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EFFECT OF MICROWAVE DRYING OF THE SPINES OF BOOK BLOCKS ON THE QUALITY OF PRINTED MATERIALS

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Досліджено кінетику природного та мікрохвильового висушування клейових з'єднань книжкових блоків. Визначені класифікаційні ознаки сушильних пристроїв. Розроблено імітаційну модель розподілу вологи в заклеєному корінці книжкового блока. Встановлені закономірності впливу теплопровідності матеріалів, формату видання, його товщини, характеристик паперів та клеїв на процес висушування. Визначено оптимальні режими сушіння та їх вплив на якість книг

Ключові слова: корінці книжкових блоків, клейові з'єднання, мікрохвильове висушування, якість друкованих книг

Исследована кинетика природной и микроволновой сушки клеевых соединений книжных блоков. Приведена классификация сушильных устройств. Создана имитационная модель распределения влажности в заклеенном корешке книжного блока. Установлены закономерности влияния теплопроводности материалов, формата издания, его толщины, характеристик бумаг и клеев на процесс сушки. Определены оптимальные режимы сушки и их влияние на качество книг

Ключевые слова: корешки книжных блоков, клеевые соединения, микроволновая сушка, качество печатных книг

1. Introduction

An analysis of modern designs and technologies for the production of printed books reveals that a significant part of semi-finished products in bookbinding must undergo a process of gluing. It requires an additional operation of drying, which under natural conditions is a time-consuming process. It is known that natural drying of glued joints is difficult to control because of significant fluctuations in atmospheric conditions and non-uniform rate of moisture removal from a glue layer. This leads to the instability of materials properties, the distortion of shape in book design and the decrease in strength of glued joints. These shortcomings are eliminated at artificial drying of book blocks. Modern technologies in book production employ various drying devices. Classification attributes of such dryers, according to researchers, include techniques for supplying heat to the object of drying, techniques for moving a drying agent, directions of motion of materials and a drying agent, the type of design, principles of operation. Drying devices, based on the technique of supplying heat to the object of drying, are categorized as convective, conductive, plasma, thermal radiation, induction, infrared, ultra-violet, etc.

Dryers of the conveyor type are often applied in the book printing industry. The most effective is drying using the sources of infrared radiation, however, they have the disadvantage – non-uniform distribution of radiation field.

Still unresolved are the following problems: inefficient control over the processes of drying and motion of the conveyor, imperfect models of thermodynamic interactions between the components «thermal field – the object of drying». In conveyor dryers, entire book blocks are dried next to the books' spines, causing them to deform. There are no dryers designed to dry the spines of book blocks. Given that new glues and papers with unknown physical-mechanical characteristics penetrate book printing market, it is an important task to search for the ways to improve technology of drying semi-finished products in book production, to design and implement new drying devices. In order to improve the quality of drying processes, a promising direction is the convective-radiation drying with pauses in the irradiation of book block spines, which would contribute to a more intensive and rapid removal of moisture. Of interest is the microwave drying of book blocks. The advantage of this technique is the absence of a heat carrier, explosive concentrations and losses of material. Heat dissipation occurs in the volume of a material while the intensity of heating does not depend on the aggregate state of a material. Designs of the drying chambers of microwave devices are built so that the same heating is applied in any part of the internal volume filled with semi-finished products. The optimum volume of a drying chamber is chosen taking into consideration the power and frequency of magnetron radiation.

Application of the technique for microwave drying of glued book block spines appears promising as it makes it possible to significantly reduce the overall consumption of electricity and to accelerate a technological process of manufacturing printed books; it therefore requires a deep scientific research.

2. Literature review and problem statement

An analysis of the scientific literature shows that the attention of researchers in many fields has been focused on issues of the intensification of drying of various materials, semi-finished products and finished products. There are known studies into drying devices that are used in the printing processes of book production. Thus, paper [1] describes the features of LED lamps for the drying devices of printing presses, which ensure efficiency while drying the prints. Problems in the drying of prints, formed by ultraviolet inks, and the ways of eliminating them, are discussed in article [2]. Ultraviolet printing processes that involve LED drying of prints are considered in paper [3]. The analysis of advantages and disadvantages of rotary ultraviolet dryers, which are included in modern printing machines, is reported in article [4]. Efficient use of energy in the process of drying is described in paper [5]; it, however, applies to the printing processes only. Nevertheless, the processes of drying glued joints when creating design of a book block have remained insufficiently examined up to now.

The specificity of improving the methods for estimating the statics of convective-radiation drying of materials is shown in study [6], which stresses the importance of examining these processes in order to design new structures of dryers. A change in the structure of materials or ensuring its stability while drying the materials requires that researchers perform mathematical modeling of elastic-plastic deformations [7]. This makes it possible to select the rational modes of drying for any materials and products. In paper [8], authors attempt, by using the methods of mathematical modeling and simulation, to describe the kinetics of drying wood and articled made of it. At present, however, there is no a unified approach to the kinetics and modeling of the processes of drying of solvents, coatings, dispersions, solutions and fibrous materials.

Of importance in the process of drying is the heat and mass transfer, which was investigated in article [9] in the production of tile composite materials. The authors defined coefficients of heat transfer and mass transfer in the process of filtration drying, which makes it possible to predict required consumption of thermal energy for the drying process at the stage of designing new equipment. Authors of paper [10] conduct mathematical modeling of spatial heat and mass transfer in anisotropic capillary-porous materials, emphasizing the importance of calculating internal moisture transport. A research into processes of heat and mass transfer under the action of microwave radiation is addressed in article [11]. Theoretical study of the processes of drying is tackled in paper [12]. There is a work [13], the authors of which investigate thermodynamic processes of materials drying. Kinetics of drying and the quality of fixing the binding materials with the use of dispersions and gelatinous glues are explored in paper [14]. However, still insufficiently studied are the processes of drying glued joints formed by polyvinyl-acetate dispersed and polyurethane glues. Special features of the new techniques to dry the over-printed materials are shown in article [15]. The effect of properties of glues and the techniques for gluing the blocks' spines on the operational modes of high frequency drying devices is described in paper [16]. Informational energy diagrams of thermodynamic interaction when drying printed products are given in article [17]. The authors emphasize that in order to improve effectiveness of drying processes it is necessary to define the functions of sensors and the modes of automated systems controllers, to design new algorithms and appropriate software. The authors, however, failed to consider techniques and devices for microwave drying.

In book printing production, the drying of semi-finished products is one of the final stages in the manufacturing of printed products. That is why the techniques, means and modes of drying, which are determined by the efficiency of control over thermodynamic processes, affect qualitative indicators of printed materials and their competitiveness.

An analysis of modern machinery for the manufacture of book products reveals that a number of production lines includes in their composition various drying devices. Thus, the production line «Kolbus» (Germany) includes the machine RB or machine RC for gluing and drying the spine of a book block [18]. Production lines based on machines of the type Trenbinder, Rotor-Binder, Modular Binder (Switzerland) are equipped with HF-drying devices. The firm Wohlenberg (Germany) produces machines of the model City 3000, 3600, 4000, 5000 of modular design, equipped with HF-device [19]. However, there are no devices for microwave drying in the production lines for gluing and drying the spines of book blocks, which might prove effective. Therefore, in order to recommend the implementation of such drying techniques in production, it is necessary to examine modes and parameters of microwave dryers, to estimate their material thermal balance and kinetics of drying the book blocks.

$$J = N \cdot G_c / 100 \cdot S, \tag{1}$$

where J is the intensity of drying, kg/m^{2}s; N is the drying rate, m/s; G_c is the weight of an absolutely dry sample, kg; S is the surface area of evaporation, m^2.

