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REVEALING THE EFFECT OF ADDITIVE PRINTING TECHNOLOGICAL PARAMETERS ON THE ADHESION PROPERTIES OF 3D ELEMENTS INTEGRATED INTO PRINTED SUBSTRATES

Tetiana Kyrychok
Doctor of Technical Sciences, Professor*
ORCID: https://orcid.org/0000-0002-9639-5486
Tetiana Klymenko
Corresponding author
PhD, Associate Professor*
E-mail: tetiana.klymenko@gmail.com
ORCID: https://orcid.org/0000-0002-7229-3995
Maryna Volodko
PhD Student*
ORCID: https://orcid.org/0009-0004-6198-5250
Vladyslav Doroshchuk
PhD Student*
ORCID: https://orcid.org/0009-0000-9658-3455
*Department of Printing Technology
Educational and Scientific Institute for Publishing and Printing
National Technical University
of Ukraine "Igor Sikorsky Kyiv Polytechnic Institute"
Beresteiskyi ave., 37, Kyiv, Ukraine, 03056

This paper investigates the process that forms an adhesive bond between the polylactic acid (PLA) polymer and textile substrates during direct Fused Deposition Modeling (FDM) printing, which is used to make printed products with integrated 3D elements. The task addressed relates to the insufficient understanding of the influence exerted by the structural characteristics of textile materials and additive printing parameters on the quality and stability of the adhesive layer.

This study has established patterns of interaction between PLA and fabrics of different densities, thicknesses, and surface topographies.

Mechanical pull-off tests were conducted to quantitatively assess the adhesive strength and determine the relationship between the pull-off force and the technological parameters of printing. It is shown that increased extrusion temperatures, average extruder travel speed, and minimum Z-distance between the nozzle and the base enable the formation of a more stable bond. The effect of preliminary application of an adhesive layer was investigated, which in certain cases further increases the adhesive interaction.

The results have made it possible to solve the task by comprehensively taking into account the structural features of textile bases and the physical and technological factors of FDM printing. The identified patterns are explained by a combination of thermomechanical effects during PLA extrusion and the ability of textile fibers to provide micromechanical fixation of the polymer.

The findings could be effectively used in the context of the introduction of additive technologies in printing

Keywords: FDM printing, adhesive strength, polymer composite materials, wear resistance, structural characteristics, quality

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1. Introduction

The current stage of development of the printing industry involves the active implementation of technological solutions aimed at expanding the functional and design capabilities of finished printed products.

The use of additive technologies allows the formation of three-dimensional elements with a complex configuration without significantly complicating the production process. Increasing requirements for appearance, tactile characteristics and, in general, the growth of demand for printing products manufactured by the additive method necessitates the search for new materials and technologies for their integration into conventional printing designs.

The use of textile bases in the production of book covers, album publications, notebooks, and other printing products occupies a rather important place due to the combination of protective and decorative functions.

In the context of the evolution of additive technologies, textile materials are considered as a basis for applying integrated polymers and their structures, which are formed by the method of fused deposition modeling (FDM), and not only as finishing elements.

The use of additive technologies on textile substrates provides the discovery of new approaches to the creation of three-dimensional decorative elements; at the same time, the effectiveness of such solutions is determined by the quality of the formation of the adhesive bond of the polymer with the textile base. The most common among FDM printing materials is polylactide (polylactic acid – PLA) due to its stable technological properties, availability, and environmental characteristics. In turn, the formation of the connection of textile bases with polylactide and its features remain insufficiently studied.

Therefore, during the operation of such printing products, the detachment of volumetric elements, their deformation and, in general, a decrease in the adhesion strength to textile bases may occur.

This gives grounds to determine the relevance of studying the factors that affect the adhesive strength of the connection of polylactide with textile bases and taking into account the conditions of 3D printing and the properties of materials. The results could be used to substantiate the technological modes of printing three-dimensional elements obtained by FDM printing, improve the performance properties of bindings, and expand the possibilities in modern printing design. Therefore, research aimed at establishing regularities in the adhesive bond between PLA and textile bases in printed products is relevant.

2. Literature review and problem statement

Modern trends in printing production are determined by the active combination of three-dimensional decorative and functional elements implemented using additive technologies. Recently, there has been a growing interest in the use of 3D printing to form integrated 3D elements of complex geometry in printing products [1]. The authors of work [1] considered the current state of development of biopolymers of natural origin as a promising material for various 3D printing technologies. Given that textile substrates are of cellulose nature, the results of the research can be considered a theoretical basis for evaluating the adhesive bonds of polymers (PLA materials) and textile substrates. However, the question of the regularities of the formation of adhesive bonds between polymer materials and textile substrates, as well as the influence of their structural characteristics on the adhesion strength of integrated 3D elements, remains unresolved.

At the same time, the use of textile materials in printing products is increasingly noted, in particular for obtaining book covers, albums, diaries, cases, laces, and decorative inserts. This approach increases the functionality by combining conventional and innovative technologies [2].

Paper [2] outlines the prospects for implementing additive technologies to make products with integrated 3D elements on textile bases. The authors describe the key capabilities of additive technologies that open up new approaches to creating functional products. However, the research focuses on general technological solutions for 3D printing without a detailed analysis of the regularities of the formation of adhesive bonds of polymers to textile bases.

With the expansion of the use of additive technologies in printed products of decorative and functional purposes, textiles have been used as a basis for the formation of integrated 3D elements, in particular in the form of relief inserts, fasteners, logos, as well as protective or finishing elements [3]. Study [3] confirms that textile substrates can be effectively used to form integrated 3D elements of decorative and functional purposes by direct FDM printing. However, the results mostly demonstrate applied solutions without quantitative assessment of the adhesion strength, without detailed analysis of the influence of the structural characteristics of textile substrates. As a result, the prospect of using textile substrates for the formation of integrated 3D elements is declared. However, the lack of research on the optimization of FDM printing modes and taking into account the structural characteristics of fabrics leaves the question of their practical implementation in scalable printing production technologies open.

During further operation, especially during bending, friction, or temperature changes, the adhesion strength of polylactide to the textile base is of crucial importance for maintaining the integrity of a printed product with integrated 3D elements [4].

In work [4], it is shown that during the operation of printed products with integrated 3D elements, the determining factor of their durability and wear resistance is the adhesion strength of the polymer to the textile base. The authors note that bending, friction, and temperature fluctuations can cause delamination of volumetric elements. However, the study mainly focuses on the operational consequences of insufficient adhesion strength without analyzing the technological parameters of FDM printing and structural features of the fabric. Accordingly, the work confirms the importance of adhesion strength for maintaining the integrity of products but does not answer the question about ways to purposefully increase it.

The structural features of the surface outline the mechanical and adhesive properties of materials, which are of decisive importance in forming the connection between the textile base and integrated 3D elements formed by the FDM method in additive manufacturing processes [5]. Study [5] summarizes approaches to considering textile bases as multicomponent systems, the structural features of which determine their mechanical and adhesive properties. The decisive role of the interfacial interaction of components is proven, but without taking into account the specifics of the application of direct FDM printing of polymers on textile bases. At the same time, the issue of optimizing the technological modes of additive printing when forming integrated 3D elements remains unresolved.

Work [6] demonstrates that despite the widespread use of polylactide (PLA material), its adhesive properties with respect to textile (cotton) bases remain insufficiently studied. The study focuses on determining this problem without a systematic analysis of the factors of direct FDM printing and structural features of textile materials. Thus, the work confirms the importance of studying the adhesion strength of the polymer and the fabric base but does not answer the question about the complex influence of technological and structural factors.

