Запропоновано метод експериментального пошуку оптимального співвідношення товщини Ш-подібного клейового шару корінцевої частини книжкового блоку зшитого нитками, та необхідних і достатніх зусиль що прикладаються для його перегинань в процесі розкривання блоку.

Залежність прикладених зусиль до розкривання блоку в сторінковій або стохастичній послідовності, а також місце перегинання корінцевої клейової пластини, впливають на тривалість використання книги до початку незворотних руйнівних процесів.

Показано, що збільшення товщини клейового шару призводить до збільшення зусиль, направлених на подолання пружних властивостей полімерних пластин, отриманих після полімеризації нанесеного клею, зі сторони вигнутої зовнішньої поверхні корінця блоку. А також, до збільшення поверхневого натягу ввігнутої поверхні клейового шару, що знаходиться в безпосередньому контакті з імплантованими в структуру клею швейними нитками і папером корінцевих фальців книжкових зошитів.

Збільшення поверхневого натягу призводить до зменшення показників відносного видовження клейового шару, яке негативно впливає на утворення природніх кутів розкривання книжкових блоків і вимагає прикладання додаткових зусиль для експлуатаційного використання книги.

Виявлено, що розташування точок прикладання зусиль для перегинання корінцевої клейової пластини, в зонах обмежених кутами обхвату і в дельтовидних ділянках між зошитового простору, впливає на величину прикладених зусиль.

Представлений опис пружно-пластичного стану Ш-подібної корінцевої частини книжкового блоку у вигляді розробленого алгоритму етапів впливу товщини клейового шару на деформацію корінцевої частини.

Отримані залежності зміни кутів обхвату і дотичних кутів клейового шару, на етапах дискретної зміни його товщини, представлені у вигляді взаємо залежних графічних кривих в загальній системі координат.

Результати виявленого співвідношення товщини Ш-подібного клейового шару та змін кутів обхвату і дотичних кутів сприяли розробленню нових нормативів кількісного використання клею

Ключові слова: кути обхвату, дотичні кути, профільне нанесення клейової композиції, Ш-подібний корінець

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DETERMINING THE INFLUENCE OF THE THICKNESS OF AN ADHESIVE LAYER ON A CHANGE IN THE ANGLES OF CONTACT AND TANGENT ANGLES

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1. Introduction

Mechanical damage to book products that occurs over a long time of intensive use affects the preservation of geometric parameters, the competitiveness of physical appearance, operational stability, as well as the plastic capability by the book block opening angles to reach 180°.

In the process of active reading, as well as while copying on flat devices to scan the originals, the high reproduction quality and proper image representation can be ensured only by using pages of the maximally open blocks.

Damage to book products occurs in those components, which are exposed to the greatest influence of the operational load, and which, due to structural features, lose a warranted operational resource defined by the standards for technological fabrication.

The destruction of the adhesive film of the spine part of book blocks during the long-term use of a book is one of the most common defects occurring in the use of book products. According to data from the leading German libraries that perform technological restoration of worn-out book inventories, the destruction of the adhesive film accounts for approximately 15 % of the total number of other common types of operating defects [1].

Destruction of the adhesive film causes deformation of the spine of the block and the loss of a book product presentability (Fig. 1, *a*). It also leads to the partial loss of sheets, sagging, as well as the separation of individual sections from the spine (Fig. 1, *a*), splitting blocks into parts, in any inter-section places, with the destruction of the edging tape, or without its destruction (Fig. 1, *b*).

Non-compliance with technological standards, or a separate malfunction of the adhesive apparatus, leads to glue flowing in between the section- or page space (Fig. 1, *c*). There are defects related to the partial discrete gluing of the tangent sections or paper pages in a book block, in the areas of the inner spine part of section folds, in places of needle punctures and of preliminary fastening of sections with threads.

Due to defects in the unpredictable zones of gluing that restrict the movement of the spine part of a block during its operational opening, there is gradual destruction and loss of operational stability in the period much less than warranted.

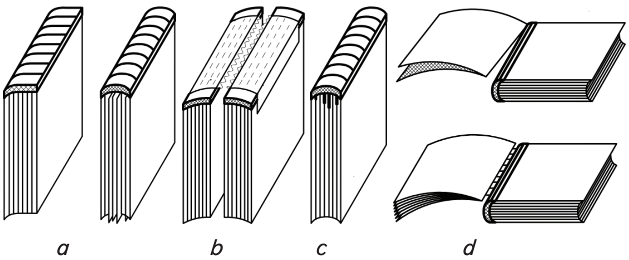

Fig. 1. Certain types of destruction of the spine part of book blocks stitched with threads: *a* — deformation a block spine and the loss of individual sheets, or sections; *b* — splitting the spine of a block with the destruction of an edging material; *c* — glue penetrates the space between sections; *d* — separation of bookends, detachment of the first or last sections

Separation of bookends and Nachsatzen from the first and the last sections of a block, as well as the separation of sections at the beginning and end of a book (Fig. 1, *d*) indicates the lack of proper fastening of the spine part of the book block by an adhesive polymeric film.

Searching for the optimum conditions of the technological manufacture of book products relating to fastening the spine part of a book block, sewn with threads, by adhesive compositions is an important area of research aimed at determining the main destructive factors and ways of their minimization, or significant elimination.

2. Literature review and problem statement

The world publishing is characterized by an active innovative search of development directions, which is manifested in the assortment features of book products in terms of the structural, energy-saving, and ergonomic components of their production [1]. One of the factors affecting prolonged use of book products is to ensure reliable fastening of the W-shaped spine part by the stitches of binding threads and by the application of adhesives, which together provide for the durability of fastening and resistance to plastic deformation.

Paper [2] reports a study that showed that one of the many advantages of adhesive connection is that it opens up new opportunities for connection of materials with different physical and geometric characteristics, without causing changes in the structure of these materials. Newest processes to glue materials of different origin include a series of operations that ensure the assembly of the adhesive connection in accordance with the structure of the product, such as preprocessing the surfaces for gluing, glue preparation, adjustment of the position and assembly of structural parts, hardening of the glue. However, it should be noted that the cited paper, when enumerating technological operations of gluing individual materials, fails to address the gluing of movable composite structures, which include the W-shaped spine parts of book blocks, sewn by threads. This means that the study into the adhesive connections of materials with different geometry and physical properties has not identified the details of the process of gluing profile semicircular paper parts, which include the folded book sections, sewn by threads with pre-tension.

The expediency of using adhesive joints was confirmed in [3] by the improved mechanical stability between the structural elements of various semi-finished products that allows the gluing at high output and reliability, which ensures the durability of finished products during long-term storage. However, the cited work did not investigate the still-unclarified impact of destructive operational factors on the capability of glued products to be used over time.

It should be noted that, as shown in paper [4], the past few years have seen a significant reduction in the circulations of book editions and the rapid increase in their titles. Limited editions of books, printed digitally, can consist of only a few copies. Accordingly, for limited circulations, when fastening the spine part of a book, there is no possibility of adjusting the adhesive apparatuses for the specified thickness of adhesive application, which is in practice adjusted by using a significant number of book blocks that are discarded. In practical terms, this causes difficulties due to overspending of quality semi-finished products, so the thickness of the adhesive layer is always excessive, in order to prevent premature destruction of book blocks, and is due to the absence of auxiliary objective indicators.

As argued by authors of [5], a promising area of research aimed at possible reduction of adhesive consumption is to determine the indicators of strength and adequacy of the thickness of the adhesive layers, applied by a cylindrical glue roller, without the consideration of the rounded geometry of the folds of sections, stitched by threads into a book block. Despite the practical significance of the reported results, the authors did not consider the possibility of applying the adhesive by a shaped roller, whose geometry is close to the W-shaped surface of the spine part of book blocks sewn by threads.

In contrast to the results reported in [5], the data obtained in [6] on the intensity of the destruction of book block spines, fastened by the non-binding adhesive technique, make it possible to identify influencing factors that reflect the physical-mechanical properties and structure of contact materials. The authors consider the discreteness and pulse nature of the external force applied by a reader to open the book, the presence of deformations, changes in the geometry of the spine, and its structure. Therefore, there are reasons to believe that the cause of the destruction of the spine of the book block fastened by a non-stitching adhesive technique may be the concentration of stresses in the adhesive joint, which is observed along the edges of the glue seam. That may be the consequence of the difference in the deformation of the adhesive film and paper, in the value of their modulus of elasticity, as well as the physical and mechanical properties of adhesive compositions. However, no practical testing has been undertaken to confirm these assumptions. The factors, specified in the cited paper in the research into the spines of book blocks, fastened by a non-stitching adhesive technique, were not matched, due to possible conversion coefficients, or other optimally close indexes, to the operational properties of the spines of book blocks, sewn by threads and edged by glue compositions.

An example of the non-stitching adhesive bonding has shown [7] that obtaining credible numerical indicators of the deformation of an adhesive layer at the spine of a block, as well as establishing a dependence between the action period and stresses arising at block spine bending, must match the conditions for experiments. It should be noted that one must consider both the initial factors of the use of book products and the same estimated thickness of adhesive composition application on the spine of a book block, which is in a static state until opening.

Work [8] considered phenomena of the stressed-strained state of a narrow fragment of the flat spine adhesive layer with a thickness defined by the structure of the book block selected for the experiment. The studied fragment is separated from the general array of the connecting adhesive film and is in the tangent zone of two adjacent pieces of paper sheets. It should be noted that the established analytical dependences in the deformation of a spine's adhesive film helped investigate the influence of technological factors on the durability of the non-stitching adhesive fastening of book blocks. That means that taking into consideration a given factor provides an opportunity to adjust the thickness of an adhesive layer at the spine part of the book block, bonded by a non-stitching adhesive technique (NAT), directly under conditions of circulation production of books. However, unlike the reported results for blocks made by NAT, paper [8] gives no identical studies for the W-shaped spines of book blocks stitched with threads.

To expand the directions of research into the operational deformation of book spines' adhesive plates, work [9] separated the adhesive layer, with a small fraction of the spine folds of a book block, on a paper-cutting machine. The authors modeled the conditions under which the edges of the adhesive layer of a book block, fastened by a non-stitching adhesive technique, were clamped, and turned at a predefined angle when opening the book. The opening is carried out along the line between two sheets of paper, position-based, anywhere in the book block. At known approximation, the reaction of the adhesive layer on bending can be taken proportional to the elastic deflection of the singled-out area. The reported study made it possible to explore the nature of changes in the stressed-strained state of the flat spine's adhesive plate of the non-stitching adhesive bonding of a book block's sheets when opening the book. However, there are reasons to believe that the experimental efforts applied for bending the examined adhesive plates [9] do not fully correspond to the efforts that form the natural opening angles of book blocks when reading, therefore, additional research must be undertaken in this direction.

However, it is impossible not to notice that the results reported in [8, 9] regarding a change in the stressed-strained state of the spines' adhesive plates take into consideration the binding of book blocks only by a non-stitching adhesive technique. This binding applies to the block consisting of individual sheets, after trimming the spine part, rather than a block of separate folded sections.

