 m/min.

The obtained indicators were in good agreement with the predicted ones calculated based on mathematical modeling.



a *b*

Fig. 7. Post-processing modeling:
a — force load from the cutting wedge across the fibers; *b* — the same for the case of action along the fibers

Grinding (as a mechanical effect with the simultaneous action of a heat source in the form of a surface heated by contact) proves that thermal phenomena prevail under traditional processing modes: micro cutting begins to be accompanied by softening or complete melting of the area adjacent to the processing zone, the temperature can reach 220..310°C. Sometimes during grinding, active gas evolution is observed, and the action of micro cutting forces leads to the appearance of zones of plastic deformation, similar to zones of burning during metal processing. When grinding at a speed of v_a up to 25 m/s (briefly), the surface roughness R_a was 1.2...2.5 µm.

Therefore, it can be stated that to increase the accuracy of predicting the parameters of the surface microgeometry, both the phenomena of the probable formation of new defects and the limitations associated with the tool used should be taken into account. The issue is particularly relevant for the processing of materials by grinding, which generally corresponds to the results obtained when grinding compact materials [30].

Thus, taking into account thermal phenomena during mechanical processing will improve the adequacy of the results.

Typical dependences of change in the modified layer during blade processing when changing the cutting speed are shown in Fig. 8.

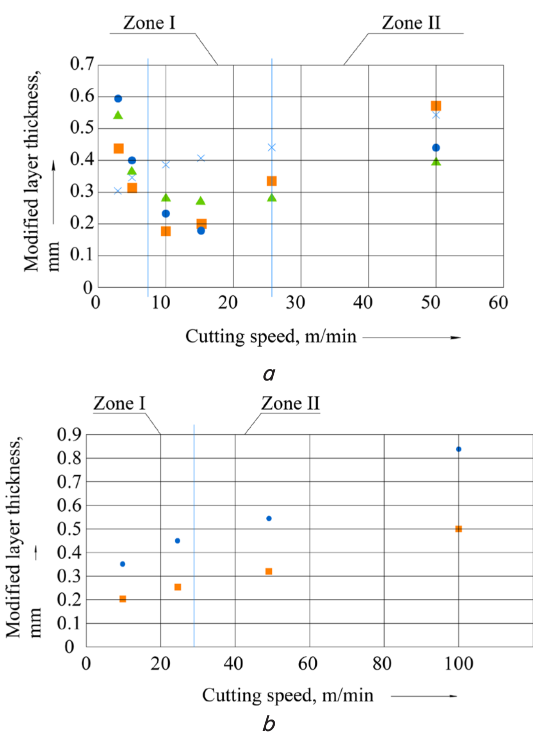


Fig. 8. Change in the thickness of the modified layer during mechanical processing: *a* — during cutting (turning, milling, drilling), *b* — during grinding; ■ — calculated value; ● — experimental results; ▲ — experimental results (drilling); ✱ — experimental results (turning)

The above illustration proves that there is a clearly defined zone I, where the thickness of the modified layer (i.e., taking into account the removed allowance) remains insignificant. In zone II, the layer increases.

5. 2. Determining the thermal effect of laser on the thickness of the modified layer

The thickness of the modification (change) of the surface layer for laser exposure was also used as a generalized characteristic. Modeling the action of a laser radiation pulse on the surface and the spread of heat into the workpiece are shown in Fig. 9, *a*, *b*, respectively.

The emphasis in modeling laser processing was on thermal phenomena. Thermal phenomena in the test prismatic body, determined from (16) to (22), were analyzed based on modeling the action of laser radiation pulses on the upper surface: the spread of heat into the workpiece with its heating to temperature T_i, which exceeds the glass transition temperature T_c, was estimated.

The parameters used for laser processing were as follows:
– power: up to 400 W (max.), specific energy – 5...80 J/mm^2;
– caustic drawdown: 0.12 mm;
– modes: scanning at a speed of 800 mm/s with track overlap of up to 25%.

In the context of laser post-processing, the workpiece is almost always rigidly fixed on the table (or substrate) to ensure the accuracy of the laser trajectory. Therefore, in the thermal problem, it is most appropriate to consider the boundary condition of the first kind since these models were used to estimate heat penetration into relatively simple workpieces of significant linear dimensions.