FDM technology makes it possible to apply three-dimensional structures to other materials, as well as using 3D elements as a basis for the purpose of their functional or decorative addition [7]. Paper [7] showed that direct FDM printing makes it possible to form integrated 3D elements on different types of textile bases to expand the functional capabilities of products. Thus, the study focuses on the technological capabilities of the additive printing process without taking into account the morphological features of textile bases.

A separate area of modern research focuses on printed substrates, which in printing production are considered as multilayer polymer-cellulose or polymer-fiber systems. The formation of a printed impression occurs as a result of the interaction of ink compositions, binder polymers, and the surface of the substrate, which leads to the formation of a modified surface layer with excellent physical, mechanical, and adhesive properties.

The presence of a paint layer, varnishes, or protective coatings changes the surface energy, microrelief and porosity of the printed surface, which directly affects the mechanisms of forming adhesive contact with 3D-printed polymer elements. In additive manufacturing, the efficiency of PLA bonding with printed substrates is determined by the parameters of

FDM printing and the structural and chemical features of the printed layer, which justifies the consideration of printed substrates as functional composites [8]. The authors of study [8] note that the surface roughness, preliminary preparation of the printed base and the characteristics of the first layer affect the quality of the adhesive bond, and the penetration of the molten polymer into the pores of the textile base contributes to an increase in the adhesion strength. However, the question about the role of the mass surface density and thickness of the printed base is not addressed as the work does not include an analysis of fiber structures and multifactorial interaction of direct FDM printing parameters with the characteristics of textile bases.

Within the framework of the application of modern printing technologies in the context of the manufacture of integrated 3D elements for printed products, scientific studies have been considered, the results of which are focused on investigating the technological parameters that affect the efficiency of 3D printing on textile bases. In particular, it was found that pre-treatment of cotton fabrics with a special coating can significantly increase the adhesion between the textile base and the printed 3D element [9]. Work [9] confirms the importance of surface preparation of textile substrates but does not answer the question about the natural influence of the structural characteristics of textile substrates (thickness, porosity, mass surface density) on the quality of the adhesive bond. The authors' attention is on the chemical modification of the printed surface without taking into account the morphological parameters of the textile substrate and its interaction with direct FDM printing modes.

In addition, the influence of the distance between the printing nozzle and textile substrates (the so-called Z-distance) [10] is actively studied since this parameter affects the quality of adhesion. A detailed analysis of the interaction of PLA material with different types of textile substrates, in particular cotton, is given in study [11] in which the authors applied a comprehensive approach to assessing adhesion characteristics.

The regression analysis used in [11] confirms that the adhesion strength of polymers (PLA material) to fabrics depends on the morphological characteristics of the textile substrate. In particular, the authors note the influence of fabric thickness and weave density on the magnitude of the detachment force. However, the studies are local in nature, as they are based on a limited set of textile substrates and do not take into account the variability of the technological parameters of additive printing. In particular, temperature regimes, extrusion speed and characteristics of the first layer.

In addition, a comparative analysis of the adhesion of PLA materials to various textile substrates is given, which demonstrates the dependence of the results on the microstructure of the substrate and printing parameters [12]. In [12], it is shown that the extrusion temperature, printing speed, and Z-distance significantly affect the quality of the adhesion strength of polymers (PLA materials) and textile substrates. The authors note the dependence of the results on the microstructure of the fabric. However, the study focuses on individual process parameters without a systematic analysis of their interaction with the structural characteristics of textile substrates. The work lacks an integrated process model for the formation of a stable adhesive bond taking into account the thickness and mass surface density of textile substrates.

Paper [13] gives a review of available publications on the quality of adhesive bonds of integrated 3D elements obtained by direct FDM printing and textile substrates. The work does not reflect the conduct of their own experimental studies. Based on the analyzed sources, the authors noted that the adhesion strength depends on the set of parameters of textile substrates, the type of polymer, and technological parameters of the FDM printing process. At the same time, the review of publications showed that there is no universal model for determining the quality of adhesive bonds. This is due to the unclear systematization of results, since different groups of researchers use materials of different nature, printing parameters, models of additive printing equipment and experimental methods for determining the adhesion strength.

Our review of the literature confirms that the cited studies have accumulated results on the possibilities of using the direct FDM printing method to form integrated 3D elements on printed substrates, in particular textile ones. The dependence of the influence of technological parameters of 3-D printing, in particular, extrusion temperature, printing speed, Z-distance, and structural characteristics of textile substrates on the quality of adhesion strength between the polymer and the printed substrate has been established. At the same time, most researchers analyze the adhesive properties of polymers from the standpoint of individual technological parameters of 3D printing [10, 12], without systematically taking into account the structural characteristics of textile substrates (thickness, mass surface density, surface roughness) [3]. A significant part of the research is of an applied nature [2, 3, 7]; there is no quantitative assessment of adhesion strength and analysis of the quality of formation of adhesive bonds. Even in studies in which the influence of morphological characteristics of textile substrates on adhesion strength has been confirmed [11, 12], no regularities of interaction between structural parameters of textile substrates and technological parameters of direct FDM printing have been established. The influence of the formation of the first polymer layer on the stability of the contact zone between polymers and textile substrates is superficially described. The main reasons for the unresolved issues are the lack of unified criteria for assessing the adhesion strength between polymers and textile substrates and the lack of a comprehensive approach to analyzing the influence of the morphology of textile substrates and technological parameters of 3-D printing on the quality of adhesive bonds.

Therefore, the general unsolved problem is to establish regularities in the formation of adhesive bonds between the polymer (PLA material) and textile (cotton) substrates during direct FDM printing, taking into account the influence of technological printing parameters and morphological characteristics of the substrates. Solving this task is a prerequisite for substantiating the optimal modes of FDM printing of integrated 3D elements on textile substrates in order to expand the functionality of printed products and operational durability.

3. The aim and objectives of the study

The aim of our study is to establish features of the process that forms adhesive bonds between polymer (PLA material) and textile (cotton) substrates during direct FDM printing, taking into account the influence of technological printing parameters and structural characteristics of the substrates on the adhesion strength. This will make it possible to determine the surface parameters of the textile substrate and assess the adhesion strength of printed products containing integrated 3D elements.

To achieve the goal, the following tasks were set:

– to determine the morphological and adhesive characteristics of the connection between the polymer and the surface of textile substrates after direct application of the polymer (PLA material) by FDM printing;

– to perform a microscopic study of the penetration of the polymer (PLA material) into the structure of textile substrates depending on the value of the Z-distance and structural parameters of the fabric substrates;

– to conduct mechanical tests of the adhesion strength of the polymer (PLA material) to textile (cotton) substrates and to establish the dependence of the influence of the technological parameters of FDM printing and the physical and mechanical characteristics of textile substrates on the quality of adhesive bonds.

4. Materials and methods

The object of our study is the process of forming an adhesive bond between PLA polymer and textile substrates during direct FDM printing of integrated 3D elements in printed products.

It was hypothesized that reducing the Z-distance and increasing the PLA extrusion temperature provide deeper penetration of the polymer into the fibrous structure of the fabric, which leads to an increase in adhesion strength and the formation of a more stable bond.