In the trimmed spine part, discrete recesses are formed, to increase the surface area of gluing. After application of the adhesive, some part of the spine of the block, sheet-wise, similar to reinforcement, integrates into the thickness of the adhesive, forming in the area of bonding a solid composite medium of enhanced rigidity. The phenomena of elastic deformation, inherent in it, are formed, which cannot be directly copied to be applied to the processes of deforming a W-shaped adhesive plate.

The formation of a composite environment of the W-shaped spine part of a book block stitched by threads has its own peculiarities of creation, which, first of all, include the integration into the surface part of the connecting spine's adhesive layer of sewing stitches of thread and the planar attachment of an edging tape. This means that it has not been defined how the stages of the elastic-deformed state of a W-shaped layer form and what factors influence its transformation, which requires the continuation of thorough research in this area.

A separate approach to modifying the strength, added to the adhesive layer of book blocks, fastened by a non-stitching adhesive technique (NAT), in order to improve the structural and operational durability and to ensure the maximum opening angle of blocks, was described in work [10]. It involves the technological options for bonding the edging-capturing tape to the surface of the spine part formed by NAT. The authors established regularities of the influence of the physical and mechanical properties of edging materials on the strength of books made by NAT.

At the same time, there are no studies into the influence of edging materials on the phenomena of the elastic-plastic deformation of an adhesive layer at book block bending, identical blocks with different thickness of glue, or book blocks with the W-shaped spine part.

Study [11] argued that for the processes of edging the book blocks, sewn by threads, with a W-shaped configuration of the spine, increasing the concentration of the adhesive at its constant consumption gives a significant effect of growth in strength. The two-fold increase in concentration ensures the increase in the strength of bonding sections from non-stitched types of paper for high printing by 1.5–2.5 times, and by 3.0–4.5 times in glued offset papers. The use of concentrated glue, at the constant consumption of dry matter, provides for greater strength of section bonding, better conditions for drying the spine, thereby making it possible to save glue when handing blocks made from the unglued paper.

The cited study did not investigate the profile application of the adhesive to the spine of the block, so, when calculating the thickness of an adhesive layer, the considered angles of contact were those that restrict zones only of the semi-circular areas, tangent to the folds of the sections, without the consideration of wedge plots in the space between sections. No effect of increasing the concentration of an adhesive composition was considered, at the same thickness of the adhesive layer, on the phenomena of the elastic and plastic deformation of the adhesive plate at bending.

The above studies relate to the phenomena of gluing surfaces of different materials, the concentration, and modification of adhesive compositions, operational destruction of flat adhesive layers in the book blocks fastened by a non-stitching adhesive technique. That allows us to argue that issues related to the destruction of the W-shaped spines of book blocks, stitched by threads, that reflect the physical and mechanical properties of the contact materials, can be addressed by identifying the effect of changing the thickness of the adhesive layer on changes in the angles of contact and tangent angles.

Therefore, there are reasons to believe that the insufficient definiteness and an insignificant number of confirmed practical results from studying the phenomena of the elastic-deformed state of the book W-shaped spine joints, which has so far been considered insufficiently, predetermined the relevance of our research into this area.

3. The aim and objectives of the study

The aim of this study is to detect the influence of the thickness of a glue layer of the W-shaped spine part of a book block, sewn by threads, on the changes in angles of contact and tangent angles. The dependences to be established would contribute to the creation of necessary and sufficient conditions that should ensure the strength, plasticity, and operational stability of the adhesive polymeric composition at long-term bending.

To accomplish the aim, the following tasks have been set:

– to determine the ratio of increasing the thickness of an adhesive layer and the indicators of its strength and resistance to the formation of microcracks and destructive zones, as well as determine the feasibility of additional consumption of glue per unit of product;

– to construct an algorithm describing the stages in the influence of adhesive layer thickness on the elastic-plastic deformation of the spine part of blocks using an example of gradual bending of two plates of different thicknesses, which edge the folded calibrated sections in two identical blocks;

– to measure and build the graphic dependences of change in the angles of contact and tangent angles of an adhesive layer at the stages of a discrete change in its thickness;

– to suggest constructing an estimated scheme for determining the moments of force, applied at the discrete places of bending the plates from the initial fixed thickness of t mm to the thickness of $t+\Delta_{1...i}$ mm, where $\Delta_1...\Delta_i = \text{const}$.

4. Materials and methods to study the profile application of an adhesive layer onto the W-shaped spine part of a book block

The technique of applying an adhesive composition onto the W-shaped spine part of a book block, sewn with threads, implies using the Kolbus KM 600 binding line. The line is designed for manufacturing book products whose spines are fastened using a non-stitched adhesive technique (NAT), as well as for edging book blocks that are stitched with threads. The Kolbus KM 600 binding line is a part of the compact flowline for making books in hardcovers BF-512 (Germany).

However, the layer of an adhesive applied by the Kolbus KM 600 binding line onto the spine of a block, sewn with threads, does not repeat the profile of the rounded sections' folds (1) (Fig. 2, *a*) but forms an outer surface of the adhesive close to a straight line (2) (Fig. 2, *a*) [12]. This technological feature of the production process of edging book blocks leads to partial overconsumption of glue, creates additional stresses in the adhesive plate when opening a book at readable angles, speeds up the operational destruction of the plate.

Therefore, the current research involved an experimental adhesive application mechanism that we designed (Fig. 2), mounted in the Kolbus KM 600 binding line. The mechanism employs a profile roller, which repeats the relief part of the W-shaped spine of a book block and adjusts the application of the specified discrete layers of an adhesive for our study (Fig. 2, *b–d*).

The experimental device for applying a changing dimensional adhesive layer, shown in Fig. 2, consists of the moving clamps (3), to fix the fragments of the spine part of a book block (1), before applying the adhesive and transporting them in the clamped state along the guides (4).

In addition, the device includes an adhesive bath (5) with a zone of adhesive application (6) by a profile rotating roller (7). The adhesive is applied discretely onto the defined size t_{ad}; its total thickness after each measurement is increased and denoted via t_{va}. For the experiment, we used book blocks, sewn with threads, made from the offset paper produced by Sappi (Austria), with a weight of 150 g/m^2, with 32-page sections, in which a section's thickness is 5.44 mm, and a spine rounding radius is, respectively, 2.72 mm. Measurements were carried out by an electronic paper thickness measuring instrument with a measurement precision of 0–10 mm/0.01.

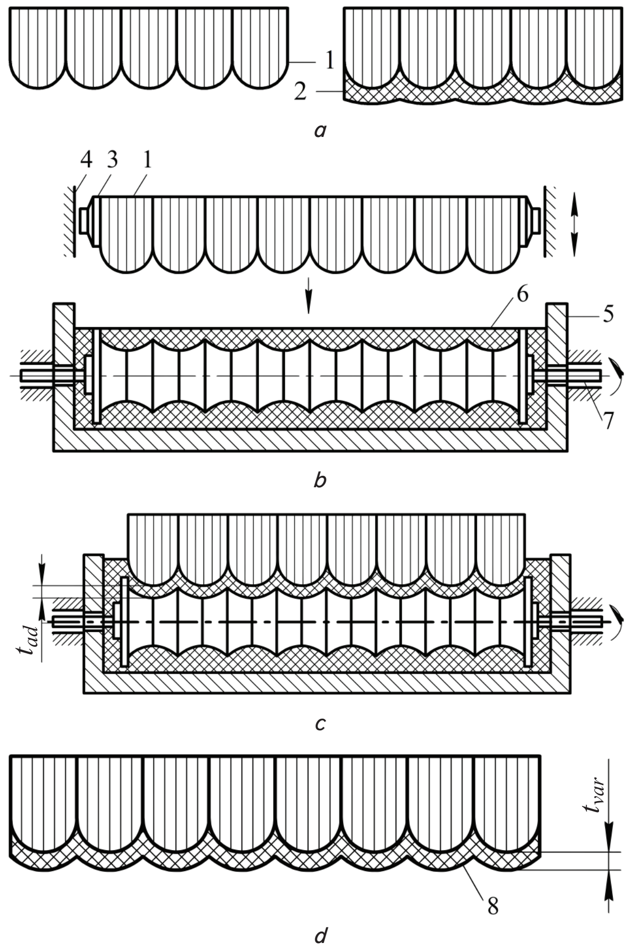

Fig. 2. The mechanism of the profile application of an adhesive onto the spine part of a book block, sewn with threads: *a* — the W-shaped spine part of a book block and the spine part of the block with the applied layer of an adhesive; *b* — the mechanism of an experimental profile application of an adhesive at the beginning of the technological cycle; *c* — profile experimental application of an adhesive; *d* — the spine part of the block with the profile adhesive layer; 1 — fragments of the W-shaped spine part of the block; 2 — an outer line of the adhesive layer; 3 — clamps; 4 — guides; 5 — adhesive bath; 6 — adhesive; 7 — profile rotating glue roller; 8 — the examined experimental W-shaped adhesive layer; t_{ad} — initial thickness of an adhesive layer; t_{var} — variable thickness of an adhesive layer

For reasons of convenience, we selected the 32-page section blocks, due to their increased gluing width between the spines' folds as compared to 16-page sections. At the same consumption of glue, the use of thicker sections would improve the strength of an adhesive layer by 10–15 % [11] and could positively affect the visibility of experimental tests aimed at determining the destructive effects of bending.

The mechanism for adjusting the feed of an adhesive and calibrating the thickness of the applied layer on the block spines was employed for the blocks whose thickness ranges between 40–70 mm and which consist of 7–12 sections.

To perform the experiments when modeling the deformation of an adhesive layer of the spine part of a book block, sewn with threads, we selected blocks that are 38.08 mm, 43.52 mm, 48.96 mm, 54.40 mm, 59.84 mm, and 62.28 mm thick. The blocks of this thickness are included in a stable range of technical capacity provided by the Kolbus KM 600 binding line.

For the above blocks, we manufactured a profile roller of the adhesive apparatus with geometric parameters of the W-shaped spine part of the selected sections. In the process of research, according to the conditions of the experiment, the constant values for applying an adhesive layer are adjusted by a computer control system of the Kolbus KM 600 binding line.

Further profile application of an adhesive under industrial conditions would contribute to the reasonable minimization of consumption, under the strict condition for maintaining the indicators of the strength of an adhesive connection and its operational endurance.

To apply an adhesive polymeric composition on the spine folds of the books, sewn with threads, the bookbinding processes commonly employ such glues as the thermal adhesives Technomelt Q3660 (Germany), BAM 1078 (UK), OGIMELT 110 (Germany), and the dispersed glue Adhesin 7236 (Germany).

For the current experimental study, we selected the thermal adhesive BAM 1078 as it ensures a strong connection strength, a fixed thickness after application, the speed of fastening, and plasticity at bending.

5. Determining the factors that influence the thickness of an adhesive layer of the spine plate, as a complex elastic body, on change in the indicators of strength and destructive stability

It is known [11] that in terms of a structural form the adhesive joints, implemented in the technological processes of bookbinding production, are divided into flat, W-shaped, T-shaped, and combined.

The flat gluing is used in the assembly of bindings, inserts into binding blocks, gluing binders, illustrations, and small parts of a sheet of paper to sections. The T-shaped adhesive joint is used for an adhesive non-stitched binding, and the combined adhesive joints – for the edging of spines in the process of sewing and gluing and when the blocks are covered by covers before release.