Table 1

Characteristics of the types of paper for making model book blocks

No. of entry	Indicator name	Offset paper Mega mat	Chalk overlay paper M-Real Zanders	Paper for covers 2610
1	Mass of 1 m^2, g	80	90	160
2	Volumetric mass, g/cm^3, not less	0.85	0.9	0.85
3	Breaking length (average, in two directions), m, not less	2.400	2.500	2.500
4	Number of double folds (average, in two directions), not less	8	11	11
5	Degree of gluing, mm, not exceeding	0.75	1.25	1.2
6	Whiteness, %	90–92	96	90–92
7	Ash content, %, not less	10	–	–
8	Regulatory documents	GOST 9094-88	GOST 2144-83	GOST 7950-77

3. The aim and objectives of the study

The aim of present work is to intensify a technology for the production of books using a method of microwave drying of glued joints of book blocks.

To accomplish the set aim, the following scientific tasks must be solved:

– to construct a simulation model of the distribution of moisture in the glued spine of a book block in the process of drying;

– to explore the kinetics of natural and microwave drying of glued joints of book blocks, to optimize the modes of drying, and to determine the impact on the performance indicators of printed materials.

4. Materials and methods for studying the processes of microwave drying of book blocks

4. 1. The examined materials and equipment used in the experiment

In the course of present study, we used book blocks made from offset paper of brand Mega mat (Finland) and from chalk overlay paper of brand M-Real Zanders (Germany), which were dried in the designed microwave device. Technological characteristics of the paper used, regulated by normative documents, are given in Table 1.

We used a modified dispersed glue, based on PVAD, for sealing the blocks' spines. The application of the contactless electron moisture gauge S-200 made it possible to determine moisture content in the spines of book blocks in certain moments of drying and to construct graphical dependences of moisture content and temperature of drying on the drying time. By using graphical differentiation of the drying curve for an average moisture content of book blocks, we obtained the curves for drying rate, which demonstrate dependence of the drying intensity on the moisture content. The intensity of drying was determined from the following formula:

By employing a method of graphical differentiation, based on the drying curve, we determined a rate of drying as a tangent of the angle, created by the tangent, drawn through a given point of the drying curve. By using a method of optical microscopy (stereoscopic microscope Olympus SZ-11 with the digital camera Camedia (resolution is 3 megapixels)), we determined changes in the structure of paper and the gluing film in the spine of book blocks before and after drying.

4. 2. Procedure for studying the microwave drying and the performance indicators of book blocks

We studied the processes of microwave drying of book blocks on the basis of the theory of heat and mass transfer, simulation and mathematical modeling, electron weighing and graph-analytic methods, optical microscopy. The processes of drying the spines of book blocks, glued with water-dispersion adhesives, were investigated in the designed microwave drying installation [20].

Strength of the produced and dried book blocks was examined in the tester Zihloch (Germany). Resistance of glued joints to multiple folds without loading the spine of a book block, and with loading (50 N), was determined using a Flex-Test method; the sheet pull-off strength, which characterizes durability of publications, – by the Pull-Test method in line with a standard procedure. Methods of mathematical statistics were employed to process the results of our study.

5. Results of the study of processes of drying the spines of book blocks and effect on the quality of finished printed materials

An important task in the technology of drying is to search for the optimal modes. The processes of drying, which belong to physical processes, have not been clearly defined, which is why it is important to construct equations of optimal control for them. To do this, it is required to establish dependences between the variables of state and the variables of control, using the method of evolutionary optimization. Based on the analysis of factors that influence the process of drying the book blocks, we developed a directed graph that shows their relations (Fig. 1).

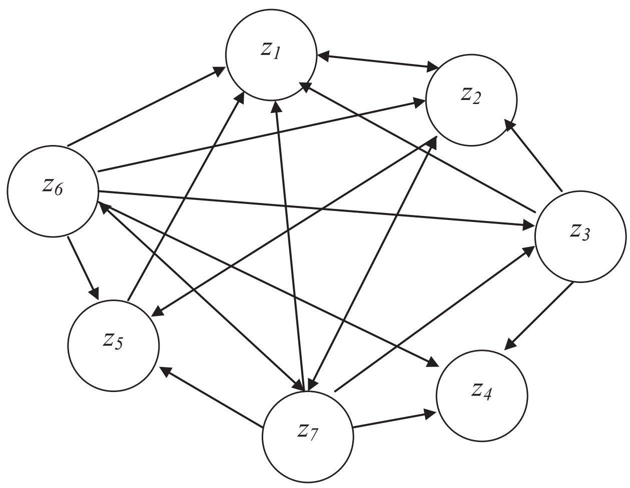


Fig. 1. Graph of relations between parameters of the drying of book blocks: Z_1 – the type of paper that the book blocks are made from; Z_2 – glue composition; Z_3 – temperature of drying; Z_4 – humidity of the surrounding medium; Z_5 – thickness of a book block; Z_6 – drying time; Z_7 – intensity of drying

The study of the distribution of moisture content in the spine of a book block in the process of drying showed that the main portion of excessive moisture immediately after applying the glue is in the gluing layer. During first moments of drying, the moisture is quickly enough released from the side of an open layer into the atmosphere. Due to the porosity of paper of the block, significant amount of the moisture is quickly adsorbed by the paper pores. Along with the liquid phase, the glue penetrates the pores of paper, which leads to gluing the sheets. Thus, it appears important that, in order to enable the adhesion, during first moments of drying the motion of moisture inside the middle of the paper block in the form of liquid is ensured. If the moisture at this point of drying moves as steam, then the glue molecules would not be able to deeply penetrate the pores of the paper and firmly hold its fibers afterwards. Total water yielding capacity of the glue layer during period is very large. Weight loss, which is determined only by the release of moisture into the atmosphere, is less than the dehydration of a glue layer. However, when drying the open adhesive layer, this period is characterized by the most intensive release of moisture into the atmosphere. This period determines the maximum value of drying rate and is mapped on the curve in the form of a section with constant speed (Fig. 2). The magnitude of rate and duration of a given period depends on the nature of glue, the mode of drying, and the properties of paper. Based on the simulation, we constructed a model of the process of distribution of moisture in the spines of a block, shown in Fig. 2.