It was assumed that the structural characteristics of textile substrates provide the formation of a stronger adhesive contact due to the mechanical penetration of the polymer into the fibrous structure of the fabric and the formation of a mechanical closure at a minimum Z-distance, except for low-relief substrates.

The following simplifications were adopted in the study:

– the chemical interaction between PLA materials and cotton fibers was not taken into account since the main mechanism of adhesion was considered to be the mechanical penetration of the melt into the fabric structure;

– internal thermal stresses in the textile base during printing were not modeled, the analysis focused on the influence of geometric and temperature parameters;

– the surface energy of the fabrics was considered a constant value for each type of textile material and was not subjected to additional measurements;

– only two PLA layers were used for microstructural analysis, which allowed us to standardize the penetration depth and minimize the influence of multilayer effects;

– a factorial approach was used during the experiments, in which the three main technological parameters of FDM printing were maintained constant with alternating variation of only one of them. A separate series of experiments, quantitatively the most representative, involved changing the Z-distance between the extruder nozzle and the surface of the base as this parameter directly determines the conditions of initial contact of the PLA melt with the printed base.

For experimental studies, CAD models were built by using Blender 3D 3.5 software (Fig. 1). The CAD models constructed were saved in the *.STL format [14]. 3D printed elements of 7 × 15 cm were printed using direct FDM printing on textile (cotton) substrates measuring 5 × 20 cm. In the study, for each experimental group of samples, two layers of PLA material were applied to the surface of the textile substrate with subsequent preparation of cross sections for microscopic analysis; each group included five separately prepared samples.

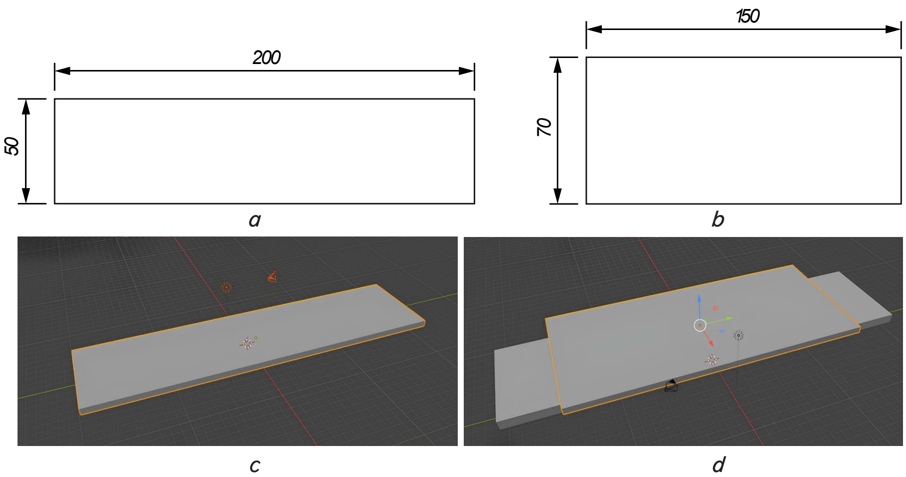


Fig. 1. Models of the experimental integrated 3D element: *a* – view of the 2D model of the first layer; *b* – view of the 2D model of the second layer; *c* – CAD model of printing the textile base with the first layer; *d* – CAD model of printing the textile base with two layers

PLA plastic manufactured by MonoFilament [15] was used as a consumable material.

The choice of filament is based on the minimum emission of toxic substances during the printing process, its environmental friendliness, and the possibility of using it in experimental equipment [16].

The properties of the PLA material used are given in Table 1.

Table 1

Characteristics of PLA plastic produced by "MonoFilament" [15]

No. of entry	Characteristics	PLA
1	Filament diameter, mm	1.75
2	Shrinkage coefficient, %	0.2–0.25
3	Glass transition temperature, °C	55–60
4	Strength, MPa	45–65
5	Density, g/cm^3	1.24–1.25
6	Elastic modulus, MPa	1968
7	Moisture content, %	<0.3
8	Decomposition temperature, °C	250–280
9	Extrusion temperature, °C	190–220
10	Printing speed, mm/s	30–100
11	Layer thickness, mm	0.05–0.8
12	Elongation at break, %	4

Samples of textile (cotton) base were placed and fixed on the 3D equipment platform using double-sided tape to prevent displacement.

3D printing of printed products was carried out on a 3D printer "XYZprinting da Vinci XYZprinting da Vinci Super" [17] with the set parameters given in Table 2.

Table 2

Characteristics of printing parameters of integrated 3D elements with PLA [18]

No. of entry	Characteristics	PLA
1	Extrusion temperature, °C	200
2	Printing speed, mm/s	55
3	Printing speed of the first layer, mm/s	22
4	Height of the first printed layer, mm	0,5
5	Fill density, %	100
6	Platform heating temperature, °C	60

The PLA FDM printing parameters were selected within the operating ranges recommended by PLA plastic manufacturers [15] and 3D equipment [17] to enable stable extrusion, sufficient melt viscosity, and efficient first layer formation [18]. The reduced speed and increased first layer height were used to improve wetting and compensate for surface micro-unevenness, while platform heating helps reduce thermal stresses and stabilize contact in the bonding area [19].

To assess the influence of additive printing parameters on the quality of adhesive bonds between the textile base and integrated 3D elements, four technological parameters were investigated: Z-spacing, first layer printing speed, extrusion temperature, and platform temperature.

In further studies, three of the four investigated parameters remain fixed, while one (Z-spacing) varies within the permissible range. The variation limits of each parameter are determined based on the technical characteristics and recommendations of the manufacturers of the PLA plastic and 3D equipment used.

The choice of Z-distance values ($Z = 0.8$ mm and $Z = 0.5$ mm) is due to the need for a comparative analysis of the modes of formation of the first PLA layer, which correspond to different mechanisms of adhesive interaction of the polymer with the bases.

The $Z = 0.8$ mm mode is used as one that excludes mechanical compression of the material by the printing head. In this case, the molten PLA settles on the surface of the tissue groups, and the adhesive interaction is formed mainly due to wetting of the surface and partial penetration of the polymer into the interfilament spaces.

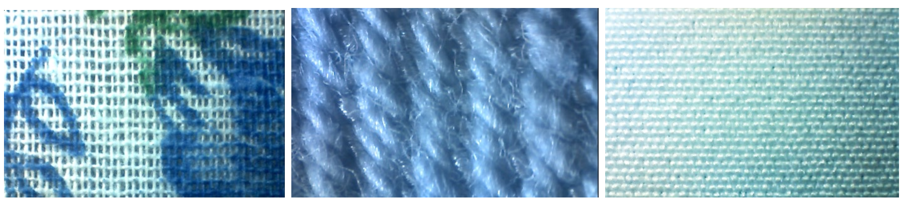
The value of $Z = 0.5$ mm was chosen as the minimized working Z-distance, which is closest to the thickness of most groups of studied textile bases and at the same time corresponds to the technical capabilities of the applied 3D equipment. This allows us to experimentally distinguish the mode of surface adhesion without compression of the textile base and the mode of enhanced adhesion, which is formed as a result of a combination of thermal and mechanical effects during the application of the first layer of PLA.

Six different groups of textile base samples (cotton fabrics) (Fig. 2) were selected for the study, which differ in structural and physical-mechanical properties (Table 3) [20]. The choice of materials is due to their prevalence in printing production and suitability for additive printing [21].