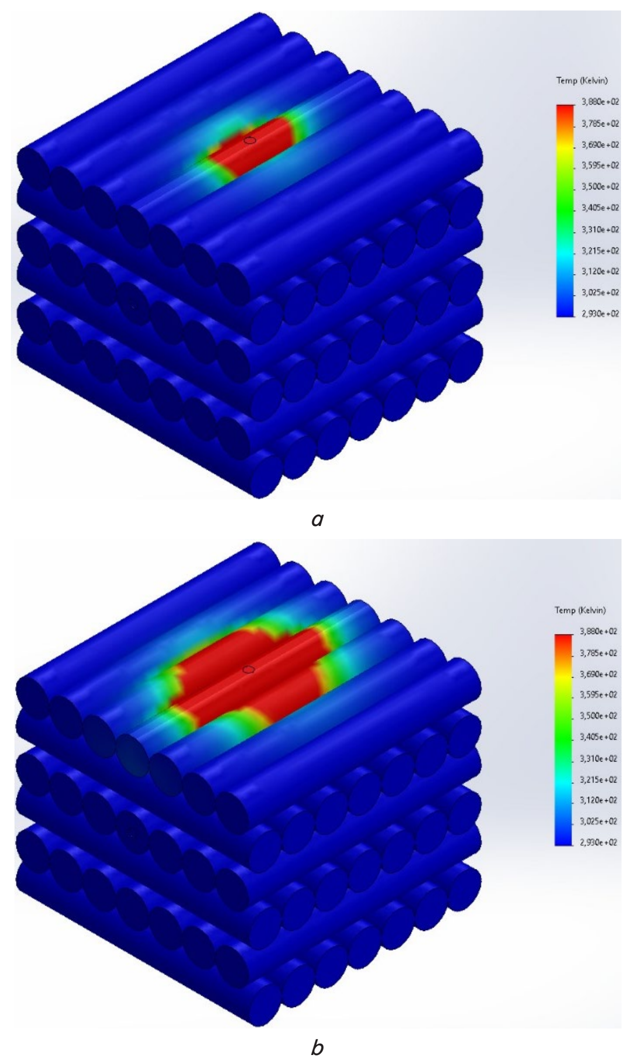


Fig. 9. Effect of a laser pulse: *a* — on the surface; *b* — heat spread into the workpiece

Modeling of thermal effects for the action of a pulsed laser has shown that heating occurs unevenly, with the predominant spread of heat along the irradiated fibers, and in 0.5 s it can cover strips up to 5...8 fibers wide (up to 3.5 mm relative to the focus point); however, the temperature of transformations is localized mainly in the surface layers within 1...2 fibers. Therefore, the modification of the surface layer will occur to a depth of mm.

During the experiments, laser processing allowed us to achieve roughness indicators $Ra = 0.5...1.0$ μm.

Experiments under the conditions specified above showed that laser exposure makes it possible to obtain a minimum thickness of the modified layer at the level of 0.2...0.5 mm; an increase in specific energy of more than 80 J/mm^2 with a simultaneous decrease in speed to 0.5 m/s leads to melt-through and damage to the article.

The geometric accuracy of the dimensions and mutual arrangement of the surfaces for thermal and chemical effects remains without significant changes, in contrast to mechanical processing, when a certain layer of material is removed from the surface of the material.

The dependence of thickness of the modified layer on the conditions of laser scanning is shown in Fig. 10. In two zones, the growth of the modification depth was close to linear at a specific energy limit of 80 J/mm^2.

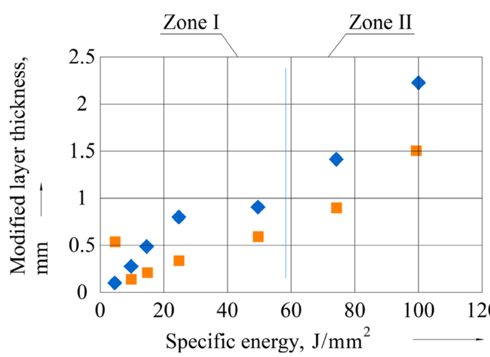


Fig. 10. Dependence of thickness of the modification of surface layers on the specific laser energy: ◆ — calculated value; ■ — experimental results

The presence of two zones of modified layer thickness values T_d^t is obvious. However, going beyond zone II can lead to a sharp deterioration in surface quality, the appearance of melt-throughs and burn-outs.

5. 3. Determining the depth of surface modification by ketone solvent vapors

For chemical reagents, the thickness of the modification (change) of the surface layer was also chosen as a generalized characteristic.

Chemical treatment was investigated based on the analysis of the flow around the test body by vapors of a substance (ketone solvent). The flow around the fibers by vapors is illustrated in Fig. 11. In this case, it was assumed that the workpiece material is leaky and allows the penetration of gases, vapors, or liquids of volatile substances in the interfiber and interlayer gaps.

Unlike previous approaches, two workpiece models were analyzed:

1) a regular structure with uniform contact of all strands of the laid filament;

2) a model that had gaps between rows and layers measuring 0.05 × 0.25 mm. These gaps simulated the permeation of volatile vapors through the extruded layer, which is typical for conventional filament printing.

In the general case, the workpiece has an approximately constant voidness, with some changes in the outer layers.

The parameters used for chemical treatment were as follows:

– solvent: technical acetone Acetone+(toluene) (TM "Khimrezerv");

– temperature of the liquid in the bath: 30°C;

– holding time: 60 min;

– movement of acetone vapors is free, from the evaporation surface.

Since the assessment of the change in the state of the surface, in particular, the roughness parameters R_a, R_z during chemical interaction from the point of view of mass transfer was not performed, only the depth of impregnation of the layers was established, based on the condition that a concentration of 50% of the substance is capable of causing chemical transformations. According to the modeling conditions, the thickness of the modified layer was 1..2 threads, i.e., $T_d^h = 0.5...0.9$ mm.

Experimental verification of the results of chemical treatment with ketone vapors requires keeping the article above the bath for more than 60 min; while it is 0.3...1.1 mm and is determined by the temperature of saturated vapor, the diffusion rate, which depends on the density of the workpiece. Over time, due to the formation of a modified film on the surface, the diffusion process is significantly reduced.