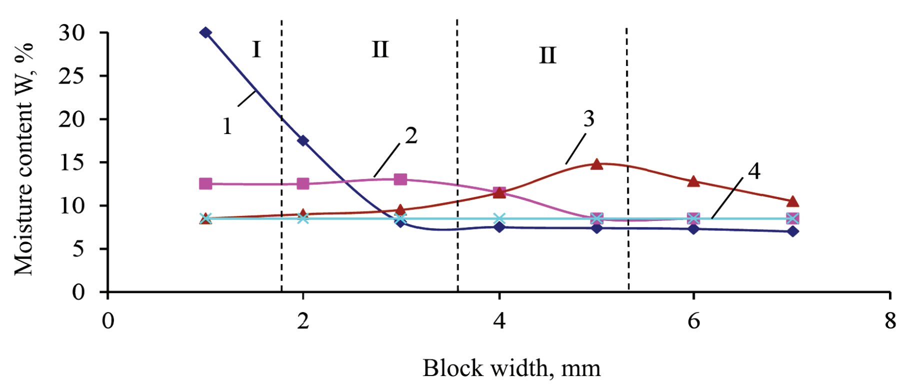


Fig. 2. A simulation model of the process of distribution of moisture in the spine of a book block during different stages of drying: 1 – initial period of drying; 2 – moisture accumulated in the second layer; 3 – moisture moved into the depth of the block; 4 – moisture attained equilibrium. I – III – layers

After applying the glue to the spine of a block, the moisture inside it, before drying, is distributed along line 1, that is, in layer I, all the moisture is contained mostly in the gluing film and partly in the pores of the ends of paper sheets that have a large number of micro and macro pores. In the process of block drying, after some time, the moisture inside it will be distributed along line 2, the moisture content of layer I will reduce because part of the moisture is evaporated from the surface of the film into the environment, while the second part will pass into layer II. Thus, layer II is moistened while the moisture content of layer III remains at the level of paper moisture content. While the drying proceeds further, the moisture inside it, after some time, will be distributed along line 3, that is, the moisture content of layer I will change due to evaporation into the environment, while the moisture of layer II will partly move to layer III. Further drying will lead to the establishment of equilibrium moisture content (line 4) for paper and a gluing film. Upon completion of the first period of drying, the moisture continues to be released from the surface of a gluing layer into the atmosphere. However, in most cases, the surface of the adhesive layer loses a significant portion of moisture with the formation of a dry film at its border with air, which inhibits moisture release into the atmosphere. The following period of a slowing rate, which is characterized by the penetration of moisture inside the paper, also slows down. Moisture from the inner layers of a block begins to move to the surface relatively faster than it is released into the atmosphere. In this case, there is a saturation of adhesive film with moisture. Drying comes to a second critical point. The rate of drying, that is, the rate of removal of moisture from an adhesive layer, slightly slows down. At falling rate, the moisture is removed from the block's paper and a glue layer; moisture content of all layers reaches equilibrium. In most cases, the equilibrium moisture content of an adhesive layer that corresponds to the relative room air humidity of 50–65 % is reached at the state when it acquires maximum strength, but at large rigidity of the film. Thus, in order to perform high-quality treatment of the spine, the moisture content of an adhesive film must not be brought to the equilibrium, but rather stop drying at the optimum moisture content of the film and the boundary adhesive layer.

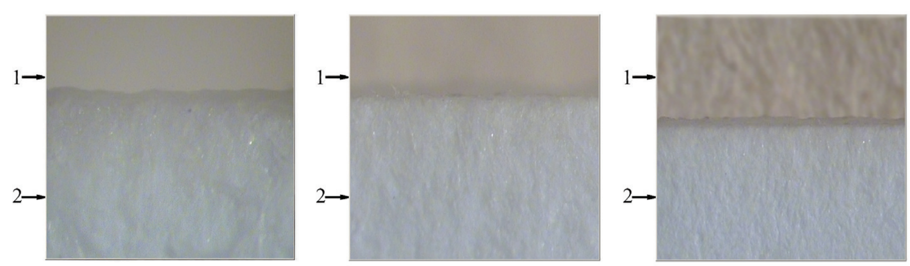
The process of removal moisture from the glue film on the spine of a book block is performed through coagulation or combining dissimilar particles of polyvinyl-acetate dispersion.

When contacting paper, which is a fiber material, moisture is sucked into it that results in the disruption of the system (dispersion creates a glue film). Water remains weakly bound to the polymer and it is transformed into wetting moisture; moisture removal from an adhesive layer does not require large amounts of heat. Part of the moisture is retained by a stabilizer – colloid of polyvinyl alcohol. Water is stronger bound to this polymer, as well as to a colloid material, and its removal requires heat and time. The adhesive film, formed from a dispersion, holds the sheets of textbooks that comprise the block firmly enough. However, mechanical strength of the glue seam is still insufficient for the rounding and cashing of the spine of a book block because the paper fibers of the spine part of a block remain very much moistened. Before taking the block to the subsequent treatment, it is necessary to bring moisture content to 12 %. In this case, strength of the paper is sufficient for mechanical treatment. The surface of the film at such moisture content dos not get off, and, during treatment, the glue is not separated from the spine. Optical-microscopic study show changes in the structure of the adhesive film based on PVAD, applied on the spines of blocks made from different grades of paper, prior to the onset of drying, in the process of drying, and after compete drying. Fig. 3 shows that the adhesive composition deeply, but not uniformly, penetrates the thickness of offset paper, which ultimately results in a strong glued connection.

An analysis of the microphotographic images (Fig. 4) reveals that the adhesive composition applied on the spine of the block made from chalk overlay paper of brand M-Real Zanders is evenly distributed across its surface. The formation of a clear border of the adhesive film on the surface of paper contributes to the rapid release of moisture into the environment.

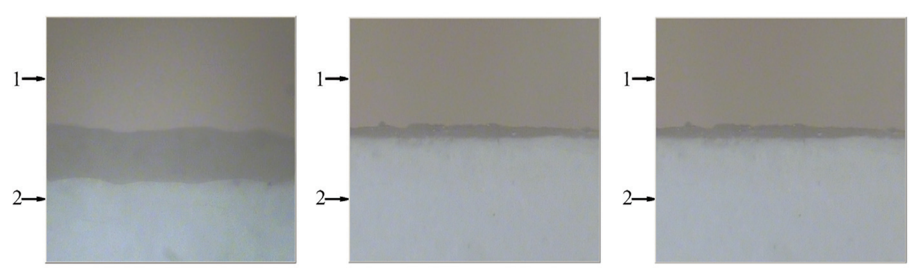
A microscopic study shows that the depth of penetration of a glue is affected by the capillary-porous structure of papers. As it is known, the offset paper's structure is well developed and in the chalk overlay paper – hidden by a filler, probably kaolin. The structure of paper influences to a larger degree the evaporation of moisture and uniformity of the formation of the adhesive film during drying. Moisture content of the boundary layer of a spine of thickness 2 mm immediately after gluing the block, sewn without gauze, is approximately 20 % (with using a glue based on polyvinyl-acetate dispersion containing a dry residue – 25 %). The first critical point corresponds to the moisture content of 14–16 %. The optimal moisture content (12 %) is reached by a layer over the period of falling rate at the section of the second critical point. When making books with a rounded spine of the block, it is recommended to apply a thicker layer of glue – then the moisture content of a spine is about 28–30 %. The optimum moisture content should be 12 % because, after drying and trimming the block, there follows the mechanical treatment of its spine. Thus, when drying a block, sewn with gauze, it is necessary to remove more moisture than while drying the one sewn without gauze. This is related to the increased time of drying and a large intensification of the process.