The study was performed using direct additive printing with PLA filament on a textile base. For a detailed analysis of the influence of FDM printing parameters and material structure on the formation of PLA adhesive joints, groups of samples 2, 4, and 6 were selected as representative models of knitted, twill, and linen materials, respectively. These groups cover different ranges of parameters critical for determining the adhesion strength and are characterized by a stable nature of adhesive failure without damage to the textile base, which ensures the correctness of the comparative analysis.

Before testing, groups of cotton textile substrates were kept for 24 h under climatic conditions in accordance with ISO 139:2005 [22], namely: temperature – 23 ± 2°C, relative humidity – 50 ± 4%.

The mass per unit area of the sample groups was determined according to the DIN EN 12127 standard [23] – by weighing samples with an area of (10 × 10 cm) on a Goyojo Analytical Lab Balance [24] with subsequent conversion to g/m^2.



a *b* *c*

Fig. 2. Examples of the studied textile (cotton) bases: *a* — plain weave; *b* — twill weave; *c* — knitwear

Table 3

Characteristics of the studied cotton textile substrates

No. of entry	Type	Characteristics		
		Mass surface density, g/m^2	Surface roughness, R_z, μm	Thickness, mm
1	Knitwear	276.2	79.08	0.71
2	Knitwear	198.8	61.27	0.48
3	Twill weave	302.4	101.34	0.46
4	Twill weave	297.7	49.16	0.41
5	Plain weave	312.2	59.52	0.49
6	Plain weave	116.4	41.03	0.20

The surface roughness of the textile substrates was estimated by parameter R_z by a non-contact method on a 3D laser microscope VK-X100 [25] with data processing by the software of the KEYENCE VK-X series microscope (vertical resolution – 0.01 μm).

Since the groups of textile base samples are characterized by a pronounced macrorelief caused by the interweaving of threads, the obtained R_z values reflect the structural roughness of the fabric.

The thickness of the textile bases was determined in accordance with the DIN EN ISO 5084 standard [26], namely by measuring their thicknesses with a digital indicator thickness gauge PROTESTER 5317-25 [27] in three different zones of the sample groups with subsequent averaging of the obtained values.

Preliminary preparation of the sample groups with integrated 3D elements was carried out in accordance with the methodology for making metallographic micro sections, adapted for polymer-fibrous materials according to the ASTM E3 Standard Guide for Preparation of Metallographic Specimens [28].

Cross-sections of samples with printed layers of 3D elements on textile substrates were made by mechanical cutting of the samples perpendicular to the surface after cooling them, with a desktop precision cutter IsoMet 1000 [29]. The study was carried out without further application of additional polishing in order to avoid deformation of the fibers and the polymer layer.

To visualize the depth of PLA penetration into the fibrous structure of the textile substrate, analysis was carried out using a digital light microscope VHX-600 (Keyence, Japan) [30] with an optical magnification of up to 2000× and a spatial resolution of up to 1 μm.

To determine the adhesion strength of the connection between integrated 3D elements of printed products and the textile substrate, various mechanical loading schemes are used, depending on the specificity of the study, in particular, perpendicular tear-off, tear test, and peeling test [31]. The perpendicular peel test allows one to determine the adhesive strength of the connection under normal loading to the contact plane, while the tensile test involves stretching the sample and characterizes the resistance to fracture under shear-tensile loading.

The peel test method was used to test the adhesion strength between integrated 3D printed elements and a textile base [32]. The adhesion strength was determined by measuring the detachment force of groups of samples required to separate the polymer layer and the textile (cotton) base using a universal testing machine Testometric DBBMTCL-250 kg [33].

The maximum value of the detachment force obtained was considered as an integral indicator of the adhesion strength, without normalization to the contact area. During testing, the textile base and 3D-elements of the printed polygraphic product were fixed in the corresponding position in the clamps of the machine. The detachment force was recorded during the test, and the maximum value of this force was considered as an indicator of the adhesion strength (detachment force) between the printed element and the textile base. Each measurement was performed in three independent series of experiments using separately prepared groups of samples, after which the average value was determined.

5. Results of investigating the adhesive bond between textile bases and polymer material

5. 1. Results of investigating the morphological and adhesive characteristics of the connection of polymer (PLA material) and textile bases

Fig. 3 shows the dependence of the local detachment force of 3D elements (PLA) on the distance along the separation line, which reflects the spatial heterogeneity of the adhesive interaction for different groups of samples. The values of the local detachment force vary within approximately 0.2–3 N at a distance of 0–60 mm and characterize the instantaneous forces that arise in the process of gradual destruction of the adhesive bond. The dependences were derived by averaging the test results for five independently prepared samples in each experimental series ($n = 5$).

Fig. 3 demonstrates that the lowest values of the local detachment force were obtained for the group of samples 6, namely for the textile bases with the smallest surface thickness (0.20 mm). This indicates that the adhesive bonds are of a superficial nature. The values for the group of samples 4, characterized by the average thickness of the surface of the textile base (0.41 mm), indicate that the formation of adhesive bonds between the polymer and the textile (cotton) base is more stable. The highest values of the local detachment force were recorded for the group of samples 2, which have the largest surface thickness of the textile base (0.48). This indicates a homogeneous formation of the adhesive layer.

The resulting values of the local detachment force reflect the features of the formation of the contact zone.

5. 2. Results of microscopic study of polymer (PLA material) penetration into the structure of textile bases

The dependence of the degree of interpenetration of PLA plastic into the fibers of the textile (cotton) base on the value of Z-distance is clearly shown in Fig. 4. For selected samples, two layers of PLA were printed on cotton fabric at an extrusion temperature of 210–220°C and a printing speed of the first layer lower than 25 mm/s, and a cross-section was made. An assessment of the influence of Z-distance on the depth of penetration of the polymer (PLA material) into the structure of textile (cotton) bases is given in Table 4 and Fig. 4, 5.

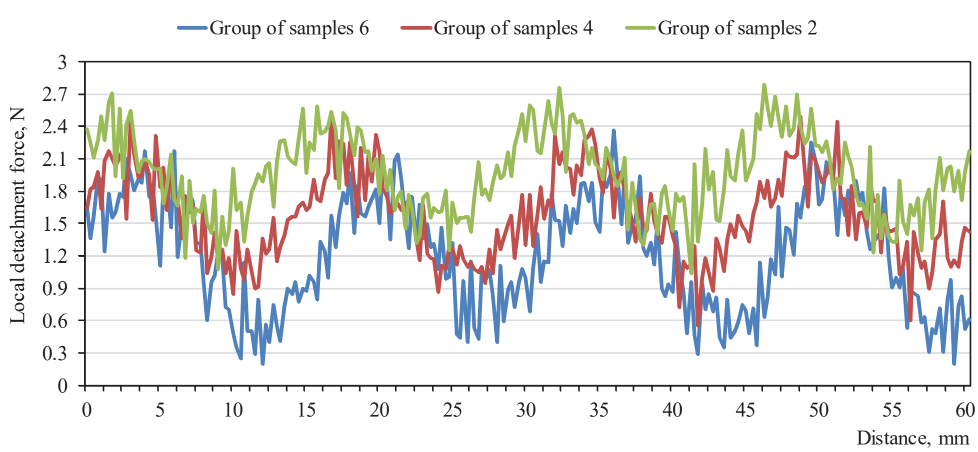


Fig. 3. Local detachment force of 3D-printed PLA elements along the contact line with the textile base for different groups of samples