The adhesive joints of the W-type are used in the bookbinding processes of edging book blocks, pre-stitched by threads, to ensure the physical integrity of the product. The operational strength, elasticity, and plasticity of the spine part of a book ensures the discrete opening of a block, in any part of it, at angles close to 180°.

The return of a block to the ascending position after opening should occur without irreversible strain signs that lead to the loss of physical appearance and reduction of the period of technologically predictable use, defined by industry standards. The opening of a book during reading or copying should involve no efforts that could result in premature destruction of the spine.

When flipping the pages of a book block, sewn only with threads, the gaps occur between the sections, which do not provide enough strength to fastening the spine part of the book block. In subsequent technological operations, they are eliminated by the glue that fills the gaps, formed by the semicircular sections' folds, which fit tightly to each other inside a clamping device of the adhesive system (Fig. 2, *b*).

Most widespread for stitching the blocks is the use of nylon and cotton threads in three, four, and six assemblies, which provide for the high tensile strength and technological breaking elongation. Other advantages of bookbinding threads include a smooth surface, the resistance to moisture and abrasion, as well as high adhesion permeability in the process of wetting the spines of sections with liquid adhesive compositions in the form of solutions, dispersions, or melts [6].

When analyzing the processes of sewing book blocks with threads, it should be noted that the tightening and density of stitches depend on the type of paper used in book sections, the quality of sections, the accuracy of folding, and the formation of a technologically defined shape of the sections' spines.

This contributes to high-quality stitching without distortions in the technological positioning, piercing and stitching areas, as well as due to the properties of the used threads, which, during sewing, are not subjected to disruption and critical elongation.

The magnitude of adjustment of a thread-guiding system, on the one hand, should ensure the maximum tension of threads for the dense fastening of the spine part of a block; on the other hand, should not exceed the boundary effort, which would lead to the destruction of the holes formed by the needles-punctures in the spine part of sections. Because of holes with destructive defects, it is possible that a glue partially penetrates the middle of the sections, when edging book blocks, and pages inside the spine part of the folded sections of the book are glued in some points.

The use of synthetic nonwoven materials, special microcreped paper tapes, tapes made from dense offset papers, craft, and other bookbinding materials, resistant to destruction, forms an additional reinforcement of the spine part of a book block, in addition to sewing with threads and by gluing.

Modern high-speed lines for the production of books by a non-stitched adhesive technique or books whose blocks are sewn with threads ensure the application of adhesive polymeric compositions of the predefined thickness onto the spine part of a block. The technological process of application is carried out over a single run, taking into consideration the binding properties of such compositions; the gluing of edging and captal tapes is ensured, as well as soft covers.

Because the adhesive layer does not have an open surface for evaporation (on one side, there is a spine part of the block, on the other – an edging material), it is not, therefore, possible to achieve the natural technological polymerization over a short time.

The technologically defined prolonged drying, book lines include the transporting devices of the rotary type, which provide for a sufficient linear length of the moving conveyor belt for the required time of fastening the adhesive, as well as a limited space within a production facility.

Modern polymeric compositions ensure proper wetting, as well as absorption in the process of gluing the binding components of the spine part of book blocks. These components include the outer paper part of the folded sections, with a dense discrete layer of cotton or synthetic threads at the surface of the folds, as well as a paper edging tape.

The layer of glue fills the pores and capillaries of these components and forms a polymer plate created after the polymerization of the applied adhesive composition, whose estimated thickness ensures the highly technological opening capacity of a block, as well as long operational stability [13].

The thickness of such a plate ranges widely, defined by the formats of an edition, the number of sections and pages in the sections, the types and mass of the paper in a book block, as well as the kinds of sewing stitches, the cross-section of threads, and the raw materials which these threads are made from.

Fig. 3 shows the cross-section of a fragment of the adhesive polymeric plate of the spine part of a book block, sewn with threads, whose structure of the main array of the W-shaped layer of an adhesive (Fig. 3, *b*) hosts, on the side of the concave surface, the implanted stitches of binding threads (Fig. 3, *a*), which form a dense connecting spatial structure for the spine folds of the sections.

The outer surface of the adhesive plate (Fig. 3, *c*) is edged with a paper tape, which, given the high adsorption properties of binding glue, creates a surface composite part of the main array of the adhesive on the spine of a book block.

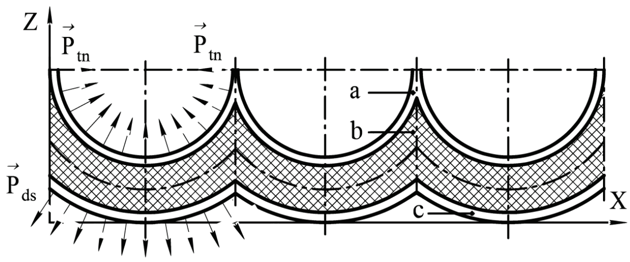

Fig. 3. The cross-section of a fragment of the adhesive polymeric plate of the spine part of a book block, sewn with threads: *a* — the spatial plane of thread stitches; *b* — an array of the W-shaped adhesive layer; *c* — paper edging tape; $\overrightarrow{P_{tn}}$ — vectors of efforts of the tension of threads implanted in a layer of the adhesive; $\overrightarrow{P_{ds}}$ — vectors of efforts of the discrete destruction of a paper tape $\overrightarrow{P_{tn}}$

The adhesive structure of the spine part of a book block, stitched with threads (Fig. 3), is formed by the W-shaped array of a binding glue, with the thread stitches and paper tape implanted into the inner and outer surface. It is possible to assume that such an adhesive composition forms an elastic composite environment, with the main element of the environment being a binding adhesive, and inclusions from other materials, which are the binding threads and an edging paper tape.

Vectors $\overrightarrow{P_{tn}}$ (Fig. 3) denote the directions of the total efforts of thread tension, some of which occur in the process of stitching book blocks at a sewing machine and dense tightening of their spine part. Others occur at the moment of opening book blocks and bending a composite adhesive plate whose structural component is the thread stitches.

Vectors $\overrightarrow{P_{ds}}$ (Fig. 3) denote the directions of efforts for destroying an edging paper tape, which arise at the moments of prolonged operational opening of book blocks when reading or scanning information from the pages of a book unfolded at the angles of 150–180°.

The results of analyzing operational indicators demonstrate the greater reliability and durability of multicomponent plastic environments compared to the homogeneous ones. The spine part of a book block can be considered as a complex elastic body (matrix) whose main and defining component is the polymeric adhesive, to the structure of which the sewing threads and an edging paper are implanted. The threads and paper are distributed in the structure of the adhesive from the side of the inner and outer surfaces of the spine's adhesive plate.

When exposed to the action of operational loads, gradual wear, and destruction of such materials, the specific interaction between the matrix (an adhesive composition) and the components of the inclusions, despite the fact that they account for, in comparison with the matrix, a small weight part, significantly affects the strength and durability of the adhesive composition [14].

Such a composite adhesive polymeric plate has a heterogeneous anisotropic structure, the components of which are glue, thread, and paper. In terms of percentage, the quantitative index of the materials of threads and paper in the composite polymeric plate is significantly lower than the material of the glue. For the convenience of modeling the operational processes and destructive effects, we assume that the adhesive polymeric plate of the spine part of a book block, sewn with threads, is an isotropic body.

The distribution of destructive stresses in the adhesive polymeric plate, considered to be a physical isotropic body, when turning the pages of a book and, accordingly, at the discrete bending of the plate, is divided into two main and defining directions.

The first type of stresses arises at the free opening of a book without additional efforts on the inner part of the block and while forming the natural angles of block opening at 70–120° only under the action of the weight of the pages of the open book formed in sections. At the place of opening, the block is divided into two disproportionate parts, which bend the spine's adhesive plate toward the more weight of the pages. On the proportional part, the block is divided only in one case – at the opening in the middle, but the natural opening angle of a block can deviate from the central position due to the heterogeneity in page bending with different levels of the pre-acquired residual deformation.

The second type of stresses implies additional efforts to force open a book block to the angles of 170–180°, for comfortable reading or scanning.

During the period of reading or scanning, there is the formation of residual deformation ε in the structure of an adhesive plate, which, after long-term bending, leads to the destruction of the edging plate and the entire book block:

$$\varepsilon = f\left(P, \tau\right) = \frac{\mathrm{d}P}{\mathrm{d}\tau}, \tag{1}$$

where *P* are the efforts aimed at opening a block and discrete bending of an adhesive plate; τ is the duration of loading a spine's plate.

The operational stability and resource of using a spine's composite polymeric plate depend and may vary at the fluctuation in thickness and structural geometric configuration of the W-shaped adhesive layer. It also depends on the paper density, its mass, the number of pages in the sections, and, consequently, the thickness of the sections, which determines the size of the rounded parts of the folds as the surface for applying an adhesive composition while edging the block [15].

Prolonged bending of the book block's spine part during reading or scanning form constant changes in the external geometric parameters of the adhesive plate. Given the sign-changing nature of the efforts applied at bending, there is a projected transition from the phenomena of elastic deformation and temporary preservation of the operational properties of the plate to the phenomena of residual and viscous deformation [16]. These phenomena occur during the life cycle of a book product, over which the critical destruction of its components is formed.

While maintaining the geometric dimensions and thicknesses of sections in book blocks, a change in the types of paper in the sections changes their weight, plasticity at deviation, which leads to an increase or decrease in the natural opening angles of the blocks. There are changes in the conditions of the operational load on the spine part of a book block, which predetermine the conditions for a differentiated approach to the calculation of an adhesive layer thickness [17].

On the one hand, the minimum and sufficient thickness of an adhesive layer ensures the good opening capacity of a book block, which does not require considerable efforts; on the other hand, the operational period of using such a book block is close to the warranted life cycle.

A significant and necessary condition, at first glance, to ensure the reliable edging, by an adhesive composition, of the W-shaped spine of a book block, sewn with threads, is to increase the thickness of the adhesive layer, to provide for further long-term use of the book.

However, increasing the thickness of the adhesive layer should correlate with its strength and resilience indicators, which ensure prolonged use of the book block, which significantly exceeds the warranty period.

In addition, it should relate to the indicators of the appropriateness of additional adhesive consumption per unit of a finished product, which ensures the necessary and sufficient amount of it when edging a book block's spine.

6. Constructing an algorithm of influence exerted by the stretching and compression of the concave surface of an adhesive layer on the elastic-plastic deformation of a block's spine

A transition through the optimal limit for increasing the thickness of an adhesive layer contributes to the more rapid destruction of the concave side of the polymeric plate, which is stretched, over a long time, exposed to additional maximum loads when opening a book [18].

Fig. 4–7 show the stages of the influence exerted by a thickness of the W-shaped adhesive layer on the elastic-plastic deformation of the spine parts of book blocks, sewn by threads, using two spine's adhesive plates. The plates are formed when edging two identical book blocks: in a first one – a layer of an adhesive corresponds to the size of t mm; in a second one – a layer of an adhesive is enlarged and corresponds to the size of $t+\Delta_{gl}$ mm.

Fig. 4 shows the transverse cross-section of the W-shaped layers of the polymeric adhesive, through which the edging of book blocks, sewn by threads, is performed; the book blocks are closed, are in the static condition, the pages are not turned.

