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OPTIMIZING THE TECHNOLOGICAL MODES OF LAMINATION OF DIGITAL PRINTS

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The intensive use of lamination technology for the decoration of printing prints made by various printing techniques, as well as a wide range of films, require solving an urgent problem – optimization of influencing factors to ensure the quality of laminated products. The objects of research were prints of inkjet and laser printing on paper, photo paper, and cardboard. A glossy film based on bio-oriented polypropylene BOPP was used for lamination. Studies of densitometric indicators of prints after lamination confirmed an increase in optical density by 0.28 units. This is especially true for inkjet prints. However, after lamination, all digital prints showed a tendency to improve colorimetric characteristics, namely an increase in the brightness of CMYK colors.

The relationship between the technological regimes of lamination (speed and temperature) and the strength of the laminates, estimated by breaking and pressing forces, was established. To describe the dependence of the laminate strength on the temperature and speed of lamination, polynomial models were built that reproduce the values of the breaking and pushing forces of the laminate with satisfactory accuracy. The selected algorithm for calculating the parameter values of these models is based on the application of the Chebyshev approximation of the functions of many variables. The optimization models built will allow, if necessary, for making corrections in the technological process of laminating printing prints to ensure the predicted required quality and strength of laminates

Keywords: digital printing, prints, lamination modes, densitometric indicators, optimization of quality of laminates

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1. Introduction

The print lamination process has already become commonplace in the printing world. Polymer films not only protect printed images from moisture and mechanical damage but also improve the aesthetic appearance of products. In the process of lamination, a print-film system forms, the properties of which are determined by many technological factors, the main being the conditions for the formation of adhesive contact during the interaction of the adhesive and substrate. World practice uses the following techniques for joining polymeric material with paper: adhesive, adhesive-free, extrusion. The adhesive technique has advantages as it makes it possible to laminate the print under any conditions with a relatively cheap single-layer film. The disadvantage of the technique is the use of toxic solvents, low speed of lamination.

The glueless technique of lamination does not have the disadvantages of the previous one but requires the use of special two-layer films. The extrusion technique makes it possible to use cheap raw materials – polymer granules and apply a melt layer at maximum speed (up to 100 meters per minute). In addition, cold and hot lamination are distinguished. Cold lamination uses an adhesive-coated film that adheres to the print at room temperature under pressure. The ratio of the adhesive layer to the base of the film is indicated by a fraction – 50/50, 60/40. The smaller the adhesive layer, the stiffer the film – regardless of its actual thickness [1]. Such lamination is energy-saving due to the absence of heating elements. It is often used to decorate large-format prints of digital printing.

Hot lamination technology is mainly used for paper and cardboard prints. It differs from cold lamination in that it increases the brightness and saturation of colors on the print. For hot lamination, films with a thickness of 8 to 250 microns are used. Usually, these are moisture-resistant polypropylene (PP) films [2]. Biaxially oriented polypropylene BOPP films are especially popular – glossy or matte, elastic, soft, and at the same time extremely strong and resistant to any impact. Due to their properties and varieties, such films are extremely popular for laminating packaging for food products. Films based on polyvinyl chloride (PVC) are used for processing advertising products and business cards, which give products elasticity, stickiness, and stability. Known films are resistant to ultraviolet light, plastic, and even after long storage in a roll they can easily acquire their original shape, therefore they are used for the production of outdoor advertising. Films (PET) based on polyester, with a thickness from 25 to 250 μm give the product strength, have good resistance to moisture and mechanical damage. Depending on the thickness and type of film, the heating temperature of the laminator in the hot technique is selected, which can vary from 110 °C to 160 °C. After all, insufficient or too high heating temperature of the laminator shafts could lead to poor adhesion of the film to the print, and sometimes to damage of the printed image and document [3].

Our review of modern technologies for laminating prints shows that each of them has advantages and disadvantages and is accordingly recommended for certain types of printing and packaging products. Since hot lamination technology is becoming more and more popular for decorating digital prints, research into technological factors affecting the quality of laminates is relevant.

2. Literature review and problem statement

Theoretical and practical aspects of the process of laminating prints attract the attention of many researchers. Thus, in [4], the results of establishing the relationship between the parameters of the technological process of lamination and the strength of laminates are given. The authors proposed to use the coefficient of strengthening of blank paper and print to determine the strength of the adhesive joint during lamination. However, this coefficient will be different for each option, which creates corresponding difficulties in its calculation. In order to ensure high-quality lamination, the researchers also suggest adjusting the equipment before pressing the film to the print according to the calculation of regression equations that take into account the pressing force of the laminator shafts from the speed of lamination. However, they do not take into account the temperature conditions of the lamination process, which is very important in the hot lamination technique.