It is important to determine the form of a bond between moisture and material in different periods of drying, in order to establish the minimum time of drying the products. The influence of moisture content on thermal conductivity of materials that are exposed to drying depends on temperature. At high values of temperature and average values of moisture content, thermal conductivity is quite large and reduces both at low and high values of moisture content. That is why thermal conductivity of a moist material at different stages of the process of its drying is different. Study revealed that the processes of drying are significantly affected by the thermal conductivity of dried areas of the spine of a block. The course of the process depends also on the heat exchange with the environment. It is to a lesser extent influenced by thermal conductivity of the wet adhesive layer. Fig. 5 shows that the coefficient of thermal conductivity of book blocks in the process of drying reduces and, at the same value of moisture content, increases with an increase in the temperature of drying.



a *b* *c*

Fig. 3. Microphotographic images of the structure of adhesive layer applied on the spine of a block made from the offset paper Mega mat (magnification × 100 times): *a* – prior to drying; *b* – after partial drying; *c* – after complete drying: 1 – glue; 2 – paper



a *b* *c*

Fig. 4. Microphotographic images of the structure of an adhesive layer applied on the spine of a block made from paper M-Real Zanders (magnification × 100 times): *a* – prior to drying; *b* – after partial drying; *c* – after complete drying: 1 – glue; 2 – paper

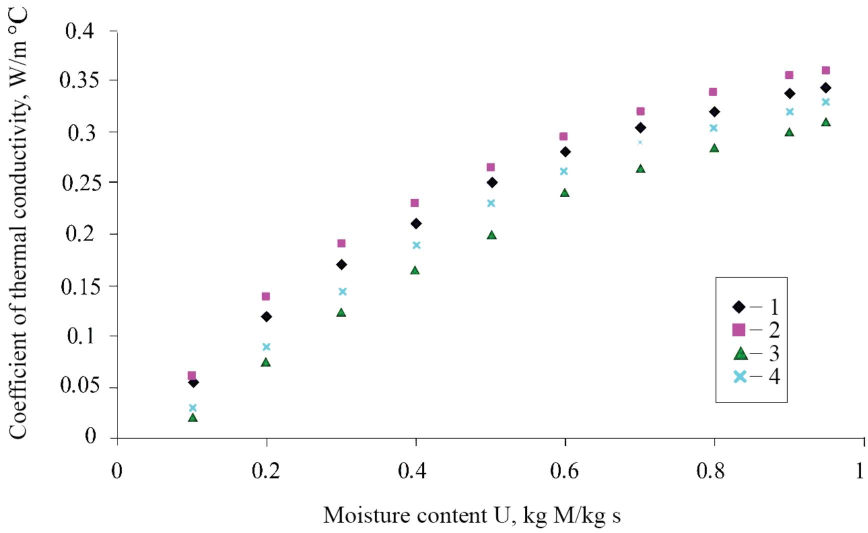


Fig. 5. Dependence of moisture content on the thermal conductivity coefficient of a book block made from: chalk overlay paper at a temperature of drying: 1 — 40 °C, 2 — 75 °C; offset paper at a temperature of drying: 3 — 40 °C, 4 — 75 °C

For the book blocks made from chalk overlay paper, values of coefficient of thermal conductivity are greater than those for the book blocks made from offset paper, which is obviously due to the influence of porosity and the degree of gluing the paper. Therefore, the thermal conductivity of book blocks fixed with dispersed adhesives during drying is affected by the type of paper that the book block is made from, the temperature of drying and the nature of adhesive composition.

The choice of specific parameters of drying in a drying device depends on the impact of changes on the rate of moisture removal. Studies have shown that at microwave drying an increase in the air temperature, its humidity and motion speed differently affects changes in the rate of removal of moisture from the adhesive layer applied on the spine of a block [21].

An analysis of dependence of drying time of blocks on moisture content (Fig. 6) shows that during first moments of drying the moisture content rapidly decreases. This is due to the evaporation of moisture from the surface of the adhesive layer into the environment. The rest of the moisture penetrates depth of the paper. Section AB (AB′), along which the rate of drying is constant, is the period of constant rate of drying, which is often difficult to capture in the process of experimentation. Section BC (B′C′) is the period of the first falling rate when the evaporation of moisture from the surface of the adhesive film occurs slower than penetration into the depth of the block. Section CD (C′D′) is the period of the second constant rate when due to the changing sign of the moisture conductivity gradient, moisture from the inner layers of the block starts moving to the adhesive film and evaporates through it into the environment. Starting at point D (D′), the process of drying slows, followed by a period of the second falling rate when the moisture content of the third layer is larger than that of the second one.

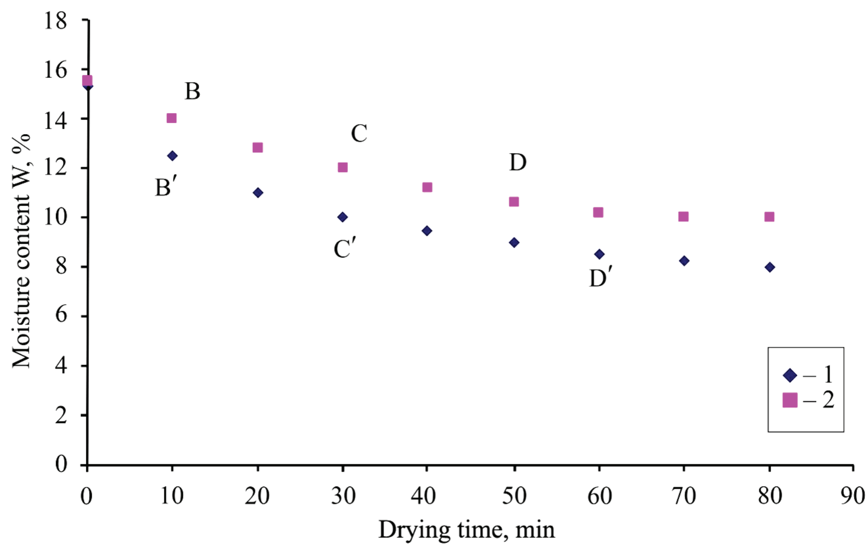


Fig. 6. Dependence of drying time of blocks, under natural conditions, made from: 1 — chalk overlay paper of brand M-Real Zanders (Germany); 2 — offset paper of brand Mega mat (Finland), on moisture content

Duration of the drying of the spines of book blocks to the equilibrium moisture content $Wp=10\,\%$ is the shortest for the blocks made from chalk overlay paper [24]. Fig. 7 shows curves of the microwave drying ($tc=40$ °C) of glued spines of the book blocks. An analysis of graphical dependences showed that it was possible to register the first constant (section AB) and the first falling (section BC) rates of drying only for the blocks made from chalk overlay paper (Curve 1).

It is typical that in the course of a study one can capture only second periods of drying. These periods can be divided into two linear charts.The first one illustrates the decisive role of the process of evaporation, which is confirmed by theoretical calculations. The second one demonstrates a decrease in the rate of evaporation of moisture due to the increased heat losses caused by thermal conductivity of a book block. Thus, as is the case for natural drying, the minimum duration of drying in a microwave drying device is typical for the blocks made from chalk overlay paper.