Fig. 5 shows the cross-section of an adhesive layer at the onset of turning the pages of the book blocks and the gradual bending of the spine's polymeric plates, the formation of stressed areas under the influence of the stretching and compression forces.

Fig. 6 shows the enlarged fragments of adhesive layers depicting the stretching and compression zones of the wedge-shaped deltoid part at the time of opening a book block.

Fig. 7 shows the enlarged, separated from the fragments of adhesive layers, graphic areas of the stretching and compression of the central part of the wedge-shaped deltoid plots, the vector groups of efforts of stretching and compression.

Fig. 4 demonstrates the fragments of the cross-sections of edging adhesive polymeric plates, two identical book blocks, with different glue thickness of t and $t+\Delta_{gl}$ mm, in a position corresponding to the closed book, until the beginning of the block opening.

The adhesive plates have the proper linear nature of arrangement in a book block with a direct spine, whose structure, in contrast to the rounded one, is selected for the clarity of modeling the bending and observing the arising loads.

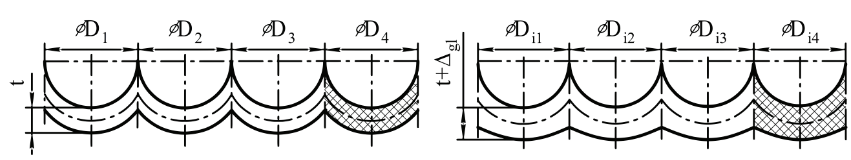

Fig. 4. The fragments of the cross-section of the adhesive plate with a glue thickness of t mm and $t+\Delta_{gl}$ mm

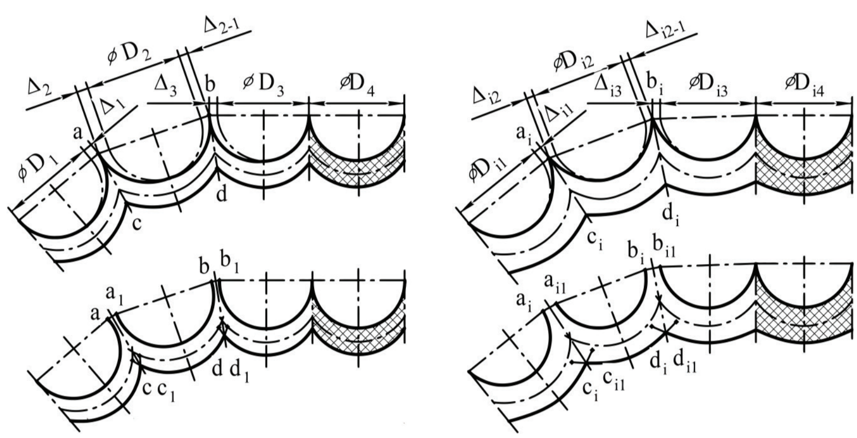

Fig. 5. Bending the adhesive plates, the formation of stretching and compression zones

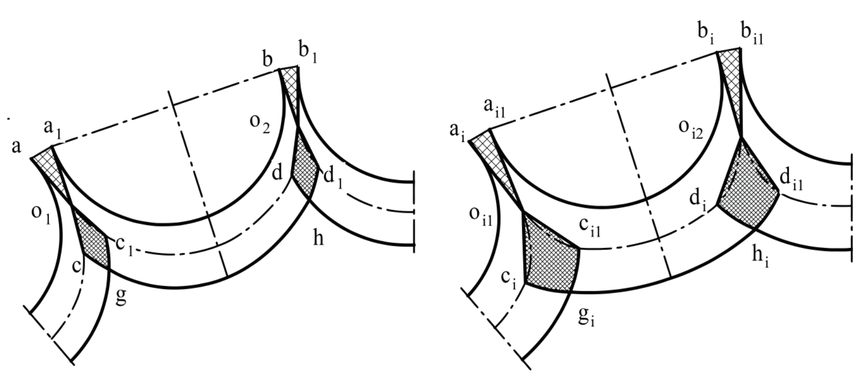

Fig. 6. Distribution of stretching and compression efforts

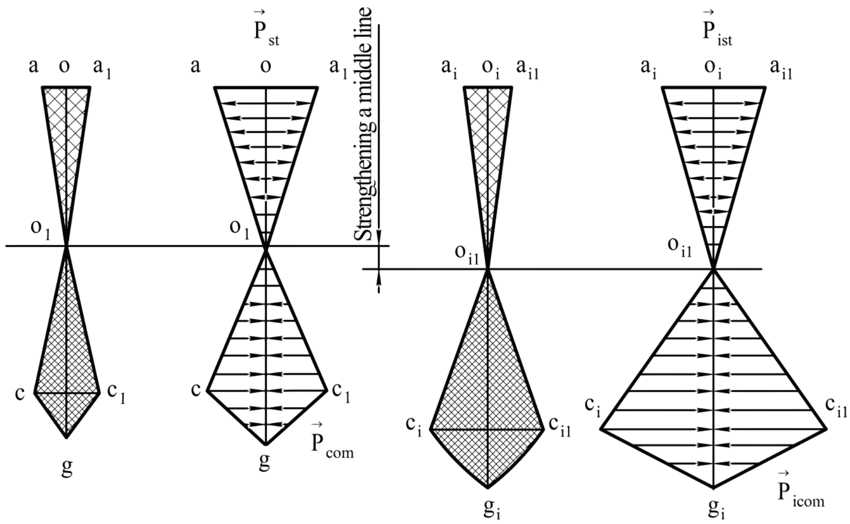

Fig. 7. Influence of the glue layer thickness on the elastic-plastic deformation of the spine part of book blocks, the diagrams of stretching and compression efforts

To ensure the credible modeling of plate bending, the diameters of rounding the spine's folds are identical, according to the practically satisfied condition for the experimentally formed identity of sections, in the number of pages and the uniformity of the material, from which both book blocks are made. That is:

$$\varnothing D_1 = \varnothing D_2 = \varnothing D_3 = \varnothing D_4 = \varnothing D_j = \text{const}, \quad (2)$$

$$\varnothing D_{i1} = \varnothing D_{i2} = \varnothing D_{i3} = \varnothing D_{i4} = \varnothing D_{ij} = \text{const}. \quad (3)$$

Partial bending of the adhesive plates, when opening book blocks, distorts the properly concave semicircular contours of the inner part of the plates, which correspond to the geometry of the initial state of the book blocks before opening, at variable additional values Δ (Fig. 5).

The experimental bending of the plate takes place between sections along the directions of the intersecting lines marked as the *ac*, *bd*, a_ic_i, b_id_i lines. The lines pass through the zone of protrusions, which are formed when glue fills the tangent semicircular surfaces of neighboring sections and have the configuration of a deltoid with the concave sides.

When turning the pages of the book page by page, the efforts that are applied for the discrete block opening at any point have an inhomogeneous dimension value. The heterogeneity of the efforts that defy precise measurement, moreover, calibration, would correspond to the geometric difference in the deformation of the adhesive plate.

The deformation of stretching and compression leads to the greatest destructive phenomena along the concave surface of the adhesive layer, tangent to the semicircular surfaces of the spine folds of book sections (Fig. 3).

Consider a plate in Fig. 5, where, for $\varnothing D_1$, we accept its linear size to be S_1; then the increase of linear deformation for $\varnothing D_1$ in the vicinity of point a would equal $\varnothing D_1 + \Delta_1$ or $S_1 + \Delta_1$. The linear deformation ε_1 in the vicinity of point a shall equal:

$$\varepsilon_1 = \lim_{S_1 \to 0} \frac{\Delta_1}{S_1}. \quad (4)$$

For $\varnothing D_2$, we accept its linear size to be S_2, then the increment in the linear deformation for $\varnothing D_2$ in the vicinity of points *a* and *b* would equal $\varnothing D_2 + \Delta_2 + \Delta_{2-1}$ or $S_2 + \Delta_2 + \Delta_{2-1}$.

The linear deformation ε_2 in the vicinity of points *a* and *b* is equal to:

$$\varepsilon_2 = \lim_{S_2 \to 0} \frac{\Delta_2 + \Delta_{2-1}}{S_2}. \quad (5)$$

For $\varnothing D_3$, we accept its linear size to be S_3, then the increment in the linear deformation for $\varnothing D_3$ in the vicinity of point *b* would equal $\varnothing D_3 + \Delta_3$ or $S_3 + \Delta_3$.

The linear deformation ε_3 in the vicinity of point *b* is equal to:

$$\varepsilon_3 = \lim_{S_3 \to 0} \frac{\Delta_3}{S_3}. \quad (6)$$

Accordingly, the plate in Fig. 5, where, for $\varnothing D_{i1}$, we accept its linear size to be S_{i1}, then the increase in the linear deformation for $\varnothing D_{i1}$ in the vicinity of point *a* would equal $\varnothing D_{i1} + \Delta_{i1}$ or $S_{i1} + \Delta_{i1}$.

$$\varepsilon_{i1} = \lim_{S_{i1} \to 0} \frac{\Delta_{i1}}{S_{i1}}. \quad (7)$$

For $\varnothing D_{i2}$, we accept its linear size to be S_{i2}, then the increase in the linear deformation for $\varnothing D_{i2}$ in the vicinity of points *a* and *b* would equal $\varnothing D_{i2} + \Delta_{i2} + \Delta_{i2-1}$ or $S_{i2} + \Delta_{i2} + \Delta_{i2-1}$.

The linear deformation ε_{i2} in the vicinity of points *a* and *b* would be equal to:

$$\varepsilon_{i2} = \lim_{S_{i2} \to 0} \frac{\Delta_{i2} + \Delta_{i2-1}}{S_{i2}}. \quad (8)$$

For $\varnothing D_{i3}$, we accept its linear size to be S_{i3}, then the increase in the linear deformation for $\varnothing D_{i3}$ in the vicinity of point *b* would equal $\varnothing D_{i3} + \Delta_{i3}$ or $S_{i3} + \Delta_{i3}$.

The linear deformation ε_{3i} in the vicinity of point *b* would equal:

$$\varepsilon_{i3} = \lim_{S_{i3} \to 0} \frac{\Delta_{i3}}{S_{i3}}. \quad (9)$$

The discreteness of efforts applied to open a book block, both at the point of application and at the time of finding certain zones of the adhesive plate under load, forms a geometrically different increase in linear dimensions in each fixed zone of bending the polymeric plate, so:

$$\Delta_1 \neq \Delta_2 \neq \Delta_{2-1} \neq \Delta_3 \neq \Delta_{i1} \neq \Delta_{i2} \neq \Delta_{i2-1} \neq \Delta_{i3} \neq \text{const}. \quad (10)$$

Fig. 5 shows the phenomena of stretching the upper part of the spine plates at points *a*, *b*, a_i, b_i, where the stretching zones a–a_1, b–b_1, a_i–a_{i1}, b_i–b_{i1} are formed. However, at points *c*, *d*, c_i, d_i, there occur the compaction and crumpling of the inner structure of the adhesive plates, the displacement of the inner polymeric layers, denoted by sections c–c_1, d–d_1, c_i–c_{i1}, d_i–d_{i1}, which promotes the accumulation of elastic deformation efforts and creation of the energy reserve to return a bent adhesive plate to the original position after the book is closed, as well as the return of the stretching zones at points *a*, *b*, a_i, b_i to the ascending state.