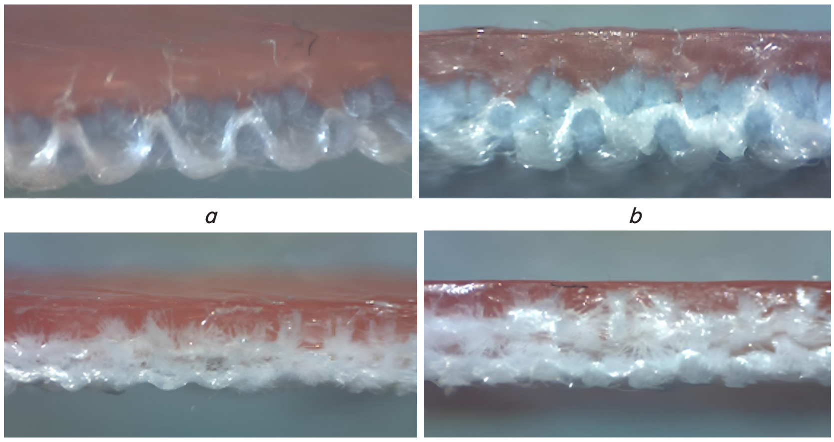


Fig. 4. Cross-sections of printed layers of 3D elements (two layers) on a textile base: *a* — representative sample from sample group 2, distance $Z = 0.8$ mm; *b* — representative sample from sample group 2, distance $Z = 0.5$ mm; *c* — representative sample from sample group 4, distance $Z = 0.8$ mm; *d* — representative sample from sample group 4, distance $Z = 0.5$ mm

Table 4

Dependence of the influence of Z-distance on the depth of penetration of the polymer (PLA material) into the structure of textile (cotton) substrates

Sample group No.	Measurement No.	Polymer penetration depth, μm	
		Z-distance = 0.8 mm	Z-distance = 0.5 mm
2	1	194.81	438.12
	2	215.17	457.34
	3	264.25	528.63
	4	269.25	554.10
4	1	104.25	221.25
	2	115.19	243.37
	3	144.62	288.54
	4	149.23	294.28

The microscopic images shown in Fig. 4 give a clear idea of how Z-distance affects the interpenetration of the fabric substrate and the printed PLA. The pink color of the polymer (PLA material) stands out clearly against the light fabric (cotton) substrate. 3D printing at two different Z-distances (0.5 mm and 0.8 mm) is compared. It is clearly seen that a smaller Z-distance leads to a stronger penetration of the polymer (PLA material) into the textile substrate.

Fig. 5 shows the dependence of the penetration depth of the polymer (PLA material) into the structure of textile (cotton) substrates on Z-distance between the print head and the textile substrate. Each point on the plot corresponds to the average value obtained from the test results of five samples of sample group 2 and 4.

In Fig. 5, one can see the significant influence of Z-distance on the penetration depth of the polymer (PLA material) into the structure of the textile base. The lowest values of the polymer penetration depth for sample group 2, not exceeding 195 μm, were recorded at a Z-distance of 0.8 mm. At a Z-distance of 0.5 mm, the highest values (554 μm) were obtained. For sample group 4, the behavior of the polymer penetration depth formation is similar. This confirms the formation of a more developed heterogeneous contact zone at a smaller Z-distance, which correlates with an increase in the adhesive strength of the connection.

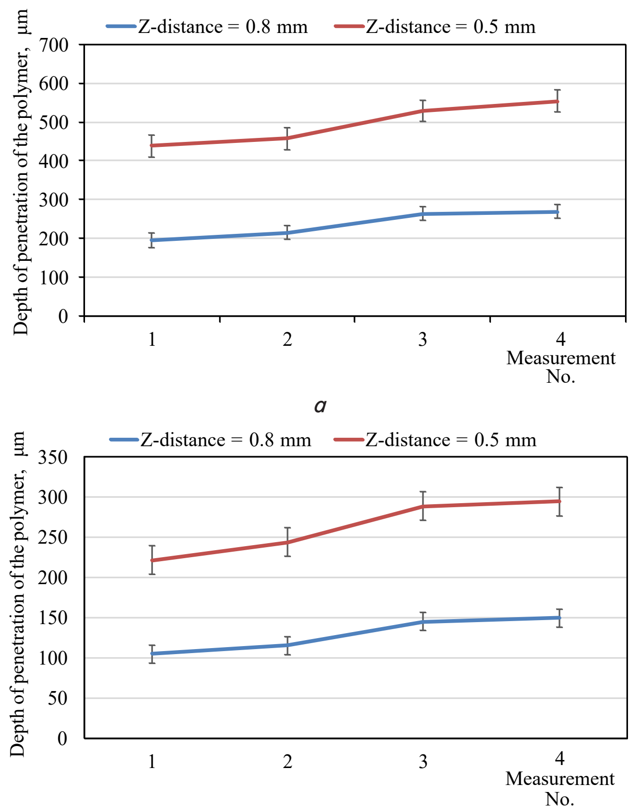


Fig. 5. Dependence of the influence of Z-distance on the depth of penetration of the polymer (PLA material) into the structure of textile (cotton) bases: *a* — samples of group 2; *b* — samples of group 4

When forming the contact zone between the print head and the printed (cotton) base during the application of the first layer of PLA with a Z-distance of 0.5 mm, local mechanical compression of sample group 1 occurs. Fig. 6 shows representative images from the corresponding sample groups; similar behavior was observed for all samples in the group.

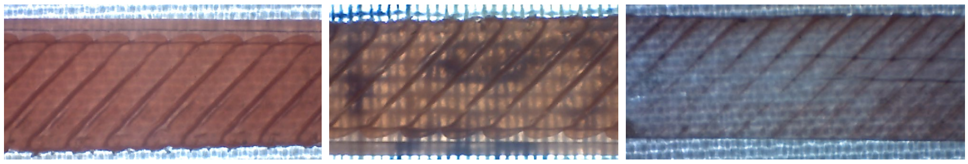


Fig. 6. Formation of the contact zone between the print head and the printed substrate during the application of the first PLA layer with a reduced Z-distance of up to 0.5 mm: *a* — representative sample from sample group 6; *b* — representative sample from sample group 4; *c* — representative sample from sample group 1

The compression phenomenon occurs because the thickness of the textile substrate of sample group 1 is 0.71 mm and exceeds the Z-distance set for printing the first layer.

5. 3. Results of mechanical tests of the adhesive joint caused by the penetration of the polymer (PLA material) into the structure of the textile bases

To quantitatively assess the strength of the joint, the maximum adhesive detachment force was used, recorded during the complete separation of the 3D element from the textile base. The obtained values of the adhesive detachment force reflect the resistance to fracture of the joint without normalization to the contact area and are used for comparative analysis of the influence of the technological parameters of FDM printing and the structural characteristics of the textile bases. For groups of samples 2, 4, and 6, a stable nature of adhesive fracture was recorded without violating the integrity of the textile (cotton) base. This allows us to consider these groups as representative in the analysis of the adhesive characteristics and the influence of the technological parameters of FDM printing on the formation of the PLA adhesive bond.

The assessment of the influence of the physical and mechanical properties of textile (cotton) substrates (density, thickness, surface roughness) and printing parameters (printing speed, Z-distance, platform temperature) on the efficiency of the adhesive bond was performed after applying the polymer (PLA material) by FDM printing. The values of these dependences are given in Tables 4–9. These dependences are illustrated in Fig. 7–10.