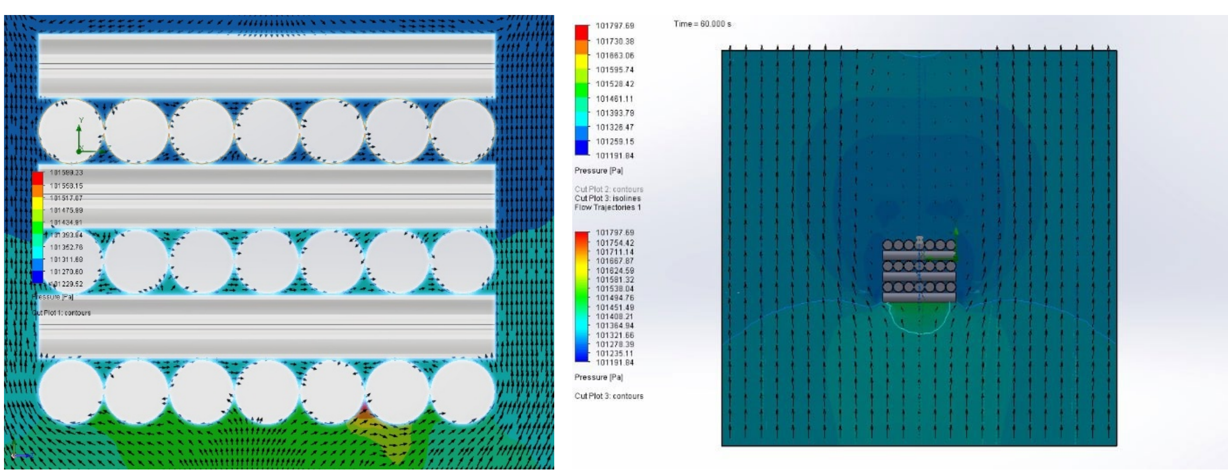


Fig. 11. Vapor flow: *a* — fibers; *b* — workpiece as a whole

The dependence of thickness of the modified layer on the duration of treatment is shown in Fig. 12.

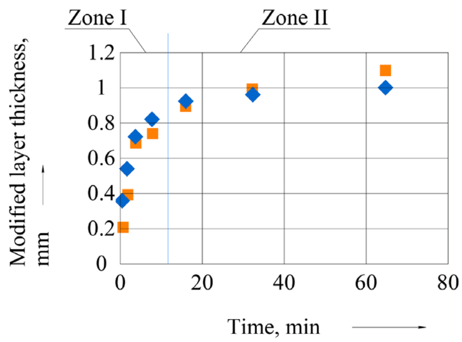


Fig. 12. Change in the thickness of the modified layer over time: ■ – calculated value; ◆ – experimental results

The illustration shows that an active increase in the depth of modification is observed in zone I, while when moving to zone II, a slowdown in this parameter is observed, with a cessation after exposure in a steam bath for more than 1 hour.

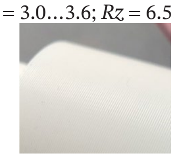
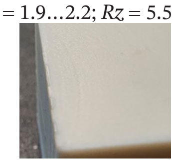
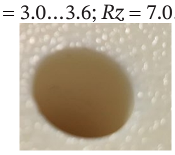
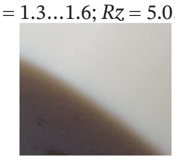
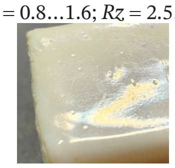
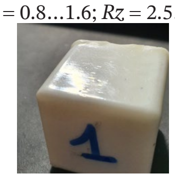
5. 4. The principle of choosing the type of post-processing based on the conditionality of mechanical properties by the thickness of the m odified layer

Test parts in the form of cylindrical and prismatic bodies were subjected to post-processing, and then strength tests were performed. The surface quality under certain cutting modes is given in Table 2. After performing mechanical tests to determine the tensile strength and endurance limit, the corresponding curves were constructed, shown in Fig. 13.

The thickness of the modification layer T_d under different types of processing is determined by the processing modes (how much this or that effect is "sparing" and local for the structure and material of the article), i.e., the characteristics of D_m^i – mechanical cutting (D_m^1 – turning, D_m^2 – milling, D_m^3 – drilling, etc.); D_a – abrasive processing; D_f – physical-technical processing; D_h – chemical processing. The relationship between the mechanical characteristics of the article, in particular, the ultimate strength σ_b and the fatigue strength σ_m is shown in Fig. 13. In the case of mechanical processing of test blanks, the change in these characteristics has the character shown in Fig. 13, *a*, changes from the action of the laser – in Fig. 13, *b*, and during chemical processing (etching) – Fig. 13, *c*.

Table 2

Surface quality with different post-processing options for additive articles made of PLA and ABS

Process	Tool used	Cutting modes	Surface photo and roughness parameters, microns
Turning	Through-hole cutter T15K6	Speed 570 rpm, feed 0.14 mm/rev, cutting depth 0.2 mm	Ra = 3.0…3.6; Rz = 6.5…7.5 
Milling	End mill, 4 mechanical clamping plates, T15K6	Feed 71 mm/min, 800 rpm milling modes, cutting depth 0.2 mm	Ra = 1.9…2.2; Rz = 5.5…6.0 
Drilling	Drill D = 8.0 mm P6M5	570 rpm, feed 5 mm/s	Ra = 3.0…3.6; Rz = 7.0…7.5 
Grinding	White electro corundum 25A, circle diameter 250 mm	Rotational speed 3000 min^{-1}, feed 30 mm/s	Ra = 1.3…1.6; Rz = 5.0…5.5 
Laser processing	Power – 400 W (max), wavelength 1062 nm, caustic drag 0.12 mm, power and pulse energy adjustable	Scanning at 800 mm/s, track overlap up to 25%	Ra = 0.8…1.6; Rz = 2.5…10 
Chemical treatment	Solvent – technical acetone Acetone + (toluene) (TM "Khimrezerv")	The temperature of the liquid in the bath is 30°C, the holding time is 60 minutes	Ra = 0.8…1.6; Rz = 2.5…10 