An important problem in lamination is ensuring adhesion of the adhesive base of the film to the prints. Paper [5] investigates the adhesion of polypropylene films to the surface of electrographic prints in the lamination process. The authors found that the temperature and speed of lamination (which determines the duration of contact of the surfaces at temperature) have the greatest influence on adhesion, that is, the strength of the adhesion of the film to the surface of the print. However, the optimal temperature conditions for lamination have not been determined.

Work [6] examines the technological features of leaflet lamination. The authors proposed an algorithm for the technological process of product lamination, which takes into account the weight of the paper print, which is not entirely correct, since the topography of the print surface, and not its weight, is a more important factor. The change in temperature conditions of lamination on the quality of products is also not taken into account.

The classification of factors affecting the quality of offset prints is described in [7]. The influence of the morphological structure on the quality of lamination of prints with polypropylene films has been confirmed. It has been proven that the smoother the surface of the impression, the lower the strength of the adhesive connection during lamination. Based on the built three-dimensional model, the impact of the surface structure of the prints and their mass on the lamination strength was confirmed. However, the influence of the optimal values of the product lamination speed is not taken into account.

In [8], experimental studies of the performance characteristics of laminated prints of digital printing are given, in particular, attention is focused on the influence of toner on the quality of laminates. The technological modes of lamination, which determine the quality of products, remain outside the author's attention. Features of production of adhesives for lamination of medical packaging materials, adjustment of their properties are described in [9]. The authors emphasize the importance of taking into account the properties of adhesives when laminating products, which to a certain extent determine the strength of laminates. However, they do not investigate the behavior of adhesives when temperature conditions and lamination speed change.

The adhesive bond when laminating cardboard with a polyvinyl chloride film is studied in [10]. The influence of the structure of the substrate and the film, the thickness of the adhesive layer and the uniformity of its application on the strength of the laminate connection is shown. Unfortunately, the method of pressing the film, the modes of operation of the equipment, which ensure consumer properties of laminates, are not taken into account.

The quality of laminated prints on cardboard printed by digital jet printing is studied in [11]. In particular, the authors investigate the effect of lamination on the change in densitometric indicators of prints, such as optical density, gradation transfer, tonal reproduction. However, the influence of technological modes of lamination on the quality of printed images and operational indicators of laminates remains neglected.

The review of scientific sources shows that the lamination process is affected by many technological and regulatory factors, such as film thickness, topography of the print surface, the presence of an ink layer, and the printing technique, which should be taken into account to ensure product quality. However, for manufacturers, an important aspect is establishing the relationship between lamination modes (temperature and speed) and strength characteristics of laminates. It is these performance characteristics that are important to many consumers who use lamination technologies for a variety of paper packaging materials that are printed with popular digital printing. That is why it is so important to determine and optimize the factors affecting the quality of laminates, to establish the magnitude of their influence on increasing the strength of laminated products, as well as the possibility of technological forecasting of the required quality of laminates to meet the demands of the most demanding consumers.

3. The aim and objectives of the study

The aim of this study is to optimize the technological modes of lamination of digital prints. This will ensure satisfactory strength and quality of laminates.

To achieve the goal, the following tasks were set:

– to investigate the densitometric indicators of digital printing prints before and after lamination;

– to establish the relationship between the mode factors of the lamination process (temperature and speed) and the performance characteristics of laminates (tear strength and compression strength);

– based on the results of experimental studies of the breaking and pushing forces of laminates, to build and investigate mathematical models connecting the technological regimes of lamination and operational indicators.

4. The study materials and methods

4. 1. The object and hypothesis of the study

The object of our study was digital prints on paper substrates. The main hypothesis of the study assumes that there are optimal technological regimes of lamination (temperature and speed), which ensure the quality of laminates, expressed by satisfactory operational indicators (strength of breaking and pressing of laminates). The work accepts that the speed and temperature of laminating prints affect the quality of laminates.

4. 2. Materials and equipment used in the experiment

The research used prints on UPM Digi Color chalked paper (300 g/m^2) and Arktika cardboard (200 and 300 g/m^2), which were obtained on a Ricoh Pro C751 laser printer, as well as prints on Fujifilm photo paper (200 g/m^2), obtained on the Noritsu QSS-3501 PLUS inkjet printer. Lamination was carried out with glossy polypropylene film (BOPP) Lamiroll Glossy (thickness 24 μm) on a Foliat 520 roll laminator. The characteristics of materials and lamination modes are given in Table 1.