The shaded graphic zones of stretching, crumpling, and shear with different filling areas are enlarged for clarity in Fig. 6; they are marked as $aa_1o_1cgc_1$, $bb_1o_2dhd_1$, as well as $a_ia_{i1}o_{i1}c_ig_ic_{i1}$ and $b_ib_{i1}o_{i2}d_ih_id_{i1}$.

In Fig. 7, the area of the ao_1a_1 triangle, which reproduces the contours and a zone where the efforts of stretching the adhesive layer are applied, is almost identical to the area of the o_1cgc_1, deltoid, which reproduces the contours and a zone where the crumpling efforts are applied.

Thus, at a minimum thickness of the adhesive layer, sufficient to ensure the operational stability of a book block's spine, stitched with threads, the efforts that are applied, when opening the book, to overcome the elastic forces of the inner structure of the polymeric plate, in the part of the zone in the shape of a deltoid, correlate almost evenly to the efforts of stretching the adhesive layer in the upper pointed part in the shape of a triangle.

Fig. 7 illustrates a change in the proportionality, after increasing the thickness of the adhesive layer, between the stretching area of the upper part of the adhesive plate, in the shape of a triangle, and the shear and crumpling zone of the plate, in the form of a deltoid.

Increasing the thickness of the adhesive layer shifted its middle plane; accordingly, the area of the $a_io_{i1}a_{i1}$ triangle changed in size in comparison with the area of the ao_1a_1 triangle.

The aa_1 and a_ia_{i1} bases of the triangles remained unchanged, due to intermolecular bonds between an adhesive polymeric composition, which limit the dimensional zones of stretching before the onset of destruction. The height o_io_{i1} increased, compared with the height oo_1, by the size of the displacement of the middle plane. Displacement size does not significantly affect the difference in the configuration of the triangles' zones of stretching ao_1a_1 and $a_io_{i1}a_{i1}$.

In contrast to the triangles of stretching, the o_1cgc_1 and $o_{i1}c_ig_ic_{i1}$ deltoids of the shear and crumpling zones, on the side of the curved surface of the adhesive layer, demonstrate a significant difference in terms of the dimensional values, towards a significant increase in the plate of thickness $t+\Delta_{gl}$ mm.

Hence, it follows that when opening a book, to overcome the elastic forces of the inner structure of the spine's polymeric plate, subject to the increase in adhesive layer thickness, it is necessary to apply considerably more effort. The efforts that would stretch and destroy the surface part of the adhesive plate under the increased stress and operational load are graphically reproduced by the enlarged plane in the form of the $o_{i1}c_ig_ic_{i1}$ deltoid.

The total area of the zones, which graphically indirectly reproduce the efforts of stretching and crumpling the first adhesive plate $S_{\Sigma 1}=S_2+S_3$,

$$S_2=S_{\triangle aa_1o_1}=\frac{aa_1\cdot oo_1}{2}=\frac{a\cdot h}{2}, \quad (11)$$

where $aa_1=a;\ oo_1=h,$

$$S_3=S_{o_1cgc_1}=\frac{cc_1\cdot o_1g}{2}=\frac{d_1\cdot d_2}{2}, \quad (12)$$

where $cc_1=d_1;\ o_1g=d_2,$

$$S_{\Sigma 1}=\frac{a\cdot h}{2}+\frac{d_1\cdot d_2}{2}=\frac{1}{2}\left(a\cdot h+d_1\cdot d_2\right), \quad (13)$$

Then, for the second adhesive plate:

$$S_{i\Sigma 1}=\frac{a_i\cdot h_i}{2}+\frac{d_{i1}\cdot d_{i2}}{2}=\frac{1}{2}\left(a_i\cdot h_i+d_{i1}\cdot d_{i2}\right), \quad (14)$$

where $d_i<d_{i1}$, and $d_2<d_{i2}$, respectively: $S_{\Sigma 1}<S_{\Sigma i1}$.

Vector charts in Fig. 7 reproduce changes in the efforts of stretching $\overrightarrow{P_{st}}$, $\overrightarrow{P_{ist}}$ and compressing $\overrightarrow{P_{com}}$, $\overrightarrow{P_{icom}}$ the adhesive plates, at the place of bending, due to a change in the thickness of an adhesive layer toward an increase from proportionally equilibrium to those that alter the equilibrium of efforts in the compression zone to additionally destructive at points *a* and b_i (Fig. 5).

7. Experimental measurement of the angles of contact and tangent angles of the discrete adhesive layers applied by a profile roller

To study the influence exerted by the thickness of an adhesive layer on the conditions for bending the polymeric plate and the emergence e of destructive defects when opening a book, we shall consider Fig. 8, *a*, which shows the W-shaped fragment of the spine part of a book block, with the following designations: *F* – a separated spine part of folded sections, 1 – the first single layer of an adhesive, the thickness of which is marked in Fig. 4 as *t* mm.

The central section of this fragment, outlined by the intersecting lines xx_1 and yy_1, is enlarged and shown in Fig. 8, *b*. In addition to the initial glue layer, t_1 thick, we applied several more adhesive layers $t_2t_3t_4t_5$, which consistently increase from the original size t=0.50 mm by the same magnitude Δ_{gl}=0.10 mm.

The profile application of an adhesive for each layer corresponds to the radii of the formed sectors R_{k1}, R_{k2}, R_{k3}, R_{k4}, R_{k5}. In the experimental measurements, we took into consideration 10 operations for the profile consecutive application of the additional layers of an adhesive, whose thickness and angular parameters are given in Table 1.

Fig. 8, *b* shows two semicircular spine folds of the book sections, marked with anchor points as the a_1aphg and $femaa_1$ areas. When applying a first layer of the adhesive, separately onto these areas, or onto a first one, or onto a second one, from the curved side, the natural angle of contact of the adhesive composition of the semicircular part of the fold of a book section corresponds to the areas marked as ab_1h_1h, or ee_1c_1a.

These areas correspond to the natural angles of contact γ and γ_1. However, at the continuous profile application of an adhesive to the entire surface of the W-shaped spine part of a book block, there is a change in the homogeneity of the adhesive layer in areas shaped as a deltoid with the concave sides, marked as $ab_1d_1c_1$, $ab_2d_2c_2$, $ab_3d_3c_3$, $ab_4d_4c_4$, $ab_5d_5c_5$.

Therefore, for our experiments, and to obtain the confidence indicators of the change in the angles of contact on the change in the tangent angles of the outer part of the adhesive layer, it is advisable to accept a condition for measuring the angles of contact at the border of the formation of deltoid zones in the gaps between sections.

The formation of angles of contact of the folds of book sections for the fixed layers of an adhesive, by increasing thickness, is carried out at the intersection of b_1d_1 and c_1d_1 plots from the center of the semicircular part of the fold, marked by point *o*, – one side of the angle. The other side of the angle is formed along the *os* straight line, which divides the angle of contact in half.

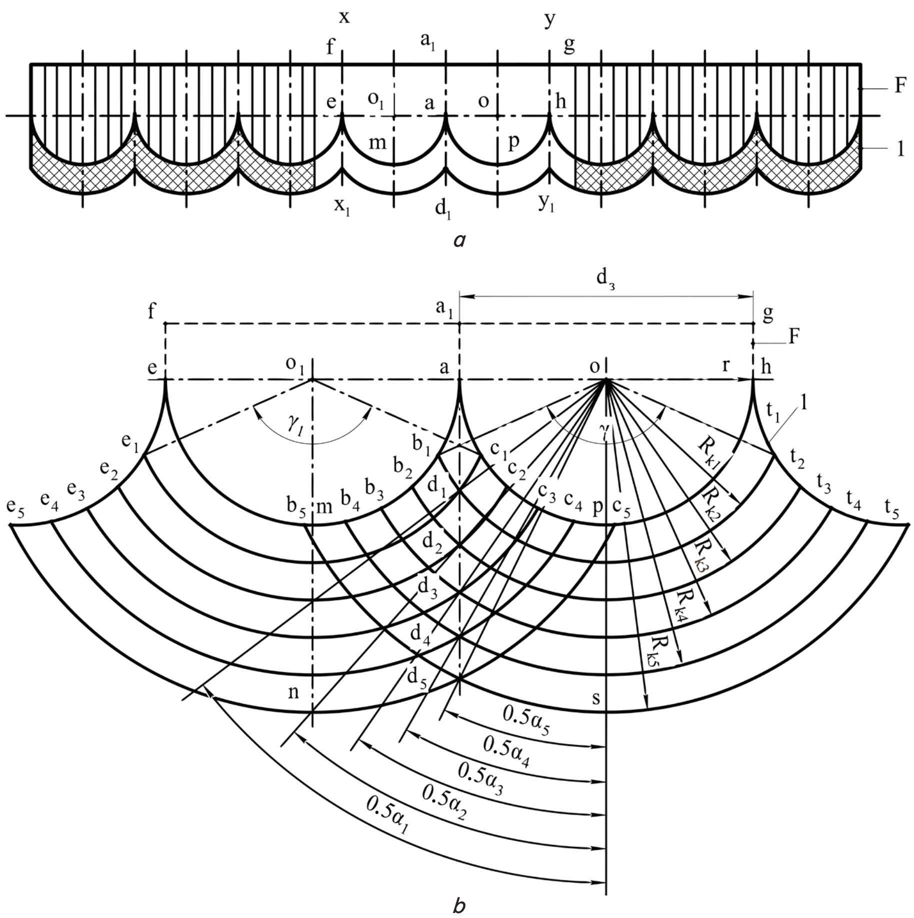

Fig. 8. Graphic dependences of change in the angles of contact of an adhesive layer on a change in its thickness: *a* — a fragment of the experimental spine part of a book block; *b* — the angles of contact of an adhesive layer with a discrete change in thickness; *F* — a separated spine part of the folded sections; 1 — the first single layer of an adhesive; 2, 3, 4, 5 — consistently enlarged layers of an adhesive, by Δ_{gl}=0.10 mm

Such measurements of the angles of contact were carried out consistently from the center *o* to the deltoids' vertices d_2, d_3, d_4, d_5, marked in Fig. 8, *b*, and farther to the vertices $d_6...d_{10}$, not marked in Fig. 8, *b*, because of possible overloading with a large number of graphic elements; their indicators, however, are given in Table 1.

Experimental measurements of the angles of contact and tangent angles are performed on the adhesive layers, applied by the experimental profile roller onto the spine part of the sections' folds, stitched with threads into a book block. The enlarged drawing was made, which was used to measure 10 dimensional angular parameters, the parameters of which are given in Table 1.

Accordingly, the angles of contact, selected for modeling and measurements, are marked as the α_1, α_2, α_3, α_4, α_5,...α_{10} angles (Fig. 8, *b*) for the growing size of the adhesive layer. For the convenience of experimental measurements, only the dimensional half of the angles of contact was registered: the angles, $5\alpha_1...0.5\alpha_5...0.5\alpha_{10}$; the obtained indicators, before committing to Table 1, were doubled.