The measurement of detachment force for sample group 4 was not carried out in the Z-distance range of 0.3–0.4 mm since, in this case, the thickness of the textile base of group 4 exceeds the Z-distance. Similarly, for sample group 2, the range was 0.3–0.45 mm.

Fig. 7 shows the dependence of the maximum detachment force (adhesion strength) of 3D printed elements on Z-distance between the print head and the textile base. Each point on the plot corresponds to the average value obtained from the test results of five samples of sample groups 2, 4, 6.

The value of Z-distance was selected taking into account the thickness of the corresponding cotton fabric (Table 1, Fig. 4). At the same time, due to the limitations of the 3D hardware firmware and software settings, it is not possible to set the Z-distance less than 0.2 mm.

It was found that with an increase in the printing speed of the first PLA layer, an almost linear decrease in adhesion is observed (Fig. 8).

However, the effect of printing speed (Table 6, Fig. 7) on the adhesion strength is less pronounced compared to the effect of Z-distance (Table 4). Despite this, it is worth considering that the printing speed of the first PLA layer remains a critical factor in ensuring proper adhesion between the materials.

It was found that with increasing platform temperature, there is an overall increase in adhesion strength (Fig. 9).

Table 5

Dependence of the influence of Z-distance on the detachment force (adhesion strength) of polymer (PLA material) to textile (cotton) substrates

No. of entry	Parameter			
	Z-distance, mm	Detachment force, N, sample group 6	Detachment force, N, sample group 4	Detachment force, N, sample group 2
1	0.30	120.2	–	–
2	0.35	117.2	–	–
3	0.40	116.0	–	–
4	0.45	110.0	121.2	–
5	0.50	105.2	115.0	120.2
6	0.55	95.2	100.2	105.2
7	0.60	87.1	91.2	97.1
8	0.65	80.4	77.4	82.2
9	0.70	72.2	72.0	73.1
10	0.75	66.1	62.1	65.2
11	0.80	58.4	58.2	57.2
12	0.85	52.1	54.0	55.4
13	0.90	40.2	43.2	45.2
14	0.95	37.4	39.4	38.1
15	1.00	31.1	35.2	34.2
16	1.05	25.1	27.2	28.4
17	1.10	19.2	20.2	19.4
18	1.15	17.4	17.2	18.2
19	1.20	15.2	16.4	17.0
20	1.25	14.1	15.2	16.1

Table 6

Dependence of the influence of printing speed on the detachment force (adhesion strength) of polymer (PLA material) to textile (cotton) substrates

No. of entry	Parameter			
	Speed, mm/s	Detachment force, N, sample group 6	Detachment force, N, sample group 4	Detachment force, N, sample group 2
1	15.0	49.1	59.2	77.1
2	20.0	45.1	53.2	71.2
3	25.0	40.2	47.1	65.2
4	30.0	36.1	41.1	60.2
5	35.0	29.2	34.1	53.1
6	40.0	26.1	30.2	49.1
7	45.0	22.2	26.2	41.2
8	50.0	18.1	22.1	30.2

Table 7

Dependence of the influence of platform temperature on the detachment force (adhesion strength) of textile substrates and PLA material

No. of entry	Parameter			
	Platform tempera-ture, °C	Detachment force, N, sam-ple group 6	Detachment force, N, sam-ple group 4	Detachment force, N, sam-ple group 2
1	30	53.1	61.1	59.1
2	40	54.0	57.1	57.2
3	50	56.2	62.2	55.0
4	60	58.2	67.0	54.2
5	70	59.1	91.2	53.1
6	80	60.1	95.1	52.2
7	90	62.0	102.1	51.1

Table 8

Influence of the surface density of textile base on the value of detachment force (adhesion strength) of 3D elements of printed products

Group No.	Mass sur-face density, g/m^2	Detachment force, N				
		Sam-ple 1	Sam-ple 2	Sam-ple 3	Sam-ple 4	Sam-ple 5
1	116.4	134.2	136.8	132.5	138.1	135.6
2	198.8	158.3	162.4	160.1	164.2	159.6
3	276.2	170.8	173.5	174.2	176.1	171.9
4	297.7	208.6	212.9	210.3	215.2	211.5
5	302.4	233.4	236.8	238.1	235.6	241.2
6	312.2	238.7	241.5	242.8	239.6	244.2

Table 9

Influence of the thickness of textile base on the value of detachment force (adhesion strength) of 3D elements of printed products

Group No.	Thickness of the textile base, mm	Detachment force, N				
		Sam-ple 1	Sam-ple 2	Sam-ple 3	Sam-ple 4	Sam-ple 5
1	0.71	246.2	243.9	247.5	245.1	248.3
2	0.48	201.2	199.6	203.1	200.4	204.0
3	0.46	187.2	185.9	188.6	186.1	189.4
4	0.41	171.1	169.8	172.5	170.4	173.0
5	0.49	204.1	202.7	205.6	203.2	206.0
6	0.24	152.2	150.8	153.6	151.4	154.1

Table 10

Dependence of the influence of surface density and thickness of textile base on the value of detachment force (adhesion strength) of 3D elements of printed polygraphic products (generalized values)

Group No.	Mass surface density, g/m^2	Detachment force, N	Thickness of the textile base, mm	Detachment force, N
1	116.4	135.4	0.71	246.2
2	198.8	160.9	0.48	201.7
3	276.2	173.3	0.46	187.4
4	297.7	211.7	0.41	171. 4
5	302.4	237.0	0.49	214.3
6	312.2	241.4	0.24	152.4

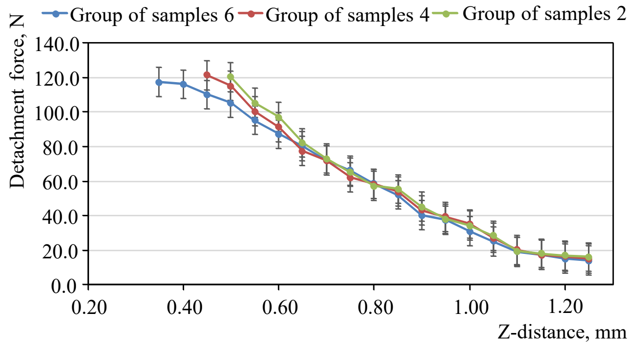


Fig. 7. Dependence of the maximum detachment force (adhesion strength) of 3D printed elements on Z-distance between the print head and the textile base

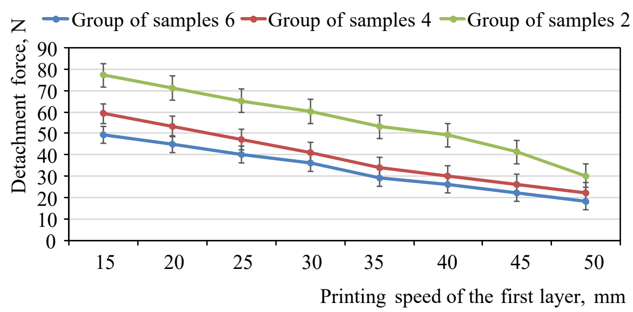


Fig. 8. Dependence of the maximum detachment force (adhesion strength) of 3D elements of printed products on the printing speed of the first layer