Table 1

Characteristics of materials and lamination modes

Paper brand	Grammage, g/m^2	Print moisture, %	Lamination temperature, °C	Lamination speed, rpm
Digi Color	300	30–40	90; 95; 116; 125; 130	2.75; 3; 3.25
Arktika	200	30–40	90; 95; 116; 125; 130	2.75; 3; 3.25
Arktika	300	30–40	90; 95; 116; 125; 130	2.75; 3; 3.25
Fujifilm	200	30–40	90; 95; 116; 125; 130	2.75; 3; 3.25

The performance characteristics of laminates (tensile strength) were investigated on a tensile machine (Fig. 1).

Fig. 1. General view of the RMB-30-2m tensile machine

To determine the punching force of laminates, a designed device based on the UK 25-1.6 installation was used.

4. 3. Procedure of research of densitometric indicators of prints

The densitometric indicators of the prints were studied on the GRETAG SPM 50 spectrodensitometer, which works in reflected light, determines the optical density of the background and dies, the compression (relative area) of raster elements, trapping, gray balance, uniformity and contrast of printing. Standardized viewing angles of 20 and 100 are used to carry out colorimetric measurements of images observed from different distances. Standardized radiation sources D50, D65, A, B, C, etc., which have appropriate spectral characteristics are used in the spectrodensitometer to predict the colors of the future printed edition under different lighting [12].

4. 4. Procedure for determining the optimal modes to laminate prints

To determine the optimal lamination regime, a number of observations were made on the experimentally determined values of the breaking force and the pushing force of laminates made of different types of paper. To describe the dependence of the strength of the laminate with respect to the breaking and pressing forces on the temperature regime and the speed of lamination, polynomial models of four parameters were built, which reproduce the values of the forces specified above with satisfactory accuracy. The parameter values of these models were calculated according to the algorithm described in [13]. Polynomial models were built using the natural values of the input variables from the ranges of lamination temperature values of prints: 90 °C, 95 °C, 116 °C, 125 °C, 130 °C, and lamination speed: 2.75 rpm; 3 rpm; 3.75 rpm.

The algorithm for calculating the parameter values of these models is based on the application of the Chebyshev approximation of functions of many variables, using the Chebyshev criterion [14]. The peculiarity of the Chebyshev approximation is that it ensures the achievement of the smallest possible error in reproducing the desired dependence for a given number of parameters [15]. Calculation of optimal lamination modes was carried out using the Maple package.

5. Results of investigating the quality indicators of test prints of flexographic printing

5. 1. Studying the densitometric indicators of prints

The results of studies of prints before and after lamination are given in Table 2.

The analysis of tabular data reveals that for all prints after lamination, an increase in the value of optical density and color difference is characteristic, which is obviously related to the use of glossy film. Indicators of optical density for prints of laser printing on Digi Color paper for 100 % saturation field of the control scale are the largest and increase from 1.76 to 2.04. The lowest optical density values are typical for Arktika cardboard (1.38 – without lamination to 1.66 – after lamination). Jet printing prints are characterized by slightly lower values of densitometric characteristics compared to laser printing prints. However, after lamination, the tendency to increase the brightness of colors is characteristic of digital and inkjet prints. So, our studies confirm that the influence on the densitometric indicators of laminates is exerted by the printing technique and the percentage of filling of the print with printing elements.

Fig. 2 shows photographs of pressing laminated prints on various papers and boards.

Analysis of microphotographs reveals that when pressing laminates, the paper base of the print is destroyed at the first stage, followed by deformation (or rupture) of the pressed film. Therefore, the process of laminating prints significantly strengthens their mechanical characteristics, as evidenced by the obtained experimental data of the breaking and pushing forces of laminates.

Table 2

Densitometric indicators of prints before and after lamination

Imprint on paper	Coating	Weight, g/m^2	Optical density, D field saturation 50 %	Optical density, D field saturation 100 %	Color difference C	Color difference M	Color difference Y	Color difference K
Digi Color	no lamination	300	1.08	1.76	1.85	1.68	1.42	1.71
Arktika	no lamination	200	0.75	1.38	1.11	1.32	1.22	1.84
Arktika	no lamination	300	0.86	1.43	1.62	1.43	1.31	1.92
Fujifilm	no lamination	200	0.94	1.56	0.63	0.48	0.57	0.69
Digi Color	with lamination	300	1.65	2.04	1.82	1.86	1.65	1.89
Arktika	with lamination	200	1.15	1.58	1.92	1.72	1.65	2.09
Arktika	with lamination	300	1.47	1.66	2.71	1.93	1.42	2.04
Fujifilm	with lamination	200	1.24	1.64	0.95	0.62	0.76	0.86