Fig. 9 shows a part of the spine fragment from Fig. 8, *b*, whose middle deltoid area is separated along the *mn* and *ps* lines. We measured the tangent angles of the outer part of the adhesive layer $\varphi_1...\varphi_5$ (Fig. 9) and $\varphi_6...\varphi_{10}$ (given in Table 1 and not shown in Fig. 9), in the areas marked by points $d_1...d_5$ and $d_6...d_{10}$, as was the case when we measured the angles of contact, in areas of joining the outer part of the W-shaped adhesive layer in a gap between the sections.

In Fig. 8, *b*, it is not difficult to notice that at increasing the thickness of an adhesive layer from the original of thickness t_1= =0.50 mm to the discretely increased $10\cdot\Delta_{gl}$ (Δ_{gl}=0.10 mm) of thickness t_{10}=1.40 mm (intermediate thickness t_5=0.90 mm), the angle of contact α changes to a smaller side, from a maximum, of the measurements made, of 115°10′, to a minimum of 41°22′ (Table 1).

At the same time, the tangent angles φ_i change in an opposite fashion, from a minimum of 64°57′ to a maximum of 138°38′ (Fig. 9).

For a general case:

$$\alpha_i, \varphi_i = f(t_i), \tag{15}$$

where α_i is the angle of contact, φ_i is the tangent angle, t_i is the thickness of an adhesive layer.

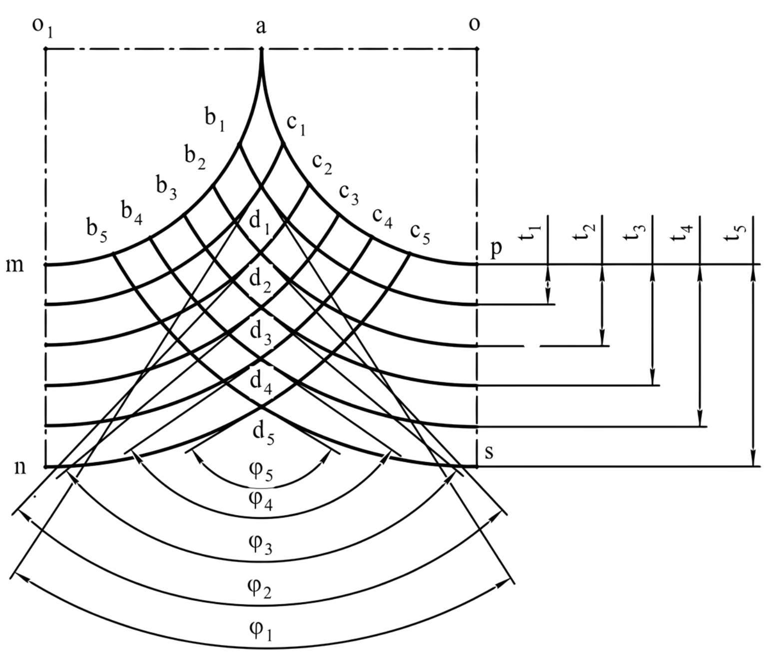

Fig. 9. Graphic dependences of change in the tangent angles of adhesive layers on a change in their thickness

The approximately equal angle of contact α_2=93°3′ and tangent angle φ_2=85°51′ are registered at the thickness of an adhesive layer t=0.60 mm (Table 1). It is possible that the angles match at the thickness of an adhesive layer within 0.60–0.70 mm.

Table 1

Dimensional indicators of change in the angles of contact α_i and tangent angles φ_i depending on change in the thickness of an adhesive layer t_i

Adhesive layer No.	Adhesive layer thickness, t_i	The angle of contact, α_i	Tangent angle, φ_i
1	t_1=0.50 mm	α_1=115°10′	φ_1=64°57′
2	t_2=0.60 mm	α_2 =93°3′	φ_2=85°51′
3	t_3=0.70 mm	α_3=79°34′	φ_3=100°20′
4	t_4=0.80 mm	α_4=69°32′	φ_4=110°43′
5	t_5=0. 90 mm	α_5=62°6′	φ_5=117°51′
6	t_6=1.00 mm	α_6=56°28′	φ_6=123°26′
7	t_7=1.10 mm	α_7=51°48′	φ_7=128°13′
8	t_8=1.20 mm	α_8=47°34′	φ_8=132°15′
9	t_9=1.30 mm	α_9=44°30′	φ_9=135°40′
10	t_{10}=1.40 mm	α_{10}=41°22′	φ_{10}=138°38′

The dimensional changes in the angles of contact (a decrease in angular indicators) and tangent angles (an increase in angular indicators), derived in the process of experimental measurements, are given in Table 1 and reproduced by chart 1 (Fig. 10).

We denote the diagonals of the deltoids, shown in Fig. 8, *b*, as $ad_1=D_1$, $d_1d_2=D_2$, $d_2d_3=D_3$, $d_3d_4=D_4$, $d_4d_5=D_5$, and of those not reproduced in Fig. 8, *b* but existing in the dimensions, given in Table 1, as $d_5d_6=D_6$, ..., $d_9d_{10}=D_{10}$, as well as the possible areas $d_id_j=D_{ij}$ for a t_{ij} layer of the adhesive.

Based on the geometry of matching the adhesive layers that edge the folds of a semicircular part of each section, stitched with threads into a book block, the consistent increase in the thickness of the adhesive application affects the increase in the tangent angles of the outer part of the adhesive layer, as well as the sequence of converting the W-shaped plate into a plane.

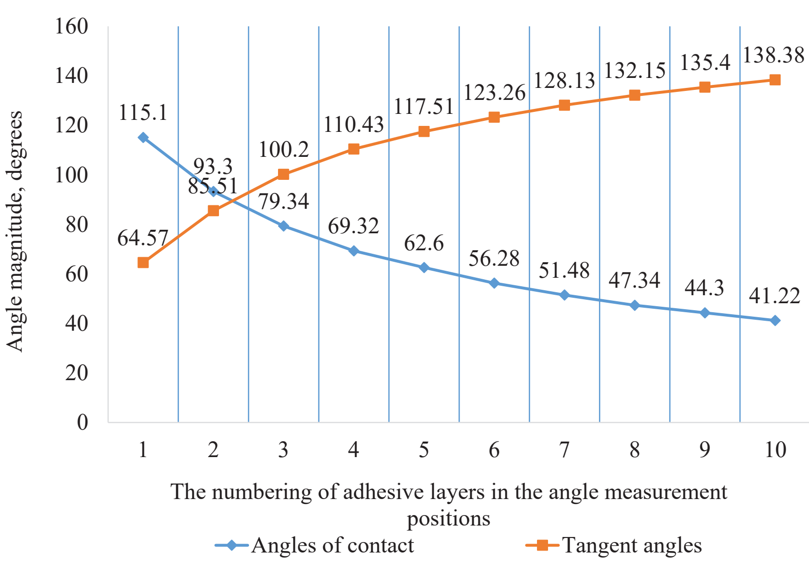

Fig. 10. Chart of change in the indicators of angles of contact and tangent angles in the process of changing an adhesive layer thickness

Matching the two parts of a first layer of the adhesive (Fig. 8, *b*), of thickness t_1, along the ad_5 line in a gap between the sections with the centers of the folds o_1 and o, forms the $ab_1d_1c_1$ deltoid with a diagonal D_1, which, in its linear dimensions, is considerably greater than the adhesive layer thickness t_1, respectively, $D_1 \neq t_1$ and $D_1>t_1$.

A discrete increase in the thickness of an adhesive layer by the same value increases the tangent angles of the outer part of the W-shaped surface and reduces the linear dimensions of areas $D_1...D_{10}...D_{ij}$ under the following conditions:

$$D_1>D_2>D_3>D_4>D_5>D_6>...>D_{10}>D_{ij}\approx t_{ij}. \quad (16)$$

In the case of a tangent angle approaching 180°, there is a condition that $D_{ij}=t_{ij}$, and the W-shaped form of the outer part of the adhesive layer is transformed, through a gradual straightening, into a plane.

8. Modeling the bending of an adhesive plate and calculating the moments of force at the specified points

To determine the effect of changing the thickness of an adhesive layer on the angles of contact and tangent angles, as well as changes in the effort applied to the opening of a book block, we built an estimation scheme (Fig. 11) for determining the moments of force applied in the discrete places of bending the plates of thickness t mm and $t+\Delta_{gl}$ mm.

Modeling the bending of the plate of thickness t mm was carried out at point c. To express it experimentally, the moment of force, due to which there is bending at this point, is applied at point a_1, which is positioned in the place of opening a block in the middle of a section, in a zone limited by the angle of contact. The next location of the place of applying the moment of force is at point a_2, which is positioned in the place of opening a block between the sections, where the deltoid glue protrusions are formed (Fig. 11, *a*).

At the same points a_{i1} and a_{i2}, we modeled the bending occurring at point c_i, for a plate of thickness $t+\Delta_{gl}$ (Fig. 11, *b*).

The part of a book block, which remains motionless during its opening at point *c*, is marked as one in which contact with the fixing plane takes place at points *c*, *m*, *n*, *p*, *s*, due to the structural features of the W-shaped surface of spine's folds. The static efforts holding this part of the block in a stationary state are denoted $\vec{P}_{st1}, \vec{P}_{st2}...\vec{P}_{st5}$ (Fig. 8, *a*).

In the first case, when, to bend the adhesive plate, point *c* is where we applied force $\vec{P}_1$, which exceeds the elastic properties, the properties of the strength and rigidity of the plate, at point a_1 there forms the initial triangle of deformation, designated by points a_1b_1c, the beginning of the movement of the vortex of which at point a_1 leads to the beginning of stretching the plate at point b_1.

Fig. 11, *a* shows the diagram of the moment of force relative to point a_1 at which the vector straight line a_1c indicates the radius-vector $\vec{r}_1$, and the straight line a_1b_1 – the force arm h_1 and at point *c* – vector $\vec{F}_1$.