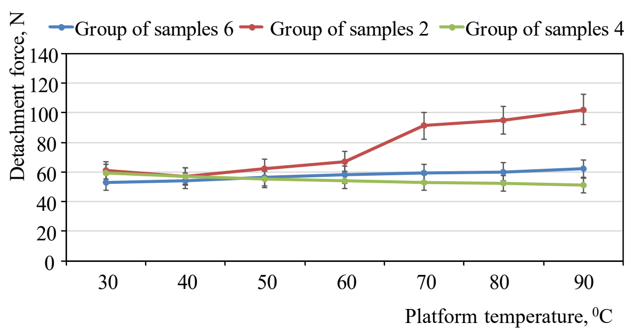
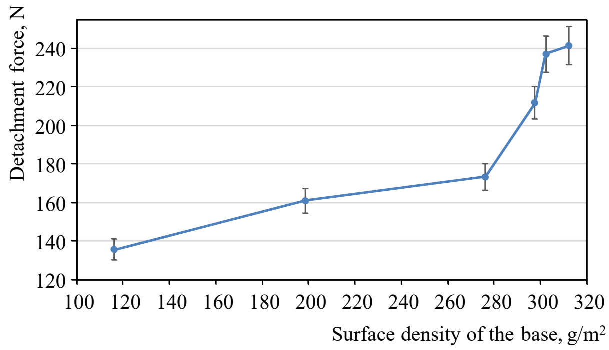


Fig. 9. Dependence of the maximum detachment force (adhesion strength) of 3D printed elements on the platform temperature

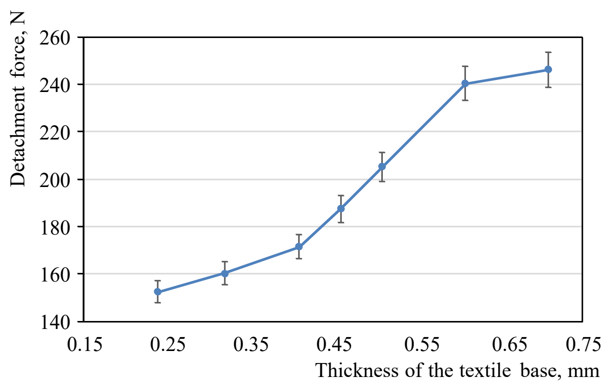
The bulk density and thickness of the textile substrates were chosen as discrete parameters, varying in the range from 116 to 312 g/m^2 (textile substrate thickness – 0.2 to 0.71 mm). These values correspond to different ranges of parameters critical for determining the detachment force (adhesion strength).

It was found that the value of detachment force (adhesion strength) for groups of samples 2 and 4 increases with increasing thickness of the textile base and its mass surface density (Tables 8–10, Fig. 10).

Therefore, changing the technological parameters of printing and structural characteristics of textile bases significantly affects the value of the maximum adhesion strength (detachment force).



a



b

Fig. 10. Dependence of the maximum detachment force (adhesion strength) of 3D-elements of printed polygraphic products on the mass surface density and thickness of the textile base: *a* – mass surface density of the textile base, g/m^2; *b* – thickness of the textile base, mm

6. Discussion of results related to the adhesive properties of 3D elements integrated in printed substrates

The results of surface morphology evaluation, microscopic analysis, and mechanical tests allow us to state that the adhesion intensity of integrated 3D-elements of printing products obtained from PLA polymer to textile bases is determined by the combination of properties of the textile base and polymer.

It was found (Fig. 3) that the samples of group 6 have a significant amplitude of fluctuations in the values of the local detachment force, as a result of the limited penetration of the polymer (PLA material) into the fiber structure of the textile (cotton) bases. In turn, the uniformity of the curves and intermediate values of the detachment force were established for the group of samples 4. The most uniform distribution of the local detachment force was recorded for the group of samples 2. Therefore, the results shown in Fig. 3 confirm that the stability and level of adhesion strength of the polymer (PLA material) to textile (cotton) substrates is determined by a combination of the structural characteristics of the surface of the textile (cotton) substrates and the technological parameters of FDM printing.

Unlike the results reported in [7, 8], which demonstrated an improvement in the quality of adhesive bonds mainly due to the variation of a wide range of FDM printing parameters and the use of modified polymer systems, our data confirm the effectiveness of the method of optimizing the platform temperature during direct FDM printing.

Importantly, earlier papers [2, 10, 11] emphasized the decisive role of the surface morphology of textile materials, interfilament gaps, and porosity of the structure in the formation of mechanical closure between the polymer and the fibrous base. The results in this study experimentally confirm these provisions for the conditions of direct FDM printing without the use of intermediate adhesive layers.

The highest adhesion strength indicators are characteristic of textile (cotton) bases with a surface roughness of 60–105 μm. The deposition of the polymer (PLA material) on too smooth surfaces is accompanied by a decrease in adhesive bonds, while excessive roughness, greater than 105 μm, leads to uneven contact and defects in the adhesive layer.

This pattern clarifies and expands the results from previous studies [6, 8, 10], which described the optimal range of roughness of textile substrates, which makes it possible to achieve maximum adhesion strength of polymeric materials. In particular, the authors of [8] established that too smooth surfaces have limited interfacial interaction and wetting, while excessive roughness causes the formation of air inclusions and unstable contact of the polymer (PLA material) with fibers. The conclusions by the authors of [6, 10] emphasize the key role of surface topography in the formation of effective mechanical closure between PLA and the textile substrate. Microscopic analysis of cross-sections of printed layers of 3D elements on a textile substrate (Fig. 4) characterizes the dependence of the degree of penetration of PLA plastic into the fibers of the textile (cotton) substrate depending on the value of the Z-distance. Therefore, for twill weave at a Z-distance of 0.5 mm (Fig. 4, *d*), there is a close contact of the first PLA layer with the surface of the printed substrate without mechanical compression (Fig. 6, *b*), which ensures the penetration of the polymer mainly between the weave threads.

Unlike sample group 2 (Fig. 4, *a*, *b*), for sample groups 4 and 6, the adhesive interaction of the first PLA layer with the printed base is determined by the surface topography and interfilament gaps, without mechanical compression of the material by the extruder. Confirmation and agreement of this is described in the results reported in [6], which analyzed the mechanism of adhesive interaction obtained when using FDM printing on textile bases, which is similar in nature.

In addition, local mechanical compression of the textile base was established for sample group 1 (Fig. 6, *c*). This occurs because the thickness of the base is 0.71 mm and exceeds the Z-distance set for printing the first layer.

A relationship was established between the mass surface density of textile (cotton) bases (Fig. 10, *a*), thickness (Fig. 10, *b*), and adhesion strength (Tables 8, 9). Textile (cotton) substrates with a thickness of 0.4–0.7 mm contribute to a larger adhesion area due to the porosity of the structure into which the polymer (PLA material) penetrates. For textile (cotton) substrates with a thickness of less than 0.3 mm, the polymer (PLA material) settles mainly on the surface, while the formation of the connection is weak and susceptible to delamination. This characteristic pattern indicates that it is important to take into account the geometric parameters and structural characteristics of textile (cotton) substrates when setting the modes for FDM printing.

Group of samples 6 (Table 9) is characterized by the smallest thickness among the studied materials – only 0.2 mm, which corresponds to the minimum Z-distance that the used 3D printer can provide. In this case, the filament during printing is placed mainly on the surface of the fabric without significant penetration into its structure. This result can be explained by the fact that the determined adhesion value is dependent on distance Z between the print head (extruder) and the printing surface. In turn, PLA plastic is a hydrophobic polymer, as evidenced by the value of the water contact angle – 77° [34]. This fact also affects the reduction of the degree of adhesion to the hydrophilic textile (cotton) base.