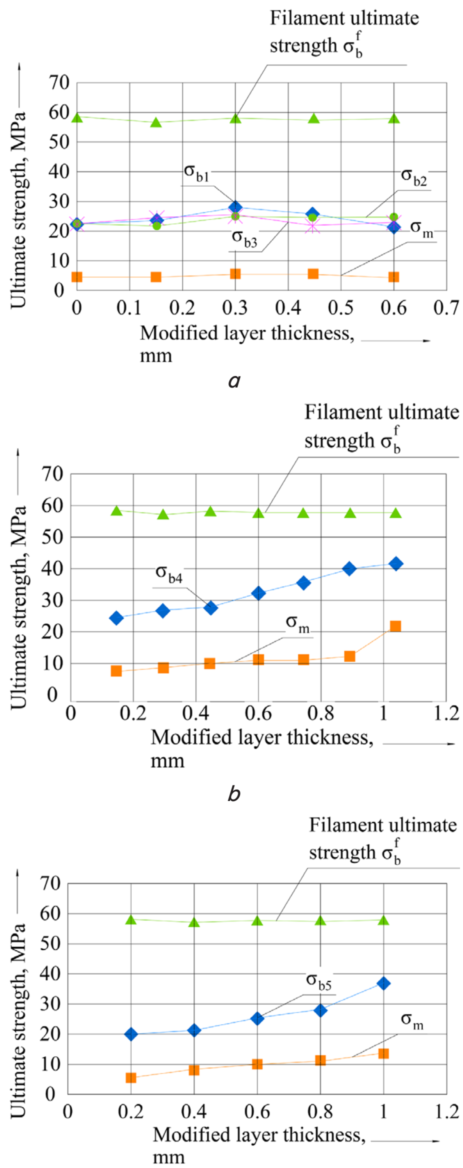


Fig. 13. Dependence of ultimate strength σ_{b1} and fatigue strength σ_m on the thickness of the modified layer formed by different post-processing methods: *a* – during mechanical processing (cutting and grinding); *b* – for the case of laser modification; *c* – during chemical modification; σ_{b1} – ultimate strength of samples after milling, MPa; σ_{b2} – respectively after turning; σ_{b3} – after drilling; σ_{b4} – for polished samples; σ_{b5} – laser modified; σ_{b6} – chemically modified

From the given diagrams it is obvious that T_d correlates with the physical and mechanical properties of the article; usually an increase in the thickness of the modified layer leads to a certain increase in the ultimate strength and long-term strength of the article, i.e.

$$[\sigma_b] = C_m\sigma_a + k_s T_d,\ \sigma_m = C_{mm}\sigma_a + k_d T_d. \quad (30)$$

Here, C_m – coefficients of difference (reduction) of the filament strength from the strength of the finished article, $C_m = 0.35...0.48$; C_{mn} – coefficients of difference (reduction) of the filament strength from the strength of the finished article, $C_{mn} = 0.12...0.15$, k_s – coefficient of influence of post-processing; depends on the type, modes, structure of the processed body.

Therefore, the thickness of the modified layer T_d is a parameter that affects the controlled values of the ultimate strength σ_{b1} and fatigue strength σ_m (30). Together with the achievable R_a levels, µm, R_z, µm, which are determined by the processing modes, this parameter determines the operational properties of the article as a whole. Since the task of finding rational post-processing methods is reduced to an enumeration of options for forming a modified layer by various methods, in accordance with (24) to (26), taking into account the results given in Table 2, it becomes possible, according to a certain criterion, for example, (29), to establish an appropriate sequence of technological actions for each surface or group of surfaces.

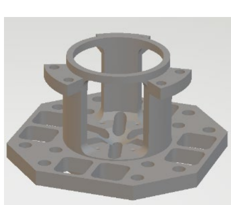
The selection of post-processing options for a fairly complicated part with numerous support elements, mating surfaces, holes, etc. is illustrated in Table 3, the general appearance of the part is given in column 3. The set of processing options as a function of the transformation of the properties P_k (column 4) formed during the FDM process into functional properties ΣP_k (column 6) allows for a comparison of options, in particular, according to (29).

It becomes obvious that the set of functional properties ΣP_k can be achieved by different options of influences; in the absence of time constraints, the surfaces of the article can be grouped according to common or similar requirements, the processing is assigned according to the approach of group technological processes.

Therefore, based on the functional dependence of the operational properties of the added article on the post-processing conditions, which, in turn, determine the thickness of the modified surface layer, it can be noted: the principle of choosing post-processing from the set of options is that the influence option is determined by the thickness of the modified layer, which, on the one hand, provides an improvement in the mechanical properties of the article as a whole, and on the other hand, provides the requirements for the roughness and mutual arrangement of the surfaces. Additionally, such influence is minimized in terms of material or time costs.