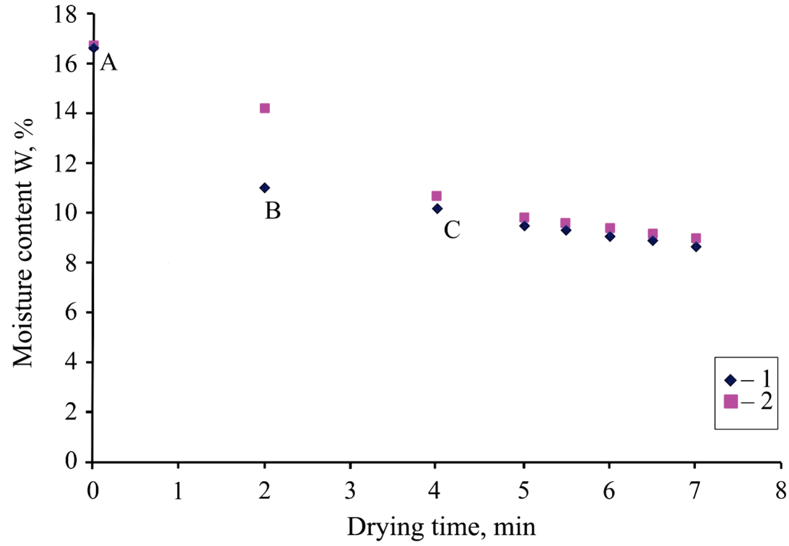


Fig. 7. Dependence of drying time of blocks made from:
1 – chalk overlay paper; 2 – offset paper, in a microwave drying device, on the moisture content

5. 1. Effect of the modes of microwave drying on the kinetics of drying process

The drying curves show changes in the average moisture content of a material depending on the duration of drying at different air temperatures (Fig. 7). With an increase in air temperature from 35 °C to 45 °C, that is, by 10 °C, the duration of drying reduces for the book block made from chalk overlay paper from 4.8 minutes to 3.5 minutes. For the book block made from offset paper, drying time decreases from 5.2 minutes to 4.1 minutes at a resulting moisture content of the sample $W=10$ %. All curves exhibit three periods of drying:

1) a period of warming the sample when the moisture content of paper decreases by some curve;

2) a period of constant rate when moisture content reduces according to the law of a straight line;

3) a period of falling speed when moisture content changes along the curve that asymptotically approaches the equilibrium moisture content.

The best temperature for drying can be accepted as 35–45 °C, at which a thermal gradient is directed toward the removal of moisture from the block. An increase in the relative air humidity leads to a decrease in the rate of drying. Moisture under the influence of a temperature gradient is directed inside the block at a temperature of the surface of the spine close to ambient temperature. The temperature of drying that is higher than the temperature of the block spine prevents the removal of moisture into the atmosphere. Considerable effect of a drying regime on the kinetics of the process can be seen on the curves of drying intensity. Fig. 8 shows the effect of relative air humidity and temperature on the intensity of drying a wetted sample. An increase in the relative air humidity results in the decrease in drying intensity and critical moisture content. With an increase in the relative air humidity from φ1=20 % to φ2=40 %, the intensity of drying decreases by about ≈2 times. At low air temperatures, the increased relative humidity does not affect the intensity of drying over a period of the falling drying rate.

The study shows that an increase in temperature results in an increase in the intensity of drying and critical moisture content. Thus, with an increase in temperature from 45 °C to 65 °C, drying intensity over the first period increases by ≈1.5 times. An increase in the air temperature during drying causes the migration of a plasticizer (dibutyl phthalate or dibutyl malonate), which is contained in the adhesive composition. This leads to excessive stickiness of the glue film and complicates subsequent treatment operations. Therefore, in order to intensify the process of drying, it is necessary to accelerate the processes of film-formation and moisture removal.

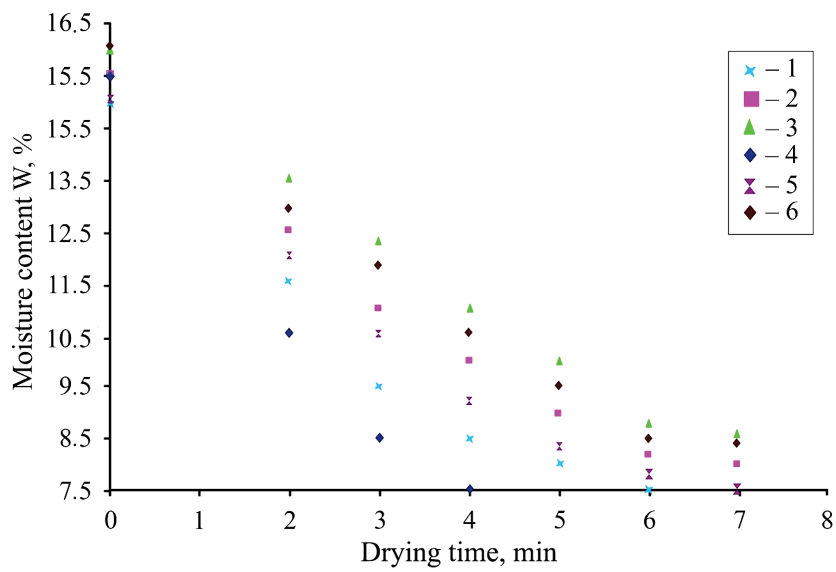


Fig. 8. Effect of air temperature on the duration of microwave drying of book blocks made from: offset paper: 1 – 65 °C, 2 – 45 °C, 3 – 35 °C; chalk overlay paper: 4 – 65 °C, 5 – 45 °C, 6 – 35 °C

To increase the rate of film-formation at the first stage of drying the layers of polyvinyl-acetate dispersion, it is necessary to create conditions for combining separate particles of the dispersion into a solid mass. In this case, it is advisable to remove the moisture, which is weakly associated with a glue film, maximally quickly. The best conditions for deep warming of the film are possible at the irradiation of the spine of a book block with a heat flow, but a long warming causes the motion of plasticizer (dibutyl phthalate) to the surface. Removing it from the surface of a film occurs very slowly, which is why the film acquires stickiness. The proposed microwave irradiation of the spine of a block eliminates detachment of the film from the spine.

Because the amount of moisture that is removed during drying differs, the conditions for drying should be adjusted. However, in all cases, it is necessary to create conditions at which the evaporation of moisture inside the adhesive layer and the creation of large steam pressure, which causes detachment of the cover from a block and destruction of the glue film, are impossible. Fig. 9 shows that the layers of paper that are closest to the adhesive layer absorb moisture and, afterwards, wetted to the maximum, pass it to the next layers. The layers of paper that are furthest from the glue are slightly wetted. Beyond 20–25 mm, the moisture content of paper almost does not change. The adhesive layer loses moisture by giving it to paper. However, no release of moisture into the atmosphere occurs in this case – it migrates into the paper of a block. The curves of natural drying of the spines of blocks made from offset paper (Fig. 10) show an insignificant rate of moisture release by a glue layer and a considerable increase in the intensity of drying in a microwave dryer.

The rate of drying the semi-products and finished books using such a technique varies in accordance with the changes in the parameters of the medium in which the drying is conducted. An increase in the speed of air that surrounds the spine of a book block, and especially the increase in its temperature, leads to the fact that the cover rapidly loses moisture and becomes too dry. The feed of moisture from the adhesive layer is delayed and an evaporation zone deepens significantly, reaching the inner layers of the cover. At a higher temperature of the air that surrounds a book, the temperature of evaporation layers is higher than the temperature of the block. Moisture from an adhesive layer intensely moves into paper and wets it heavily. When such a book, with a dry spine, leaves the drying zone, its cover is wetted again and, when cutting on three sides, the corners of the spine would be torn out with the wrinkles formed on the cover's spine.