Fig. 7 shows that the maximum level of adhesion strength, which is established with close contact of the molten polymer (PLA material) with the fiber structure of the fabric (cotton) base, is achieved by reducing the Z-distance to 0.3–0.5 mm. Conversely, increasing the Z-distance above 0.8–1.0 mm will contribute to a significant decrease in the level of adhesion strength, which occurs due to a decrease in the contact area and incomplete penetration of the PLA material into the fiber layer of the textile (cotton) base.

It has been established that the maximum values of the detachment force (adhesion strength) are achieved at a Z-distance of 0.3–0.5 mm, which provides a combination of thermal and mechanical effects on the textile base during the application of the first layer of PLA. This confirms the opinion by the authors of [35]. Under such conditions, the molten polymer intensively penetrates the fibrous structure of the fabric, forming an effective mechanical lock.

With an increase in the Z-distance to 0.6–0.8 mm, a gradual decrease and stabilization of the adhesion characteristics is observed, while an increase in the Z-distance above 0.8–1.0 mm leads to a sharp decrease in the maximum detachment force (adhesion strength) due to a decrease in the actual contact area and insufficient penetration of the polymer into the interfiber gaps.

Another important technological parameter is the speed of applying the first layer. With an increase in the printing speed of the first PLA layer, an almost linear decrease in adhesion is observed (Table 5, Fig. 8). The effect of printing speed on the adhesion force is less pronounced compared to the effect of the Z-distance (Table 5). Despite this, it is worth considering that the printing speed of the first PLA layer remains a critically important factor for ensuring proper adhesion between materials.

Among the key factors for the formation of adhesive bonds, the extrusion temperature has been identified. Increasing the extrusion temperature to 210–220°C helps reduce the viscosity of the polymer melt, which enables its deeper penetration into the structure of the textile (cotton) base, improving the interfacial interaction [12]. However, given the limited thermal stability of PLA polymers, the extrusion temperature cannot be increased indefinitely. In view of this, within the framework of further comparative studies, an extrusion temperature of 220°C was chosen as one of the controlled variables. Although the specified temperature regimes exceed the parameters recommended by filament manufacturers, they remain significantly lower than the thermal decomposition temperature of PLA plastic (PLA TD = 300°C) [36], which makes it possible to avoid its destruction and at the same time contributes to the improvement of adhesive properties. The dependence of the influence of platform temperature (Table 6) on the detachment force (adhesion strength) of textile bases and PLA is clearly confirmed in Fig. 9.

Based on the generalization of our results, there is reason to believe that the implementation of mechanical tests and microscopic analysis makes it possible to provide a quantitative and qualitative characteristic of the interaction of the polymer (PLA material) with textile (cotton) substrates at the micro level.

The obtained patterns clarify and expand the results of previous studies in the field of 3D printing on fabric (cotton) [2], as well as prove the possibility of controlling the formation of the adhesive layer by changing the technological parameters of additive printing.

The results of our study are correct when performing direct FDM printing using PLA polymer and textile (cotton) substrates with certain morphological characteristics. The established patterns cover the technological parameters of FDM printing used in the experiments, in particular, the platform heating temperature, the value of Z-distances, the printing speed of the first layer and the extrusion temperature. The condition for the reproducibility of the results is the stable fixation of textile bases during FDM printing.

The following conditions that have a decisive influence on the adhesion strength have been determined: compliance with temperature regimes that do not exceed the limits of thermal stability of the PLA polymer; the ratio between the Z-distance of the equipment and the thickness of the textile base; taking into account the structural features of the textile bases, in particular, roughness and mass surface density. In turn, the results of the study cannot be applied when using other types of polymers and textile bases with mixed morphological characteristics, specialized coatings, since the mechanism of formation of adhesive bonds may differ.

The study did not consider or investigate mechanisms behind the aging of polymers and textile substrates, as well as the influence of operational factors that limit the application of our results.

During the research, certain shortcomings were identified that may affect the completeness and universality of findings.

First, the fixation of groups of samples in the mechanical grip of the Testometric DBBMTCL-250 kg testing machine could affect the uniformity of load distribution and contribute to additional stresses during the study.

Second, we did not take into account the influence of the heterogeneity of layer formation within one sample, which may lead to errors in the measurement results. The study also did not cover the influence of sample storage and aging under the influence of ultraviolet light. Measurements were carried out using contact elements, which, despite caution, may cause errors due to the instability of contact conditions.

Further studies should be conducted with samples of multifactorial experimental design to identify possible interactions between technological parameters. Further studies could aim at studying the process of forming adhesive bonds between polymer (PLA material) and paper (cardboard) substrates with different surface structural characteristics and degrees of printing. This approach would allow us to analyze the influence of the physical and mechanical properties of paper (cardboard) substrates (porosity, surface roughness) on the efficiency of adhesive bond when using direct FDM printing. This approach would allow us to analyze the influence of the physical and mechanical properties of paper (cardboard) substrates (porosity, surface roughness) on the efficiency of adhesive bond when using direct FDM printing.

In addition, the results of our experiments provide a basis for further research aimed at setting the optimal parameters for additive printing, depending on the type of printing materials, in particular, fabric substrates with mixed fiber bases or specialized coatings.

7. Conclusions

1. We have established that the process of forming adhesive bonds when applying a polymer by direct FDM printing to the surface of textile substrates is accompanied by the formation of a heterogeneous contact zone, which is manifested in the variation of the local detachment force along the polymer delamination line. The lowest detachment force values are characteristic of textile (cotton) substrates of group 6, having a thickness of 0.20 mm. The highest values are for group of samples 2, having a thickness of 0.48 mm. This dependence is due to capillary infiltration of PLA material and local mechanical compression of the fabric by an extruder at a Z-distance of less than 0.5 mm.

2. Microscopic studies confirm the correlation between the technological parameters of FDM printing and the depth of penetration of the polymer (PLA material) into the structure of textile substrates, which is an important factor in the formation of the strength of adhesive bonds. For sample group 2, the lowest values of polymer penetration depth for sample group 2, not exceeding 195 μm, were recorded at a Z-distance of 0.8 mm. At a Z-distance of 0.5 mm, maximum values were obtained, reaching 554 μm. Similar changes in the formation of polymer penetration depth are characteristic of sample group 4. This indicates the formation of a more developed heterogeneous contact zone at a smaller Z-distance, which is consistent with an increase in the adhesion strength of the polymer (PLA material) and textile substrates.

3. The highest adhesion strength indicators are characteristic of textile (cotton) substrates with a thickness of 0.4–0.7 mm, a surface density of 275–300 g/m^2, and a surface roughness of 60–105 μm. The deposition of polymer (PLA material) on the surface of textile substrates and the decrease in the detachment force are observed at a thickness of less than 0.3 mm, a surface density of 120 g/m^2, and a roughness of more than 105 μm. This dependence is explained by the decrease in the depth of mechanical closure and the area of the contact zone for thin and low-density textile substrates.

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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The study was conducted without financial support.

Data availability

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

Use of artificial intelligence

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

Authors' contributions

Tetiana Kyrychok: Conceptualization, Methodology, Supervision, Validation, Writing – review & editing; **Tetiana Klymenko**: Supervision, Investigation, Methodology, Formal analysis, Data curation; **Marina Volodko**: Investigation, Methodology, Visualization, Writing – original draft, Project administration; **Vladislav Doroshchuk**: Software, Resources, Visualization.

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