Table 3

Shaping article properties with various post-processing options

Types of post-processing	Post-processing method		Article and its surfaces	Properties that are forming P_k	Sequence options	Functional properties ΣP_k
	1	D_m^1		P_1, P_3, P_4, P_9	$D_m^1, D_{m2}, D_m^3, D_h$	$P_1, P_3, P_4, P_5, P_7, P_8, P_9$
	2	D_{m2}		P_1, P_3, P_4, P_9		
	3	D_m^3		P_1, P_3, P_4, P_9	$D_m^1, D_{m2}, D_m^3, D_f$	$P_1, P_3, P_4, P_5, P_6, P_7, P_9$
	4	D_a		P_1, P_2, P_3, P_4, P_9		
	5	D_f		P_4, P_5, P_6, P_7, P_9	D_a, D_h	$P_1, P_2, P_3, P_4, P_5, P_7, P_9$
	6	D_h		P_4, P_5, P_7, P_8, P_9		

Let the requirements for the part in Table 3 be as follows: the part is made of ABS plastic, the accuracy of the dimensions is ± IT14/2, except for the ring landing hole (for which the D dimension is performed with a tolerance of H8), $R_a = 1.6...2.5$ µm, the obtained strength is not worse than $\sigma_b > 30$ MPa. The most appropriate option for post-processing was option 6, Table 3, since it enables through P_4, P_5, P_7–P_9 to form on surface P_1–P_5, P_7, P_9 in just two operations: D_a and D_h. In this case, the requirements are met due to the sequence of operations with obtaining the properties to Fig. 8, 13. This is due to the fact that grinding (as abrasive treatment) does not provide σ_b, which chemical treatment improves after 40 min of exposure in an acetone vapor bath, Fig. 13, *c*. The high-precision inner hole of the ring is machined, i.e., according to the D_m^1, D_h sequence.

6. Investigating the dependence of operational properties on the thickness of the modified surface layer: results and summary

The modified layer formed during mechanical processing not only removes surface defects and creates conditions for improving the roughness parameters, in particular, R_a, but also forms certain residual tensile stresses, which, on the contrary, worsen the resistance to mechanical stress. However, mechanical processing removes a certain layer of material, i.e., the modified layer is formed already under the new interface. And in this case, the stresses determined in the body by (1) to (6) will change the structure in a certain way if the surface layer was sufficiently developed at the stage of filament laying, i.e., it had a significant number of surface defects. On the other hand, the disappearance of defects from the surface of the workpiece leads to a decrease in stress concentrators and, as a result, to a slight improvement in the ultimate strength σ_{b1} and fatigue strength σ_m.

It is the action of heat that can explain the difference in the dependences of Fig. 8, *a, b*, constructed for blade cutting and abrasive cutting, respectively. In the first case, the cutting wedge acts locally, and the temperature at low speeds practically does not cause softening of the plastic and changes in the structure. In the second case, thermal phenomena already have a rather strong effect on the surface of the workpiece, as a result, significant transformations of the surface layer and a certain increase in mechanical properties, Fig. 11, *a*.

The multidirectionality of the effects of the factors of thermal force loading of the surface during mechanical processing explains that the dependence of the tensile strength σ_{b1} and fatigue strength σ_m in the function T_{dm} has a certain extremum, Fig. 13, *a*, characteristic of the most unstable operation – face milling. Other operations (turning, drilling), although they have a significant impact on the formation of the modified layer, however, its connection with the improvement of the tensile strength σ_b and the endurance limit σ_m has a pronounced nonlinear nature and should be studied additionally. At the same time, such processing ensures compliance with high requirements for the quality of the surface layer (in particular, surface roughness) and the accuracy of the performed and related dimensions.

The thickness of the modified layer (T_{dm}) depends on the processing method: for mechanical cutting with recommended feeds and cutting depth (not exceeding 10% of T_{dm}), T_{dm} is within 0.15–0.65 mm. A smaller value (0.15 mm) is observed under conditions where there is no overheating of the plastic. For grinding, this indicator is 0.1–0.25 mm. In the case when the processing is carried out with increased power (speed and removal thickness), this leads to active heating of the processed surface and its melting with a number of negative consequences.

Laser processing enables melting the surface layer with the formation of a high-quality surface with $R_a = 0.63...1.25$ µm (specific energy – up to 80 J/mm^2, speed 0.6...1.5 m/s, to a depth of up to 0.1...0.5 mm). The thickness of the layer formed in this way is about $T_d = 0.75...1.2$ mm. However, there is a danger of surface melting, as can be seen in Fig. 13, *b*.

At the same time, different materials react differently to surface heating; some are prone to sublimation (for example, PET, PLA), which also requires restrictions on the results of our studies.

Chemical treatment improved the surface condition since the formation of the ABS-acetone complex is influenced by the formation of an adsorption layer on the ABS surface when ketone compound vapors pass under a laminar-turbulent mode. This results in an effect similar to coating at the moment of contact of the ABS surface with acetone molecules, taking into account its ability to keto-enol tautomerism. The process of formation of the adsorption layer consists of two main stages. First, the migration of acetone molecules to the solid surface of ABS plastic and their orientation occurs. Polar groups of acetone (–C=O or –C(OH)) are directed towards the polar groups of ABS. This causes a redistribution of the electron density of ABS, which leads to the formation of a partial positive charge (‘$\delta+$’) at the ends of the molecule and a negative charge (‘$\delta-$’) on the benzene ring. Secondly, an adsorption equilibrium is established at a distance where molecular forces begin to act.

Here we should also talk about the formation of a dependence: the high polarity of the acetone molecule contributes to a high adsorption strength, which contributes to the alignment of polymer defects to the level of a smooth surface.