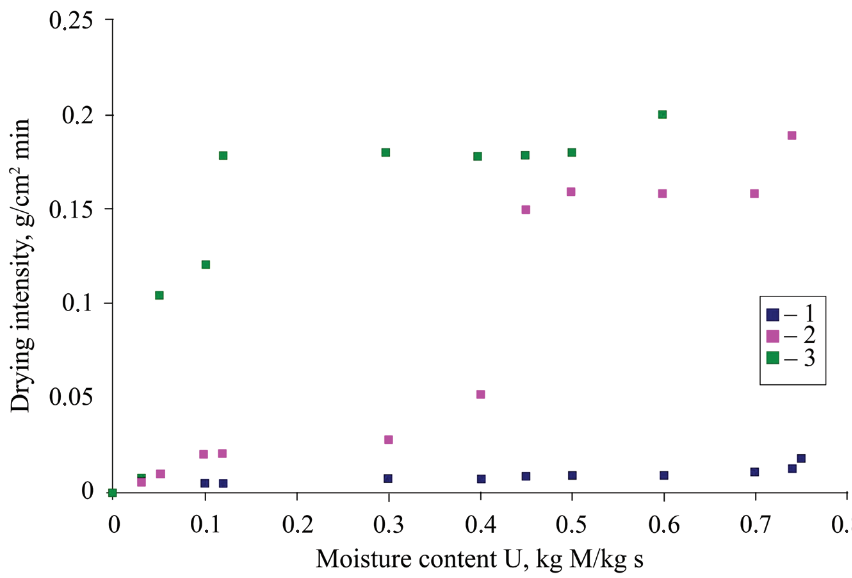


Fig. 10. Effect of relative humidity of the adhesive layer on the intensity of drying the spines of blocks: under natural conditions — 1; microwave drying: 2 — at $t = 75$ °C; 3 — at $t = 100$ °C

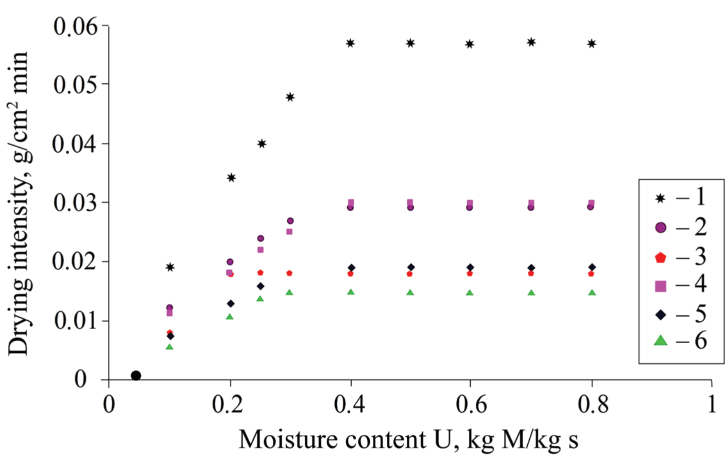


Fig. 9. Effect of relative air humidity: 1 — 20 %, 2 — 40 %, 3 — 60 %, and air temperature: 4 — 65 °C, 5 — 45 °C, 6 — 35 °C, on the intensity of drying a book block made from offset paper

To intensify the process of drying the books using a dispersed glue, it is possible, following inserting it inside the cover, to use a combined regime of drying with microwave drying. When heating a boundary layer of the book's spine the temperature inside it grows higher than the ambient temperature, and moisture is rapidly released into the atmosphere. However, a large increase in the rate of drying can lead to the intensive vaporization of an adhesive layer and tearing the cover off the block. Therefore, it is better to perform intensive short-time warming of the spine part of the book, followed by blowing with a jet of air. When using the microwave drying of the books, inserted inside the cover, the time of drying must be such that the bulk of moisture from an adhesive layer is able to migrate inside the width of the block's paper, specifically: for books compiled of textbooks, sewn by threads and covered by a book cover, is 2–3 minutes; and for the books with a non-sewn glued binding – 5–6 minutes.

The time during which moisture passes from a layer of glue to the paper of a block depends on the suction capacity of paper, on the type of bonding between moisture and a glue. The less paper is glued and the looser, the easier and faster the moisture from the glue penetrates the paper of a block and distributes inside it. The denser the paper the better its pores closed and the more hydrophobic they are the slower moisture migrates inside the width of paper.

Fig. 11, 12 show a dependence of the effort of pulling a sheet out of a book block and of the effort of tearing a book block on the time of drying in a microwave drying device at different drying temperatures (40 °C and 75 °C). Using the least squares method, we determined parameters of the optimization model.

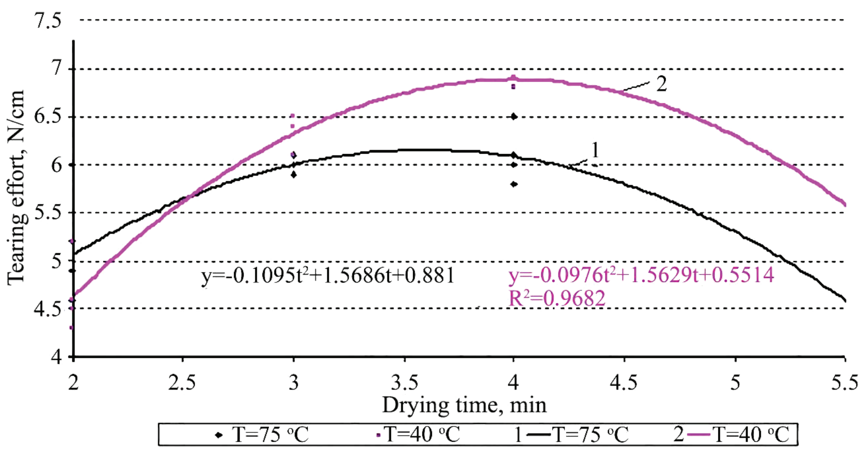
Thus, the optimal time for drying book blocks depends on the drying temperature and the type of paper. For the blocks made from offset paper, an increase in the temperature of drying from 40 °C to 75 °C leads to a decrease in the time of drying from 4 minutes to 3 minutes. Optimal drying time of book blocks made from chalk overlay paper at a temperature of 40 °C is 3.5 minutes, and at a temperature of 75 °C – 3 minutes.

The maximum effort to tear the book blocks made from offset paper, after the optimal time of drying, is 7.6 N/cm, for those made from chalk overlay paper is 7.19 N/cm. After the optimal time of drying, the maximum effort of pulling a sheet out of the book block made from offset paper is 6.9 N/cm, made from chalk overlay paper is 5.94 N/cm, which follows standards.

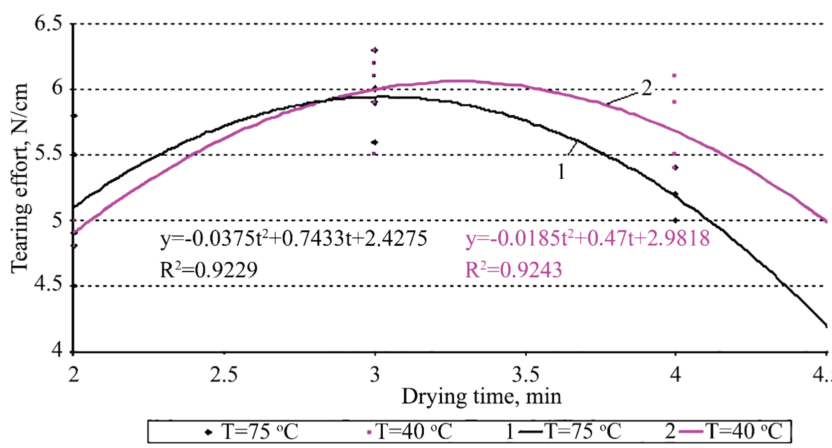
The process of moisture removal is affected by the capillary structure of papers. The moisture is removed faster from papers with a less developed capillary structure. Moisture migration in paper with high gluing is difficult, which is why the duration of drying the blocks made of chalk overlay paper is longer than that in the blocks made from offset paper. The rate of drying the blocks after inserting them inside the cover is affected by such technological factors as thickness of a book, the type of adhesive composition, the degree of paper gluing. Thick paper for covers with a high degree of gluing receives moisture of a glue inappropriately, which is why steam formation occurs in a gluing layer. In this case, a migration of moisture under the action of the moisture capacity gradient proceeds towards a cover, which at intensive heating may lead to its steaming off.