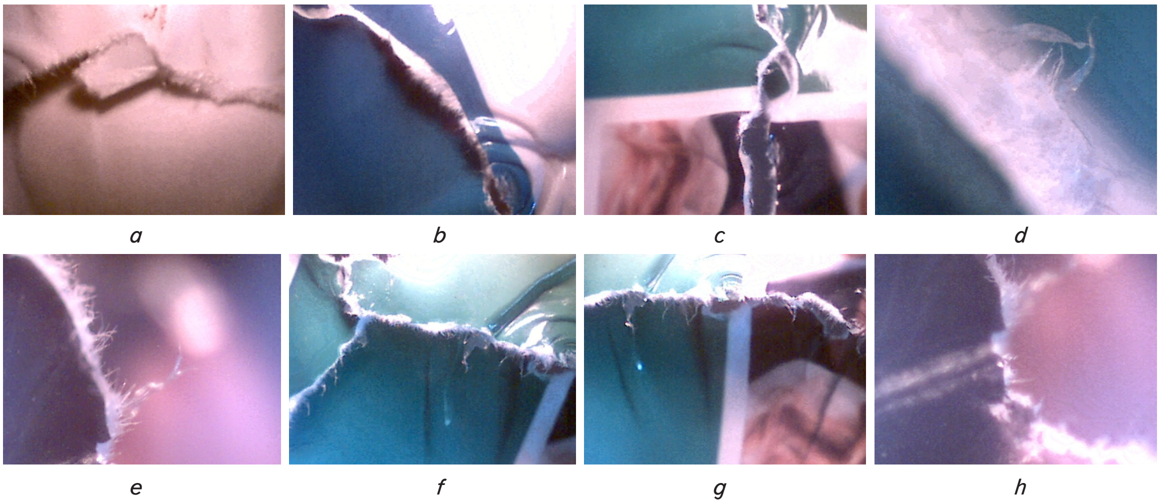

Fig. 2. Photomicrographs (magnification 60x) of prints without lamination on papers: *a* — Digi Color; *b*, *c* — Arktika; *d* — Fujifilm; with lamination on papers; *e* — Digi Color; *f*, *g* — Arktika; *h* — Fujifilm

5. 2. Study of the relationship between the regime factors of the lamination process and the operational characteristics of laminates

Experimental studies of performance indicators of laminates produced at variable temperature and speed of lamination are given in Table 3. As can be seen from the tabular data, there is a close relationship between the temperature and speed of lamination and the tensile strength of laminates.

A similar pattern is observed between the force of punching laminates and the speed of lamination. As the speed of lamination increases, the amount of punching force increases. This tendency is characteristic of all prints, regardless of the type of paper and the technique of obtaining the print. The smallest punching forces in laminated prints were found on the UPM Digi Color 300 g/m^2 paper. Laminated prints on Fujifilm 200 g/m^2 photo paper have the highest punching and tearing forces.

Table 3

Experimental values of breaking and pushing forces of laminates

T, °C	Breaking force, *F*, kg			Punching force, *P*, kPa		
	Lamination speed, *V*, rpm					
	2.75	3	3.25	2.75	3	3.25
	Prints on paper UPM Digi Color 300 g/m^2					
1	2	3	4	5	6	7
90	10	10.7	10.8	64	66	68
95	10.8	10.9	11	65	67.2	69
116	11.9	12	12.2	79	80	82
125	10.9	11	11.5	75	77	78
130	10.2	10.9	11	70	72	74

Continuation of Table 3

1	2	3	4	5	6	7
Prints on photo paper Fujifilm 200 g/m^2						
90	9.8	10	10.8	165	169	172
95	11.2	11.5	11.7	171	174	179
116	12.7	13	14	199	200	202
125	10.9	11.6	11.8	179	180	183
130	10.5	10.6	11.4	167	170	172
Prints on cardboard Arktika 200 g/m^2						
90	10	10.6	10.8	164	169	170
95	11	11.2	11.8	168	170	173
116	14.7	14.9	15.6	178	180	184
125	13.5	14	14.2	166	169	170
130	11	11.8	11.9	166	170	171
Prints on cardboard Arktika 300 g/m^2						
90	10.4	12	12.3	160	166	167
95	12.4	13.8	16	167.4	168	168.3
116	17.3	17.7	17.9	170	171	173
125	16.7	16.8	16.9	166	168	169
130	16	16.1	16.9	162	165	168

5. 3. Construction and analysis of mathematical models

5. 3. 1. Mathematical model for determining the optimal lamination mode for printing on UPM Digi Color 300 g/m^2 paper

According to the results of investigating the laminate strength of the glossy surface of UPM Digi Color 300 g/m^2 paper, a polynomial model was built to estimate the breaking force:

$$F_{UPM}(T,V) = 0.745346173V - 0.003457529827T^2 + \\ +0.765727847T - 32.7039329432, \quad (1)$$

which reproduces the breaking force of the laminate with an absolute error of 0.26 kg. The view of the surface of the values of the model $F_{UPM}(T,V)$, which describes the dependence of the breaking force of the UPM Digi Color 300 g/m^2 paper laminate on temperature and speed, is shown in Fig. 3.