When impregnating the workpiece with an adhesive solution, diffusion is determined by the development of the article surface, therefore it is usually 0.2...0.35 mm; less often, when using pre-compression means (for example, vacuumizers) T_d^h increases to 0.5...0.75 mm, Fig. 13, *c*.

A set of studies on the formation of a modified layer and surface under the influence of mechanical, thermal (laser), and chemical influences confirmed the hypothesis put forward as it was established that the thickness of the modified layer T_d correlates with the physical and mechanical properties of the article: for thermal and chemical methods, an increase in T_d leads to an increase in the tensile strength σ_b and the endurance limit σ_m, for mechanical processing this dependence is nonlinear and, as a rule, inverse: the larger the modified layer (i.e., the one that has undergone changes), the worse the strength parameters. Therefore, the thickness of the modified layer for a specific post-processing method can be chosen as a parameter that determines the final properties of the finished article.

In the illustrations given in Fig. 8–10, it is possible to distinguish zones in which the influence of the modified layer is statistically significant. In zone I, although changes in the thickness of the modified layer are significant, they have a limited impact on the mechanical properties (at the level of 10...15%), that is, at the level of error and inaccuracy of modeling and measurements. In zone II, such an impact is already significant and can be described by functional laws.

Comparison of the results of model studies of mechanical and thermal effects with the results of measurements of the levels of roughness and thickness of the modified layer T_d, obtained as a result of experiments, shows that the difference in the controlled parameters was generally within 15...25%, which for this multifaceted problem with certain simplifications and assumptions is a reasonably high level of adequacy.

The results of research into the phenomena of formation of a modified layer and assessment of its thickness along with the parameters of surface microgeometry and the formulated principle of choosing appropriate post-processing effects make it possible to reduce the time of technological preparation of production, to improve the quality of articles, their stability during operation.

The limitations of our studies are that attention was focused on the two most common plastics: PLA and ABS. However, recently a large number of modifications of these basic plastics have been released on the market, in particular, Hyper PLA, PLA-CF, ABS-Carbon. That is why, despite the preservation of general trends, the use of these materials requires a certain adjustment of the results, in particular, the connection of the thickness of the modified layer with mechanical properties. As a rule, the introduction of additional components or reinforcing elements leads to a redistribution of defect locations, changes in the places of connections, and such changes can have a multidirectional effect.

The disadvantage of these studies is that the reasoning was based on the assumption that the processed body was represented in the form of prismatic blanks, and strength studies were performed on standard samples of the "bone" type, the geometric dimensions of the cross-section of which differed from the model prisms. At the same time, real articles have a more complicated spatial shape.

Further research should be aimed at establishing regularities in the formation of a modified layer for other widely used plastics – PET, PETG, PLA-CF, NYLON, etc. their rheological properties, at clarifying the mechanisms of transformations of the surface layer, which is located at a greater depth from the surface. High-temperature plastics require special attention: PEEK, ULTEM. At the same time, it is planned to link the critical sections of the blanks from the point of view of loads with the sections of the experimentally studied samples; this will make it possible to take into account the influence of the cross-sectional area on indicators σ_{b1} and σ_m and obtain functional dependences on T_d and, for example, the density of the plastic layer.

7. Conclusions

1. The regularities of changes in surface parameters and modification of surface layers by mechanical action (cutting or micro cutting) have been established. It is shown that mechanical post-processing is mainly aimed at improving the shape and ensuring the geometric dimensions of the article as a whole; sometimes, due to cutting, it is also possible to reduce high residual stresses in the surface layer, but this phenomenon is not of a prevailing nature. The methods and techniques of mechanical processing are similar to the processing of polymeric materials, including layered polymeric composites, with a limitation of the force effect and taking into account a certain anisotropy of properties. It is recommended to perform the processing with a cutting tool with pointed wedge angles $\gamma = 5...12°$, $\alpha = 10...15°$, $\varphi = 30...45°$, ensuring the minimum possible temperature in the zone of formation of new interface surfaces. Mechanical post-processing makes it possible to obtain a sufficiently high-quality surface layer and ensures high accuracy of the performed dimensions and the mutual arrangement of the surfaces.

2. Thermal post-treatment with a laser makes it possible to obtain a minimum thickness of the modified layer T_d^t at the level of 0.2...0.5 mm; an increase in the specific energy of more than 90 J/mm^2 with a simultaneous decrease in speed to 0.5 m/s leads to melt-through and damage to the article. At the same time, the geometric accuracy of the dimensions and the mutual arrangement of the surfaces remains practically unchanged.

3. Chemical treatment with ketone vapors requires the article to be kept above the bath for more than 60 min; at the same time, T_d^h is 0.3...1.1 mm and is determined by the temperature of the saturated vapor, the diffusion rate, which depends on the density of the workpiece. Over time, due to the formation of a modified film on the surface, the diffusion process is significantly reduced. When impregnating the workpiece with an adhesive solution, diffusion is determined by the development of the article surface, therefore T_d^h is usually 0.2...0.35 mm; less often, when using pre-compression devices (for example, vacuumizers) T_d^h increases to 0.5...0.75 mm. The geometric accuracy of the dimensions and mutual arrangement of the surfaces also remains unchanged.