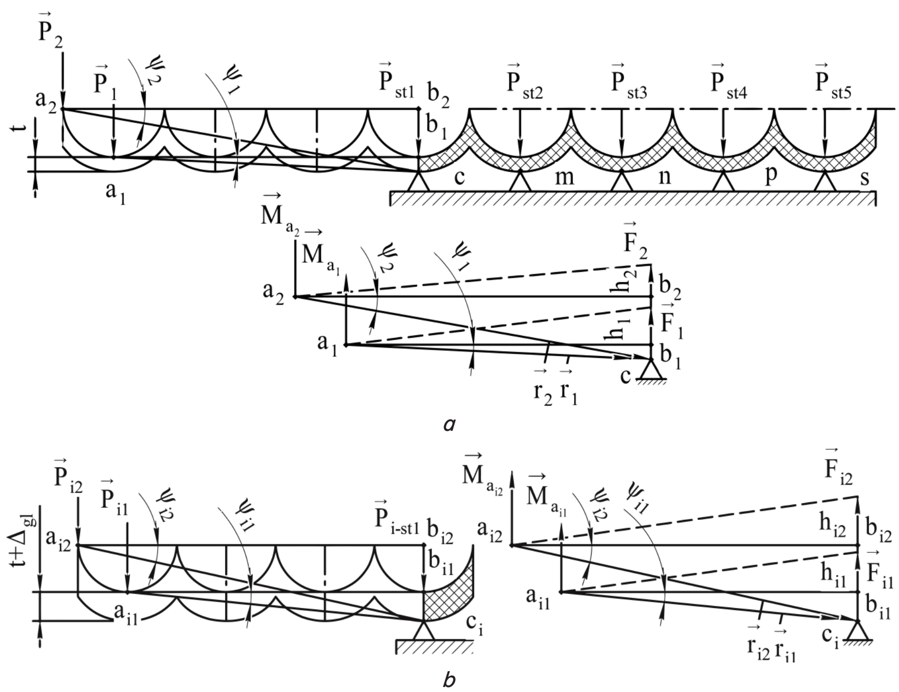

Fig. 11. The spatial system of forces applied to the spine part of a book block when opening the block: *a* — estimated scheme for an adhesive layer of thickness *t* mm; the triangles of deformation for an adhesive layer of thickness *t* mm; *b* — estimated scheme for an adhesive layer of thickness $t+\Delta_{gl}$ mm; the triangles of deformation for an adhesive layer of thickness $t+\Delta_{gl}$ mm

The moment of force $\vec{F_1}$ relative to point a_1:

$$\overrightarrow{M_{a_1}}(\vec{F_1})=\vec{r_1}\cdot\vec{F_1}, \quad (17)$$

accordingly, the force module $\vec{F_1}$:

$$M_{a_1}(\vec{F_1})=r_1\cdot F_1\cdot\sin\psi_1, \quad (18)$$

considering the force arm h_1:

$$M_{a_1}(\vec{F_1})=h_1\cdot F_1. \quad (19)$$

Fig. 11, *b* shows the diagram of the moment of force relative to point a_{i1} for an adhesive layer of thickness $t+\Delta_{gl}$ mm. While maintaining all the indicators examined in the diagram (Fig. 11, *a*), a distinguishing factor is an increase in the angle marked as angle ψ_{ij} between the radius-vector $\vec{r_{i1}}$ and the arm of force h_{ij}, respectively, the module of force $\vec{F_{i1}}$:

$$M_{a_1}(\vec{F_1})=r_{i1}\cdot F_{i1}\cdot\sin\psi_{i1}, \quad (20)$$

Under condition $h_1=h_{i1}$.

Increasing the ψ_{ij} angle relative to the ψ_1 ($\psi_{ij}>\psi_1$) angle, accordingly, the $\sin\psi_{ij}$ indicator relative to $\sin\psi_1$ ($\sin\psi_{ij}>\sin\psi_1$), increases the estimated indicator of the moment of force, which must be applied in order to bend the W-shaped adhesive plate with a thickness of $t+\Delta_{gl}$ mm.

At the moments of applying the efforts at point a_2 (Fig. 11, *a*) and at point a_{i2} (Fig. 11, *b*), located on the top of the acute part of the adhesive layers, of thickness *t* mm and $t+\Delta_{gl}$ mm, in a gap between the sections, and provided $h_2=h_{i2}$, the moments of force are calculated as the above:

$$\overrightarrow{M_{a_2}}(\vec{F_2})=\vec{r_2}\cdot\vec{F_2}, \quad (21)$$

$$\overrightarrow{M_{a_2}}(\vec{F_2})=\vec{r_{i2}}\cdot\vec{F_{i2}}, \quad (22)$$

and their force modules:

$$M_{a_2}(\vec{F_2})=r_2\cdot F_2\cdot\sin\psi_2, \quad (23)$$

$$M_{a_2}(\vec{F_2})=r_{i2}\cdot F_{i2}\cdot\sin\psi_{i2}, \quad (24)$$

considering the arm of force h_2:

$$M_{a_2}(\vec{F_2})=h_2\cdot F_2, \quad (25)$$

$$M_{a_2}(\vec{F_2})=h_{i2}\cdot F_{i2}. \quad (26)$$

By comparing the indicators of the moment of force at different points of its application during the opening of book blocks, we observe the size difference caused, first of all, by changes in the acute angles in the conditional rectangular triangles of deformation.

The triangles of deformation are built on the cross-sections of adhesive plates, in which the opposite side to the noted acute angles is the opposite cathetus, the size of which depends on a change in the thickness of an adhesive layer.

The positioning of the bending zone of an adhesive plate over an area within the semicircular portion of each section and in a gap between the sections proportionally influences the moments of force as a contour component of the a_1b_1c, a_2b_2c, $a_{i1}b_{i1}c_i$ and $a_{i2}b_{i2}c_i$ deformation triangles. The greatest efforts to bend an adhesive plate would be applied at the vertices of the deltoids, due to the additional thickness in comparison to the semicircular plots. To edge the W-shaped spines of book blocks sewn by threads, the modern Kolbus KM 600 binding line (Germany) uses not the profile but direct application of an adhesive. The rated consumption of an adhesive for such adhesive sections (the thermal adhesive BAM 1078, UK) per 1,000 copies is 780 g/m^2 of the area of the spine part of book blocks.

To determine the possibility of minimizing the adhesive consumption, we performed an experimental study under conditions that enable the application of the estimated profile W-shaped adhesive layer. The study was conducted when making circulating products, the copies exceeded 1 thousand pieces, at the stage of the technological edging at the Kolbus KM 600 binding line in the Kolbus BF-512 book line.

Using a stochastic procedure, we selected samples from the circulation products for conducting Flex Test at the analytical instrument «Zigloh», in order to determine the strength and durability of the adhesive spine joint. The selected samples of circulation products, with the applied estimated profile adhesive layer, passed the Flex Test demonstrating the strength parameters corresponding to the normative application of an adhesive onto the spine of a block sewn with threads.

We have derived the average experimental indicators for the estimated amount of the thermal adhesive that was applied by a profile adhesive roller on the spine part of a book block, as well as normative indicators, for the most common formats of book blocks, previously selected for our research; they are given in Table 2.

Table 2

The normative and experimental indicators of the consumption of a thermal adhesive for edging the W-shaped spine part of book blocks

The thickness of the spine of the book block, mm/number of sections	The format and length of a block spine									
	84×108/32 60×84/16 210 mm		84×108/16 270 mm		60×84/8 300 mm		60×90/16 225 mm		70×100/16 250	
	Thermal adhesive consumption per 1,000 books, g									
	1	2	1	2	1	2	1	2	1	2
38.08/7	6,240	5,621	8,019	7,246	8,911	7,986	6,812	6,152	7,425	6,657
43.52/8	7,129	6,403	9,165	8,271	10,184	9,221	7,617	6,841	8,479	7,732
48.96/9	8,019	7,186	10,312	9,257	11,457	1,0297	8,593	7,767	9,548	8,548
54.40/10	8,911	7,977	11,457	10,265	12,730	11,453	9,548	8,536	10,609	9,503
59.84/11	9,802	8,815	12,603	11,349	14,003	12,575	10,502	9,425	11,669	10,451
62.88/12	10,299	9,252	13,242	11,878	14,714	13,232	11,035	9,903	11,709	10,537

Notes: 1 – normative indicators of thermal adhesive consumption; 2 – estimated indexes of thermal adhesive consumption, implemented industrially

Based on the results of circulation tests, the amount of the profile W-shaped applied adhesive, calculated for 1 thousand copies, is 700 g/m^2 of the area of the book blocks' spine part. This yields 10–11 % savings in the adhesive composition, compared to the normative indicators (780 g/m^2), which are currently used in book production at the standard non-profile W-shaped adhesive application.

The derived experimental estimated parameters of the consumption of an adhesive (700 g/m^2), given in Table 2, are predetermined by the technical and technological conditions of production and the operational stability of an adhesive plate. The estimated indicators of adhesive consumption can be applied not only to the selected book blocks of a fixed thickness but for blocks of different possible thickness. The results of our study were implemented at the largest book enterprise in Ukraine – the State publishing house «Ukrainian Press».

9. Discussion of results of determining the influence of the thickness of an adhesive layer of the W-shaped spine part on a change in the angles of contact and tangent angles

In contrast to the flat isotropic adhesive layers in the book blocks fastened by a non-stitched adhesive technique, considered in chapter 2, the W-shaped spine plates, as shown by examining their cross-sections, represented by a fragment in Fig. 3, have a complex anisotropic structure.

This is due to that in addition to the adhesive polymeric composition, which forms the base of the spine part of a book block, stitched with threads, the surface structure of the concave part hosts the implanted stitches of sewing yarns, which, at pre-tension, enable the mechanical fastening of the sections' folds. Accordingly, the outer curved surface of an adhesive layer is strengthened by the planar integration of an edging paper tape.

It should be noted that changing the thickness of only the adhesive layer, for identical book blocks, in the static state does not lead to changes in the surface strength of the composite plate. It, at the same time, remains constant, both on the side of the surface with the implanted stitches of sewing threads and from the side of the edging tape.

Moreover, at the same thickness of the adhesive array in the composite W-shaped spine plate, at the moment of opening a book block, the profile surfaces are exposed to the efforts that, on one side, stretch the plate, on the other side, crumple, in the directions shown by vectors $\overrightarrow{P_{tn}}$ and $\overrightarrow{P_{ds}}$ in Fig. 3.

This means that the increase in the thickness of the adhesive layer from the original thickness, chosen for comparative studies, influences, when the adhesive plate is bent, the increasing destructive efforts applied to the surface parts of the plate's profile structure.

To prove this assertion, it would suffice to investigate the formation of residual deformation ε (1) in the structure of the adhesive plate, which, after long-term bending, leads to the destruction of the edging plate and the entire book block.

In this sense, of special interest is to study the stages of the influence of the thickness of the W-shaped adhesive layer on the elastic-plastic deformation of two spine adhesive plates, in one of which the initial thickness of the adhesive is T mm, in another, enlarged, and corresponds to the size of $t+\Delta_{gl}$ mm.

In closed book blocks, before turning the pages, the W-shaped adhesive compositions at the concave and curved surfaces are in a static state and retain proper semicircular geometry (Fig. 4). At the onset of opening a block and bending an adhesive, there is a change in the semicircular configuration of the concave surface of the adhesive layer, tangent to the folds of the sections.

The phenomenon studied, in the most visual form, is observed in the gaps between the sections of the W-shaped adhesive layer in Fig. 5. The efforts that deviate one part of the semicircular area of the adhesive plate, moving towards bending, force to stretch the second part of the semicircular area, bordering the motionless, when opening, by part of the block.

Comparing the sizes of stretching the semi-circular sections of the adhesive layer and the duration of the stretching periods indicates the acceleration of the concave surface destruction across the entire plane. The geometry of the investigated phenomenon of the concave part of the adhesive layer, atop the deltoid plots as the most prone to premature destruction, is shown in Fig. 5. The reported study agrees with practical statements, well known from works [6, 7, 9, 11].

However, in contrast to the research results published in [6, 7, 9, 11], the data obtained on changing the linear dimensions of the adhesive plate areas under the influence of elastic deformation forces make it possible to assert the following – the efforts leading to the linear dimensions change of semicircular areas influence the distribution of internal stresses, from equilibrium, across the entire structure of a spine plate, to the formation of the stretching and compressing zones.