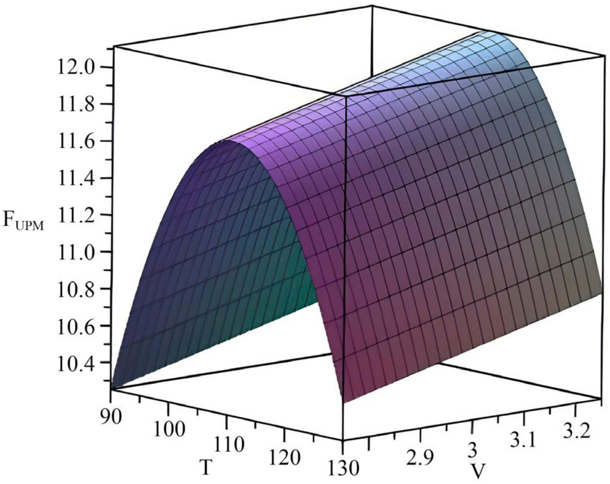

Fig. 3. The plot of model $F_{UPM}(T,V)$

It follows from the above plot that the value of the tearing force of the laminate on the glossy surface of the UPM Digi Color 300 g/m^2 paper increases with the increase in the lamination speed. The coordinates of the local maximum of the model $F_{UPM}(T,V)$ (1) are determined by equating its partial derivatives with respect to temperature and lamination speed to zero:

$$\frac{\partial F_{UPM}(T,V)}{\partial T} = 0.76572784 - 0.00691505967T = 0, \quad (2)$$

$$\frac{\partial F_{UPM}(T,V)}{\partial T} = 0.745346173. \quad (3)$$

After solving equation (2), we obtained a temperature value of $T=111$ °C, at which the largest value of the laminate breaking force is observed. Since the partial derivative of the speed is equal to a constant, the maximum value of the breaking force of the laminate on the glossy surface of the UPM Digi Color 300 g/m^2 paper is reached at a temperature of $T=111$ °C and a lamination speed of 3.25 rpm.

A polynomial model of the following form was built to estimate the force of punching the laminate on the glossy surface of UPM Digi Color 300 g/m^2 paper:

$$P_{UPM}(T,V) = 8.0116808385V - 0.022886292214T^2 + \\ + 5.29152654557T - 251.037370898, \quad (4)$$

which reproduces the laminate punching force with an absolute error of 2.15 kPa. The view of the surface of values of the model $P_{UPM}(T,V)$ is shown in Fig. 4.

It follows from the above plot that the value of the force of punching the laminate on the glossy surface of the UPM Digi Color 300 g/m^2 paper also increases with the increase in the lamination speed. Since the partial derivative of the model $P_{UPM}(T,V)$ (4) in terms of lamination speed is equal to a constant, the coordinates of the local maximum of model (4) can be specified by equating its partial derivative in terms of temperature to zero:

$$\frac{\partial p_{UPM}(T,V)}{\partial T} = 5.29152654557 - 0.045772584428T = 0. \quad (5)$$

After solving equation (5), the obtained temperature value is T=116 °C, at which the greatest force of punching the laminate is observed. Therefore, the greatest lamination punching force on the glossy surface of UPM Digi Color 300 g/m^2 paper is achieved at a temperature of T=116 °C and a lamination speed of 3.25 rpm.

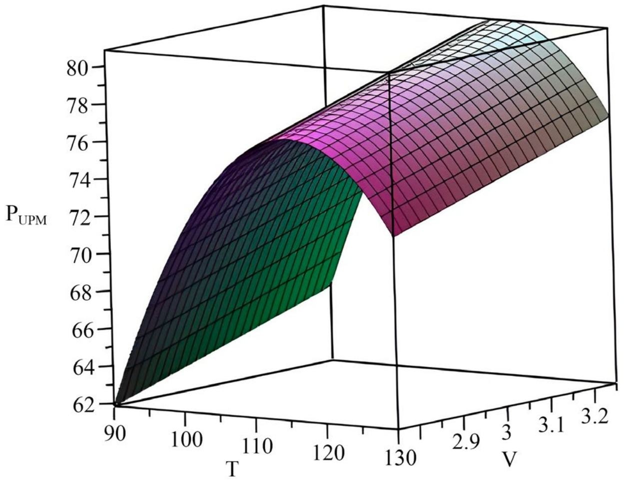

Fig. 4. The plot of model $P_{UPM}(T,V)$

The breaking and punching forces of the laminate on the glossy surface of the print on UPM Digi Color 300 g/m^2 paper, which correspond to the calculated optimal values of temperatures and lamination speed of 3.25 rpm, are given in Table 4.