4. The principle of choosing post-processing options has been proposed, which is based on setting the required thickness of the modified layer (T_{dm}) to achieve the required set of operational properties with minimal material or time costs. It is shown that the thickness of the modification (change) of the surface layer is a parameter that will determine the set of initial properties of the finished article, since changes that usually occur in the surface layer lead to a decrease in the number of defects or contribute to a decrease in the intensity of damage to the article during operation. Changing the thickness of the modified layer under thermal (laser) and chemical influences leads to an increase in the tensile strength σ_b and the endurance limit σ_m by an average of 35–60%, the effect of mechanical processing on the formed thickness of the modified layer is nonlinear and is caused by temperature phenomena (softening of plastic at temperatures above 80...110°C.

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

The data will be provided upon reasonable request.

Use of artificial intelligence

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

Authors' contributions

Oleksandr Salenko: conceptualization, methodology; **Vadym Orel**: conceptualization, methodology; **Walid Alnusirat**: formal analysis, software, preparation of the initial project; **Swook Hann**: formal analysis, software, research, visualization; **Tatyana Kozlovskaya**: formal analysis, software, research; **Anton Kostenko**: formal analysis, software, research; **Daniil Tsurkan**: formal analysis, research; **Petro Melnychuk**: formal analysis, research, data processing and analysis; **Yana Kovalenko**: formal analysis, research.

References

1. Chen, M. Y., Skewes, J., Woodruff, M. A., Dasgupta, P., Rukin, N. J. (2020). Multi-colour extrusion fused deposition modelling: a low-cost 3D printing method for anatomical prostate cancer models. Scientific Reports, 10 (1). https://doi.org/10.1038/s41598-020-67082-7
2. Doshi, M., Mahale, A., Kumar Singh, S., Deshmukh, S. (2022). Printing parameters and materials affecting mechanical properties of FDM-3D printed Parts: Perspective and prospects. Materials Today: Proceedings, 50, 2269–2275. https://doi.org/10.1016/j.matpr.2021.10.003
3. Kristiawan, R. B., Imaduddin, F., Ariawan, D., Ubaidillah, Arifin, Z. (2021). A review on the fused deposition modeling (FDM) 3D printing: Filament processing, materials, and printing parameters. Open Engineering, 11 (1), 639–649. https://doi.org/10.1515/eng-2021-0063
4. Patel, R., Desai, C., Kushwah, S., Mangrola, M. H. (2022). A review article on FDM process parameters in 3D printing for composite materials. Materials Today: Proceedings, 60, 2162–2166. https://doi.org/10.1016/j.matpr.2022.02.385
5. Ambade, V., Rajurkar, S., Awari, G., Yelamasetti, B., Shelare, S. (2023). Influence of FDM process parameters on tensile strength of parts printed by PLA material. International Journal on Interactive Design and Manufacturing (IJIDeM), 19 (1), 573–584. https://doi.org/10.1007/s12008-023-01490-7
6. Prashar, G., Vasudev, H., Bhuddhi, D. (2022). Additive manufacturing: expanding 3D printing horizon in industry 4.0. International Journal on Interactive Design and Manufacturing (IJIDeM), 17 (5), 2221–2235. https://doi.org/10.1007/s12008-022-00956-4
7. Pandžić, A., Hodžić, D., Kadrić, E. (2021). Experimental Investigation on Influence of Infill Density on Tensile Mechanical Properties of Different FDM 3D Printed Materials. TEM Journal, 10 (3), 1195–1201. https://doi.org/10.18421/tem103-25
8. Ai, J.-R., Vogt, B. D. (2022). Size and print path effects on mechanical properties of material extrusion 3D printed plastics. Progress in Additive Manufacturing, 7 (5), 1009–1021. https://doi.org/10.1007/s40964-022-00275-w
9. Erokhin, K., Naumov, S., Ananikov, V. (2023). Defects in 3D Printing and Strategies to Enhance Quality of FFF Additive Manufacturing. A Review. ChemRxiv. https://doi.org/10.26434/chemrxiv-2023-lw1ns
10. Salenko, O., Strutinsky, V., Avramov, K., Orel, V., Dzhulii, D., Havrushkevych, A., Kostenko, A. (2025). Providing technical and algorithmical support to the predictable properties of honeycomb filler obtained by additive processes. Eastern-European Journal of Enterprise Technologies, 3 (1 (135)), 58–80. https://doi.org/10.15587/1729-4061.2025.329745
11. Orel, V., Kozlovs'ka, T., Salenko, O., Melnychuk, P. (2025). Post-processing of engineering products obtained by additive layer modelling. Technical Engineering, 1 (95), 76–93. https://doi.org/10.26642/ten-2025-1(95)-76-93
12. Chojnacki, B., Chojak, A., Binek, W., Pawlik, J., Idczak, J. (2025). Accuracy of 3D printing of the samples in the prototyping of cavity-based metamaterials. Scientific Reports, 15 (1). https://doi.org/10.1038/s41598-025-98391-4
13. Tamburrino, F., Barone, S., Paoli, A., Razionale, A. V. (2021). Post-processing treatments to enhance additively manufactured polymeric parts: a review. Virtual and Physical Prototyping, 16 (2), 221–254. https://doi.org/10.1080/17452759.2021.1917039
14. Gibson, I., Rosen, D., Stucker, B., Khorasani, M. (2021). Additive Manufacturing Technologies. Springer International Publishing. ttps://doi.org/10.1007/978-3-030-56127-7
15. Jandyal, A., Chaturvedi, I., Wazir, I., Raina, A., Ul Haq, M. I. (2022). 3D printing – A review of processes, materials and applications in industry 4.0. Sustainable Operations and Computers, 3, 33–42. https://doi.org/10.1016/j.susoc.2021.09.004
16. Orel, V., Salenko, O., Melnychuk, P. (2024). Innovative additive technologies in the creation of structural elements of aircraft and spacecraft. Technical Engineering, 1 (93), 64–69. https://doi.org/10.26642/ten-2024-1(93)-64-69
17. Syrlybayev, D., Zharylkassyn, B., Seisekulova, A., Akhmetov, M., Perveen, A., Talamona, D. (2021). Optimisation of Strength Properties of FDM Printed Parts – A Critical Review. Polymers, 13 (10), 1587. https://doi.org/10.3390/polym13101587
18. Salenko, O. F., Shepelenko, I. V., Budar Mokhamed, R. F. (2020). Pidvyshchennia efektyvnosti obrobky kompozytsiynykh materialiv zastosuvanniam hibrydnoho instrumentu. Materialy konferentsiyi: pidvyshchennia nadiynosti mashyn i obladnannia. Kropyvnytskyi. Available at: https://share.google/aUR1tDkFOFwiZck2w
19. Dizon, J. R. C., Gache, C. C. L., Cascolan, H. M. S., Cancino, L. T., Advincula, R. C. (2021). Post-Processing of 3D-Printed Polymers. Technologies, 9 (3), 61. https://doi.org/10.3390/technologies9030061
20. Jabłońska, M., Łastowska, O. (2024). Enhancing of Surface Quality of FDM Moulded Materials through Hybrid Techniques. Materials, 17 (17), 4250. https://doi.org/10.3390/ma17174250
21. Khosravani, M. R., Schüürmann, J., Berto, F., Reinicke, T. (2021). On the Post-Processing of 3D-Printed ABS Parts. Polymers, 13 (10), 1559. https://doi.org/10.3390/polym13101559
22. Mathew, A., Kishore, S. R., Tomy, A. T., Sugavaneswaran, M., Scholz, S. G., Elkaseer, A. et al. (2023). Vapour polishing of fused deposition modelling (FDM) parts: a critical review of different techniques, and subsequent surface finish and mechanical properties of the post-processed 3D-printed parts. Progress in Additive Manufacturing, 8 (6), 1161–1178. https://doi.org/10.1007/s40964-022-00391-7