Thus, the microwave drying of book blocks is significantly affected by the temperature of drying, relative humidity and temperature of the air, which is fed to a drying chamber. In addition, the quality of the process depends on the total capacity of energy sources, oscillation frequency of the magnetron generator and pressure in the drying chamber. Important factors are also the volume of a drying chamber, energy cost for the removal of 1 kg of moisture, and drying time.

Based on the experimental study, using the software Statystyka 6, we constructed a correlation field of scattering of values for the stability of book blocks to variable loads and corresponding histograms (Fig. 13).



a



b

Fig. 11. Dependence of tearing effort of a book block on the time of drying: *a* — made from offset paper; *b* — made from chalk overlay paper

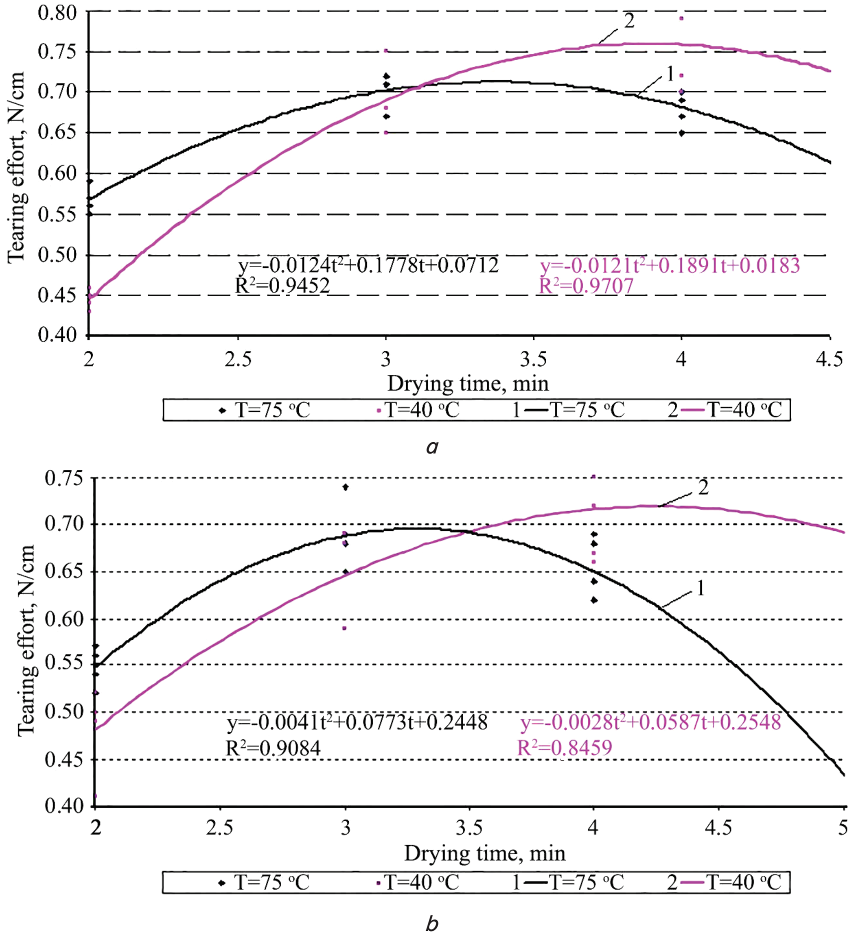


Fig. 12. Dependence of tearing effort of a book block on the time of drying: *a* — made from offset paper; *b* — made from chalk overlay paper

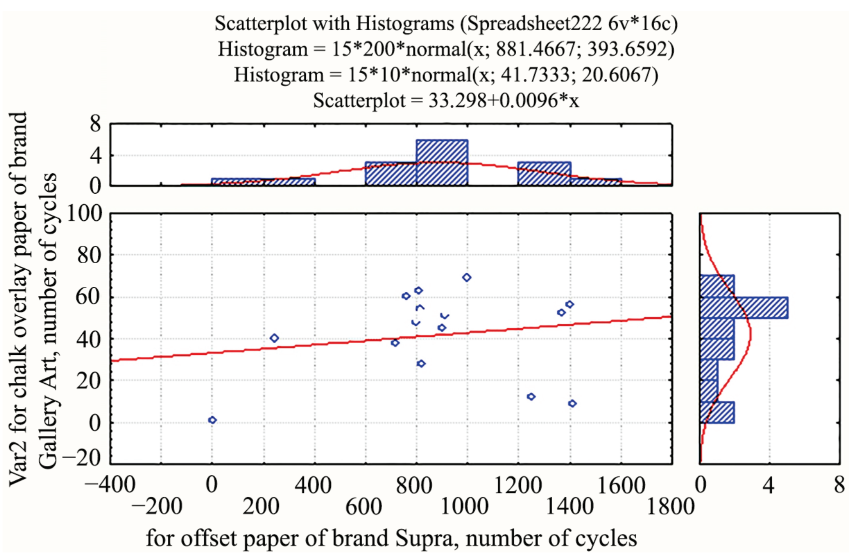
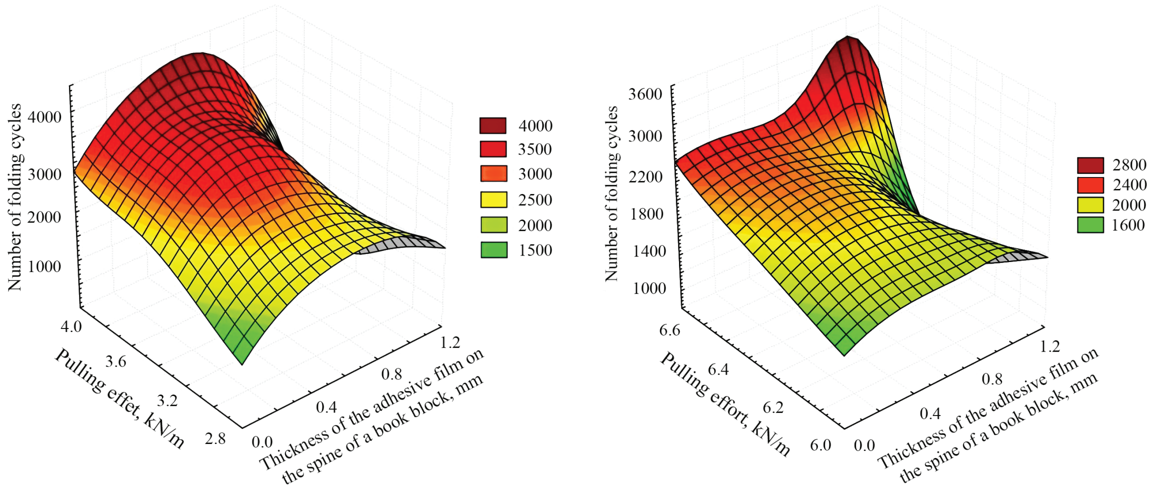