Table 4

The value of the tearing and punching forces of the print on UPM Digi Color paper

T, °C	$F_{UPM}(T,V)$, kg	$P_{UPM}(T,V)$, kPa
110.733367486	12.1142532948	80.32742425
115.6047143	12.0322060437	80.871534221
113	12.0964898102	80.715726028

The third row of Table 4 shows the value of the breaking and punching forces for a temperature of 113 °C, which corresponds to the rounded $F_{UPM}(T,V)$ average value of the optimal temperatures obtained from the models and $P_{UPM}(T,V)$. The values of the breaking force of the laminate for a temperature of 113 °C deviate from the optimal by 0.15 %, and the punching force – by 0.19 %. So, according to the $F_{UPM}(T,V)$ and $P_{UPM}(T,V)$ models, a satisfactory laminate on the glossy surface of UPM Digi Color 300 g/m^2 paper can be obtained at a temperature of 113 °C and a lamination speed of 3.25 rpm.

It is worth noting that for a non-laminated print on UPM Digi Color 300 g/m^2 paper, the breaking force is 10.4 kg, and the punching force is 60 kPa.

5. 3. 2. Mathematical model for determining the optimal lamination mode for printing on Fujifilm photo paper 200 g/m^2

To estimate the breaking strength of the laminate on the glossy side of Fujifilm photo paper 200 g/m^2, a polynomial model was built:

$$F_{Fuji}(T,V) = 1.79989224821V - 0.00726907831485T^2 + \\ + 1.60248403034T - 80.3536402092. \quad (6)$$

This model reproduces the breaking force of the laminate with an absolute error of 0.428 kg.

The model for evaluating the laminate punching force is as follows:

$$P_{Fuji}(T,V) = 12.0179460374V - 0.0764063334879T^2 + \\ + 17.0093150015T - 783.68731303. \quad (7)$$

This model reproduces the value of the laminate punching force on the glossy side of Fujifilm 200 g/m^2 photo paper with an absolute error of 4.69 kPa.

The appearance of the surfaces of the values of models $F_{Fuji}(T,V)$ and $P_{Fuji}(T,V)$, which describe the dependence of the tearing force of tearing and punching of a laminated print on Fujifilm photo paper 200 g/m^2 on temperature and lamination speed, is shown in Fig. 5.

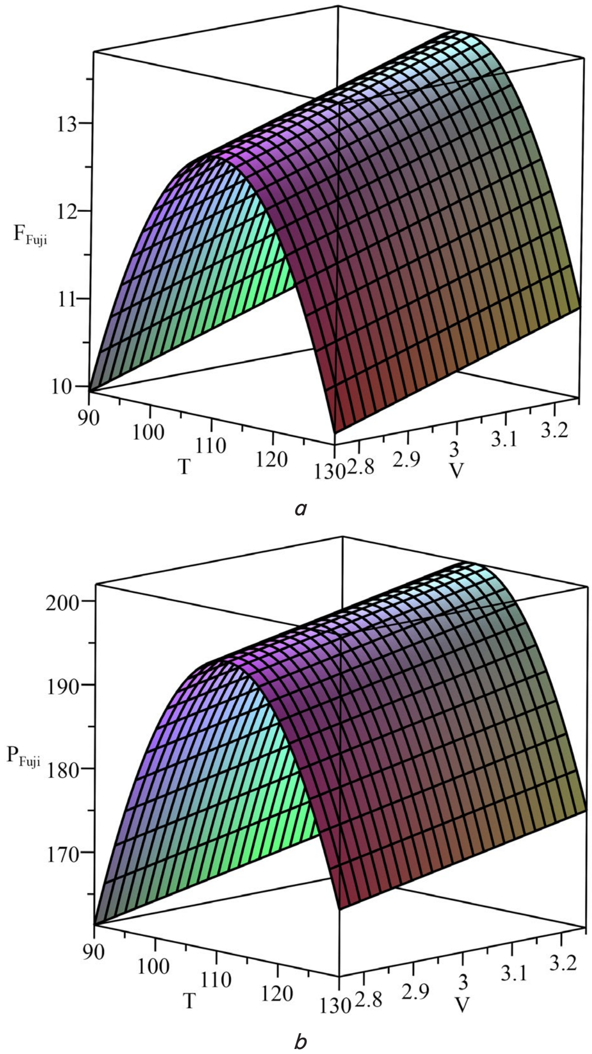

Fig. 5. The plots of models: a – $F_{Fuji}(T,V)$; b – $P_{Fuji}(T,V)$

From the above plots, it follows that the values of the forces of tearing and punching of the laminate on the glossy surface of Fujifilm photo paper 200 g/m^2 increase with the increase in the speed of lamination. Since the partial derivatives of the $F_{Fuji}(T,V)$ and $P_{Fuji}(T,V)$ models in terms of lamination speed are equal to constants, the coordinates of the local maxima of these models can be specified by equating their partial temperature derivatives to zero:

$$\frac{\partial F_{Fuji}(T,V)}{\partial T}= \\ =1.60248403034-0.0145381566297T=0, \qquad (8)$$

$$\frac{\partial P_{Fuji}(T,V)}{\partial T}= \\ =17.0093150015-0.152812666976T=0. \qquad (9)$$

Solving equation (8) gives the temperature value T=110 °C, at which the largest value of the laminate breaking force is observed, and equation (9) – the temperature value of T=111 °C, at which the largest value of the laminate punching force is observed. The studied indicators of laminate strength on the glossy surface of Fujifilm photo paper 200 g/m^2 reach the highest values at the calculated temperatures and lamination speed – 3.25 rpm.

The breaking and punching forces of the laminate on the glossy surface of the print on Fujifilm photo paper 200 g/m^2, which correspond to the calculated optimal values of temperatures and lamination speed of 3.25 rpm, are given in Table 5.

Table 5

The value of tearing and punching forces of a laminated print on Fujifilm photo paper 200 g/m^2

T, °C	$F_{Fuji}(T,V)$, kg	$P_{Fuji}(T,V)$, kPa
110.226081006	13.8137768671	201.920319711
111.308279203	13.8052636642	202.009803215
111	13.8094230482	202.002541858

The third line of Table 5 shows values of the breaking and punching forces for a temperature of 111 °C. The values of the breaking force of the laminate for a temperature of 111 °C deviate from the optimal value by 0.032 %, and the punching force – by 0.074 %. So, according to the $F_{Fuji}(T,V)$ and $P_{Fuji}(T,V)$ models, a satisfactory laminate on the glossy surface of Fujifilm 200 g/m^2 photo paper can be obtained at a temperature of 111 °C and a lamination speed of 3.25 rpm.

For the non-laminated Fujifilm 200 g/m^2 photo paper, the breaking force is 10.2 kg, and the compression force is 180 kPa.

5. 3. 3. Mathematical model for determining the optimal lamination mode for printing on Arktika 200 g/m^2 cardboard

To estimate the breaking force of the laminate on the glossy side of Arktika 200 g/m^2 cardboard, a polynomial model was built:

$$F_{Arkt\,200}(T,V)= \\ =1.81126831878V-0.00898911522817T^2+ \\ +2.02971492899T-105.313380544, \qquad (10)$$

which reproduces the value of the breaking force of the laminate with an absolute error of 0.62 kg. A model for evaluating the laminate punching force:

$$P_{Arkt\,200}(T,V)= \\ =7.97857363746V-0.0304239996316T^2+ \\ +6.62611263518T-205.005018419, \qquad (11)$$

reproduces the value of the punching force of the laminate on the glossy side of the Arktika 200 g/m^2 paper with an absolute error of 3.84 kPa.

The view of the surface of values of the $F_{Arkt200}(T,V)$ and $P_{Arkt200}(T,V)$ models, which describe the dependence of the tensile strength of the laminate for Arktika 200 g/m^2 cardboard on temperature and speed, is shown in Fig. 6.