23. Kantaros, A., Ganetsos, T., Petrescu, F., Ungureanu, L., Munteanu, I. (2024). Post-Production Finishing Processes Utilized in 3D Printing Technologies. Processes, 12 (3), 595. https://doi.org/10.3390/pr12030595
24. Francis, V., Garg, S., Saxena, K. K., Jain, P. K., Lade, J., Kumar, D. (2022). Effect of chemical and heat treatment on 3D printed parts: nanoparticles embedment approach. Advances in Materials and Processing Technologies, 8 (sup4), 2277–2288. https://doi.org/10.1080/2374068x.2022.2037876
25. Valerga, A. P., Haq, M. I. U., Fernandez-Vidal, S. R. (2023). Chemical post-processing for fused deposition modelling. Post-Processing Techniques for Additive Manufacturing, 129–153. https://doi.org/10.1201/9781003288619-6
26. Şükrü Adin, M., Kam, M. (2024). An Overview of Post-Processing of Fused Deposition Modelling 3D Printed Products. Post-Processing of Parts and Components Fabricated by Fused Deposition Modeling, 1–10. https://doi.org/10.1201/9781032665351-1
27. Gulevskis, A., Volkov, K. (2025). Computer Simulation and Speedup of Solving Heat Transfer Problems of Heating and Melting Metal Particles with Laser Radiation. Computers, 14 (2), 47. https://doi.org/10.3390/computers14020047
28. Wahab Hashmi, A., Ahmad, S., Gulam Mustafa, M., Tian, Y., Iqbal, F., Singh Mali, H. et al. (2024). Abrasive flow finishing of 3D-Printed Aerofoils: Design, numerical Simulation, and experimental analysis. Optics & Laser Technology, 174, 110578. https://doi.org/10.1016/j.optlastec.2024.110578
29. Hashmi, A. W., Mali, H. S., Meena, A. (2021). The Surface Quality Improvement Methods for FDM Printed Parts: A Review. Fused Deposition Modeling Based 3D Printing, 167–194. https://doi.org/10.1007/978-3-030-68024-4_9
30. Cao, L., Xiao, J., Kim, J. K., Zhang, X. (2023). Effect of post-process treatments on mechanical properties and surface characteristics of 3D printed short glass fiber reinforced PLA/TPU using the FDM process. CIRP Journal of Manufacturing Science and Technology, 41, 135–143. https://doi.org/10.1016/j.cirpj.2022.12.008
31. Mushtaq, R. T., Wang, Y., Khan, A. M., Rehman, M., Li, X., Sharma, S. (2023). A post-processing laser polishing method to improve process performance of 3D printed new Industrial Nylon-6 polymer. Journal of Manufacturing Processes, 101, 546–560. https://doi.org/10.1016/j.jmapro.2023.06.019
32. Khosravani, M. R., Ayatollahi, M. R., Reinicke, T. (2023). Effects of post-processing techniques on the mechanical characterization of additively manufactured parts. Journal of Manufacturing Processes, 107, 98–114. https://doi.org/10.1016/j.jmapro.2023.10.018