Fig. 13. Correlation field of scattering of values for the stability of book blocks to variable loads and corresponding histograms

It was established that the blocks made from the offset paper Mega mat can withstand, with a load on the spine without damage to the glued joints, 1.800–2.000 cycles. Much weaker to variable loads on the spine when folding pages are the blocks made from chalk overlay paper (1.300–1.500 cycles). The region of optimal values of stability of book blocks made from the offset paper Mega mat to the sign-alternating loads shows that the effort of pulling out a sheet without loading the spine is 6.5 N/cm (Fig. 14, *a*), and, while loading, is respectively, 6.3 N/cm (Fig. 14, *b*). Somewhat weaker are the efforts of pulling a sheet out of blocks made from the chalk overlay paper M-Real Zanders, 5.7 N/cm (Fig. 15, *a*), and is, while loading the spine, respectively 5.3 N/cm (Fig. 15, *b*).

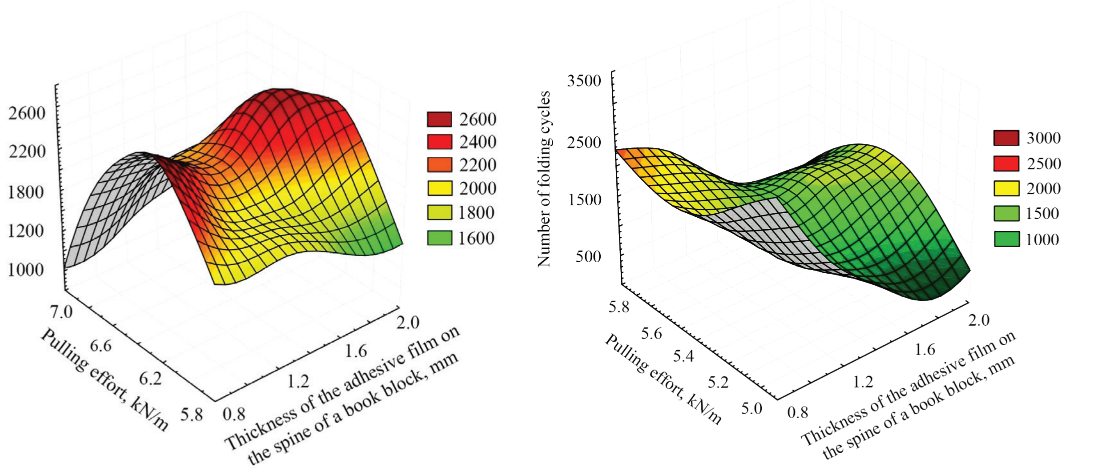
An analysis of the charts (Fig. 14) shows that the effort of pulling a sheet out of the block made from offset paper with a load on the spine (50 N) is 6.3 N/cm, without a load, 6.5 N/cm. The weaker connection is observed, accordingly, in the book blocks made from chalk overlay paper (Fig. 15); with a load on the spine, it is 5.3 N/cm, without a load, 5.7 N/cm, respectively.

The charts show that the results of research into stability of book blocks to the sign-alternating loads are within the region of permissible values, and comply with the ISO international standards. The strength of binding a block is significantly affected by the additional load on the spine and the type of paper that a book is made from.



a *b*

Fig. 14. Region of optimal values of the stability of book blocks made from the offset paper Mega mat to the sign-alternating loads: *a* — without a load on the spine; *b* — with a load (50 N)



a *b*

Fig. 15. Region of optimal values of the stability of book blocks made from the chalk overlay paper M-Real Zanders to the sign-alternating loads: *a* — without a load on the spine; *b* — with a load (50 N)

6. Discussion of results of studying the effect of modes of microwave drying of blocks on the strength of book binding

Based on the results of theoretical and experimental study, it was established that the optimum time of microwave drying of book blocks is 3–4 minutes at a temperature of drying within 40–75 °C. At the optimum time of drying of book blocks, the maximum effort of tearing a block is 7.6 N/cm (made from offset paper) and is 7.19 N/cm (made from chalk overlay paper). The maximum effort of pulling a sheet out of the book block is 6.9 N/cm and 5.94 N/cm, respectively, for blocks made from offset and chalk overlay paper. The effort of pulling a sheet, with a load on the spine (50 N) of a block, decreases (for offset paper, 6.3 N/cm, for chalk overlay paper, 5.3 N/cm).

We determined the influence of paper and thickness of the adhesive film on the optimal values of stability of the dried blocks to the sign-alternating loads on the spine. It was established that book blocks made from offset paper withstand, without a load, from 2.800–3.000 cycles to 1.800–2.000 cycles of double folding the sheets at a load on the block (50 N). Somewhat weaker are the blocks made from chalk overlay paper that can withstand, respectively, from 2.000–2.200 cycles to 1.300–1.500 cycles.

Thus, the theoretical and experimental study that we conducted has shown the prospect of using the designed microwave drying device for the intensification of book making process. The absence of a heat carrier that may pollute the treated material makes it even more attractive, while the intensity of heating does not depend on the aggregate state of a material. An analysis of quality indicators of book blocks confirmed that the microwave drying of glued joints does not lower performance indicators of books, defined by norms of the ISO international standards. However, in order to launch industrial production of microwave dryers for the drying of book blocks, in addition to the examined parameters: drying temperature drying is 40 °C, relative air humidity is 60–65 %, temperature of the air fed into a drying chamber is 20–30 °C, it is necessary to additionally estimate design parameters – volume of the chamber, power of magnetrons, oscillation frequency, pressure in the drying chamber, drying zones. It is important to accurately define the diameter of a cavity resonator and its length to ensure a uniform range of resonance wavelengths or resonance frequencies.

7. Conclusions

1. It was established that an increase in relative air humidity decreases the intensity of drying of glued joints in book blocks, and with a rise in temperature – vice versa. This is confirmed by the designed simulation model of the process of moisture transfer.

2. Based on the graph-analytic analysis of curves of the intensity of microwave drying of glued joints of the spines of blocks and mathematical modeling, we demonstrated relationship between the time of drying, temperature, and the type of paper. Thus, an increase in relative air humidity from 20 to 40 % results in a decrease in the intensity of drying by about 2 times (for the blocks made from chalk overlay paper) and by 1.5 times (for the blocks made from offset paper). An increase in temperature leads to an increase in the intensity of drying and critical moisture content. An increase in air temperature by 10 °C results in a reduction in the drying time of blocks made from chalk overlay paper by about 1.5 minutes, and of the blocks made from offset paper – by 1 minute.

3. We determined the modes of microwave drying of book blocks (time is 3–4 minutes, temperature is 40–75 °C), which ensure high performance indicators of books: resistance to the sign-alternating loads on the spine (1.300–2.200 cycles for blocks made from chalk overlay paper, 1,800–2,800 cycles for blocks made from offset paper); maximum effort of breaking a block made from offset paper is 7.6 N/cm, 7.19 N/cm (made from chalk overlay paper); maximum effort of pulling a sheet out of the block (6.9 N/cm, made from offset paper; 5.94 NG/cm, made from chalk overlay paper).

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