To prove this statement, we have graphically represented the linear deformation ε_1, ε_2, ε_{i1}, ε_{i2} in the vicinity of points on the vertices of the deltoid sections of adhesive plates (Fig. 5) with a thickness of t mm and $t+\Delta_{gl}$ mm; it is described by formulae (6) to (9). In addition, the diagrams of efforts of the vector groups of stretching $\overrightarrow{P_{st}}$, $\overrightarrow{P_{ist}}$ and compression $\overrightarrow{P_{com}}$, $\overrightarrow{P_{icom}}$ of these adhesive plates, reproducing the parts of the elastic deformation processes, separated by the midline, are shown in Fig. 7.

Moreover, the calculation of the total areas of the stretching and compression zones, represented by formulae (11) to (14), clearly demonstrates the need for applying much more effort to overcome the elastic forces of the internal structure of the plate, provided the thickness of the adhesive layer is increased.

In this case, it should be especially noted that for our experiments, and to obtain credible indicators, in contrast to the study reported in [11], the W-shaped adhesive plate is divided into several sections. One of them reproduces a semicircular array of the adhesive, tangent to the semicircular folds of the sections, while the other one fills the deltoidal areas in the gaps between the sections.

This means that taking into consideration this factor provides a possibility for the geometrically grounded formation of the angles of contact of the folds of book sections by the fixed layers of the adhesive, at increasing thickness.

It should be noted that the experimental measurements of angles of contact and tangent angles were performed on the adhesive layers applied by the experimental profile roller, which we proposed, onto the spine part of the sections' folds in a discrete step way. This, in particular, can be seen in Fig. 8, *b*, 9, where the semicircles of adhesive layers form the areas, defined by the angles of contact, as well as distinguish the deltoidal areas in the gaps between the sections.

It is simple to see that increasing the layer of an adhesive, from the initial thickness, defined for the experiments, to the discretely increased by 10 dimensional units, changes the angle of contact towards the smaller side, from the maximum to the minimum.

At the same time, the tangent angles change in the opposite manner, from the minimum to the maximum. The dimension indicators, obtained at measuring the angles of contact and tangent angles, which confirm preliminary conclusions, are given in Table 1.

It should be noted that in the diagram of changes in the angles of contact and tangent angles, in the process of changing the thickness of an adhesive layer (Fig. 10), at the intersection of curves, the angles coincide and have the same dimensions.

In turn, the intersection point of the convergent angles is projected onto a coordinate axis, which registers an indicator of the optimal thickness of an adhesive layer for edging the sections, whose characteristics were selected for our study in advance.

From a theoretical point of view, based on the geometry of the convergence of the adhesive layers, the consistent increase in the thickness of an adhesive, from the optimal, defined in Fig. 10, influences the increase in the tangent angles of the outer part of the adhesive layer, as well as the sequence of converting the W-shaped plate into a planar shape. In the case when a tangent angle approaches 180°, there is a condition of converting the W-shaped outer part of the adhesive layer, through gradual straightening, into a plane.

Such conclusions can be considered appropriate from a practical point of view because they allow a reasonable approach to determining the thickness of an adhesive layer for the W-shaped spines of book blocks.

Based on the measurements indicators of the thickness of paper of book sections for a new edition, it is possible to calculate the size of the semicircular folds and, by constructing a diagram of change in the angles of contact and tangent angles, to determine the point of intersection of their curves. The point of intersection registers the boundary thickness of an adhesive layer.

The latter relates to resolving the task not only on determining the influence of change in the adhesive layer thickness on the angles of contact and tangent angles, as well as determining a change in the efforts applied to the opening of the book blocks with a thickness of adhesive layers of t mm and $t+\Delta_{gl}$ mm.

To express it experimentally, the moment of force, due to which there is a bending of the plate, applied in one case at the point positioned in the middle of the section, in the zone limited by the angle of contact (Fig. 11, *a*). The other one is at the point positioned in the place of opening a block between the sections where the deltoidal glue protrusions are formed (Fig. 11, *b*).

When comparing the indicators of the moment of force at the different points of its application, described by formulae (17) to (26), while opening the book blocks, we observe the size difference, caused, first of all, by the changes in acute angles in the conditional rectangular triangles of deformation.

The triangles of deformation are built on the cross-sections of adhesive plates, in which the opposite side to the specified acute angles is the opposite cathetus, whose dimensional length depends on a change in the thickness of an adhesive layer.

In turn, it follows that the greatest efforts for bending an adhesive plate would be applied atop the deltoid areas, due to the additional thickness compared to the semicircular plots.

By using the identified dependences of the influence of the thickness of an adhesive layer on the angles of contact and tangent angles, we have calculated, and implemented industrially, experimental indicators of thermal adhesive consumption, given in Table 2, for edging the W-shaped spine part of the book blocks, stitched with threads, for the most commonly used book formats.

The suggested method for determining the influence of the thickness of an adhesive layer on a change in the angles of contact and tangent angles has helped define the processes of stretching and compressing the W-shaped adhesive plate, required for practical consideration. It has also determined the sign-alternating character of loads during bending, as well as peculiarities in the emergence of damage and destruction, due to the intensive use of a book. Therefore, the method can be introduced for the preliminary technological calculation of adhesive consumption when compiling technical documentation for the production of books sewn with threads.

However, it should be noted that the proposed method for determining the influence of the thickness of an adhesive layer on a change in the angles of contact and tangent angles does not take into consideration some important criteria for studying the elastic-plastic deformation of the W-shaped adhesive plates. These include:

– the anisotropic composite structure of an adhesive polymeric plate;

– the properties of the book sections' paper;

– preliminary tension of the stitches of binding threads, their thickness and tearing capacity;

– the material and thickness of an edging tape, the amount of the surface tension created by the tape after gluing;

– the elasticity module, as well as the physical and mechanical properties of adhesive polymeric compositions.

Therefore, these caveats point to certain shortcomings in the proposed method. An area of further research related to their elimination should focus on determining the impact, primarily, of the physical and mechanical properties of various types of adhesives. Such an adaptation of further studies would expand practical possibilities to apply the adhesive compositions industrially, at a minimally sufficient quantity, to ensure their long operational stability.

10. Conclusions

1. Based on our study of two identical book blocks, with different thicknesses of adhesive layers, applied on the W-shaped spine parts, a method has been proposed to experimentally find an optimum ratio of the adhesive thickness to the efforts arising when opening a book.

Specific features in the structure of the W-shaped spine part of a book block have been defined while considering it as a complex composite medium. It is formed from an array of an adhesive, as the main component, with the stitches of sewing threads implanted into a concave adhesive surface, as well as the edging tapes integrated into the adhesive surface from the curved side.

That has allowed us to argue that bending an adhesive plate changes the semicircular configuration of the concave surface, tangent to the folds of the sections, which, over the periods of prolonged stretching, becomes prone to accelerated destruction.

It is shown that the investigated phenomena of the elastic-plastic deformation of the W-shaped adhesive layer are observed, in the most visible form, in the zones between the sections of deltoid areas.

Accordingly, the data obtained on a change in the linear dimensions of the areas of an adhesive plate make it possible to argue that the efforts that lead to a change in the linear dimensions of the semicircular areas affect the distribution of internal stresses, from equilibrium, throughout the entire structure of the spine plate, to the formation of the stretching or compressing zones.

2. Our study has established patterns in the formation of a description of the elastic-plastic state of the W-shaped spine part of a book block at its bending, which imply the distribution of stages in the influence of the thickness of an adhesive layer on the structural changes and changes in its geometric dimensions.

It has been determined that bending an adhesive plate is accompanied by the heterogeneity of its semicircular sections' deformation. At the initial stage, the semicircular areas alter the configuration to the indirect linear gain Δ. This is manifested in the comparative growth of the linear deformation for the first semicircular plot $\varnothing D_1$ at the top of the first deltoid $\varnothing D_1+\Delta_1$, the next semicircular plot $\varnothing D_2$, at the top of the next deltoid $\varnothing D_2+\Delta_2+\Delta_{2-1}$, and, for a general case, $\varnothing D_i+\Delta_i+\Delta_{i-1}$. The geometric divergence in the linear increment of the adhesive plate deformation meets the condition $\Delta_1 \neq \Delta_2 \neq \Delta_{2-1} \ldots \neq \Delta_i \neq \Delta_{i-1} \neq \text{const}$.

We have investigated the phenomena of stretching the upper part of the spine plates at points atop the deltoid areas in the gaps between the sections, in which there form the zones of stretching to the straight-line segments, whose length is limited by the elastic-plastic bonds in the structure of an adhesive layer. It is also limited by the crumpling efforts, which depend on the thickness of an adhesive layer located in the central part of the semicircular plot. According to the performed experimental measurements, for the first discrete increase in the thickness of an adhesive layer by 10 % of the original area of crumpling, and, consequently, the zone of elastic deformation of compression increases by 22 %.

The offset of the inner polymeric layers of an adhesive plate contributes to the accumulation of the efforts of elastic deformation and the creation of an energy reserve to return a bent adhesive plate to its original position. Accordingly, there is a return of the stretching zones at points atop the deltoid plots to the ascending position over a long operating period.

This indicates the possibility of directed adjustment of the processes that form the W-shaped adhesive layers of thickness that can be experimentally determined, taking into consideration the zones of stretching at the tops of deltoid plots for book blocks of different formats.

3. We have performed experimental measurements of the angles of contact and tangent angles on the adhesive layers, applied by a discrete technique, at the predefined step of increasing the thickness of an adhesive.

It has been established that the angles of contact are changed with increasing thickness of an adhesive layer towards a smaller side – from maximum to minimum. At the same time, the tangent angles change in an opposite fashion, from the minimum to the maximum.

In this case, it should be noted that in the diagram of change in the angles of contact and tangent angles, in the process of changing the thickness of an adhesive layer, at the point of curves' intersection, the angles coincide and have the same dimensions.

In turn, the intersection point of the convergent angles is projected onto a coordinate axis, where it registers an indicator of the optimum thickness of an adhesive layer for edging the sections, with the characteristics selected in advance for the study.

Such conclusions can be considered appropriate from a practical point of view because they allow a reasonable approach to determining the thickness of an adhesive layer for the W-shaped spines of book blocks.

Based on the measurements of the indicators for the thickness of paper of book sections for a new edition, it is possible to calculate the size of the semicircular folds and, by constructing a diagram of change in the angles of contact and tangent angles, to determine the point of intersection of their curves. A point of the intersection fixes the limit of the possible thickness of an adhesive layer for the technological application onto a block spine.

4. To model the effect of change in the thickness of an adhesive layer on the angles of contact and tangent angles, as well as changes in the efforts applied to open a book block, we have built the estimation schemes for determining the moments of force applied at the discrete places of bending the plates on the thickness of t mm to the thickness of $t+\Delta_{1\ldots i}$ where $\Delta_1 \ldots \Delta_i = \text{const}$.

The diagrams of the moments of forces demonstrate their dimensional differences, depending on the positioning of the zone of an adhesive plate bending within the semicircular part of each section and in the deltoid gaps between the sections. It has been determined for further calculations that the greatest efforts for bending an adhesive plate would be applied at the top of the deltoid areas, due to an additional thickness compared to the semicircular plots.

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