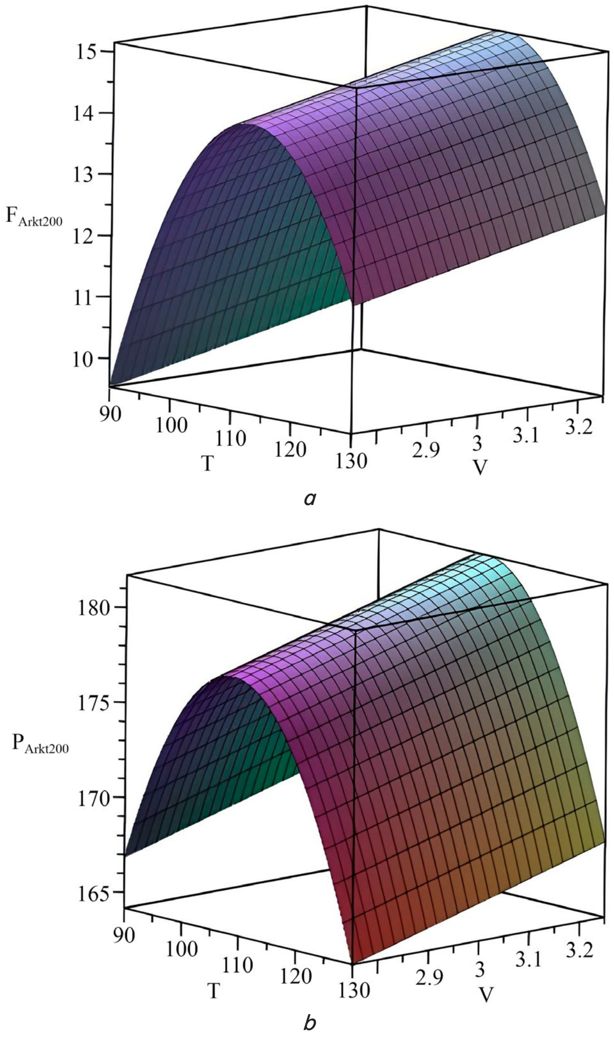

Fig. 6. The plots of models: a – $F_{Arkt200}(T,V)$; b – $P_{Arkt200}(T,V)$

It follows from the above plots that the values of the breaking and punching forces of the laminate on the glossy surface of the Arktika 200 g/m^2 cardboard increase with the increasing speed of lamination. Since the partial derivatives of models $F_{Arkt200}(T,V)$ and $P_{Arkt200}(T,V)$ in terms of lamination speed are equal to constants, the coordinates of the local maxima of these models can be calculated by equating their partial derivatives with respect to temperature to zero:

$$\frac{\partial F_{Arkt\,200}(T,V)}{\partial T}= \\ =2.02971492899-0.0179782304563T=0, \qquad (12)$$

$$\frac{\partial P_{Arkt\,200}\left(T,V\right)}{\partial T}=$$
$$=6.62611263518\ -0.0608479926 32T=0. \qquad (13)$$

Solving equation (12), the temperature value $T=113$ °C is obtained, at which the largest value of the laminate breaking force is observed, and equation (13) – the temperature value of $T=109$ °C, at which the maximum value of the laminate punching force is observed. The studied indicators of laminate strength on the glossy surface of Arktika 200 g/m^2 cardboard reach the highest values at the calculated temperatures and lamination speed – 3.25 rpm.

The breaking and punching forces of the laminate on the glossy surface of Arktika cardboard 200 g/m^2, which correspond to the calculated optimal values of temperatures and lamination speed of 3.25 rpm, are given in Table 6.

Table 6

Values of the breaking and punching forces of the laminate on the glossy surface of Arktika cardboard 200 g/m^2

T, °C	$F_{Arkt200}(T,V)$, kg	$P_{Arkt200}(T,V)$, kPa
112.898482079	15.149108761	181.217101268
108.896158255	15.005115755	181.704450972
111	15.116709884	181.569789799

The third line of Table 6 shows values of the breaking and punching forces for a temperature of 111 °C. The values of the breaking force of the laminate at a temperature of 111 °C deviate from the optimal value by 0.021 %, and the punching force – by 0.074 %. So, according to the $F_{Arkt200}(T,V)$ and $P_{Arkt200}(T,V)$ models, a satisfactory laminate on the glossy surface of Arktika 200 g/m^2 cardboard can be obtained at a temperature of 111 °C and a lamination speed of 3.25 rpm.

For the non-laminated Arktika 200 g/m^2 paper, the breaking force is 9.5 kg, and the punching force is 100 kPa.

5. 3. 4. Mathematical model for determining the optimal lamination mode for printing on Arktika 300 g/m^2 cardboard

The breaking strength of the laminate on the glossy side of Arktika 300 g/m^2 cardboard is described by the model:

$$F_{Arkt\,300}\left(T,V\right)=$$
$$=3.66217733505V-0.08110923334 11T^2+$$
$$+\,1.87663962305T-101.91480453, \qquad (14)$$

which reproduces the breaking force of the laminate with an absolute error of 0.96 kg. To estimate the force of punching the laminate, the following model was built:

$$P_{Arkt\,300}\left(T,V\right)=$$
$$=9.19968582297V-0.0209860410444T^2+$$
$$+\,4.62271798501T-109.507455368, \qquad (15)$$

which reproduces the laminate punching force with an absolute error of 1.85 kPa.

The surfaces of values of the $F_{Arkt300}(T,V)$ and $P_{Arkt300}(T,V)$ models, which describe the dependence of the tensile strength and punching of the laminate for Arktika 300 g/m^2 cardboard on temperature and speed, are shown in Fig. 7.

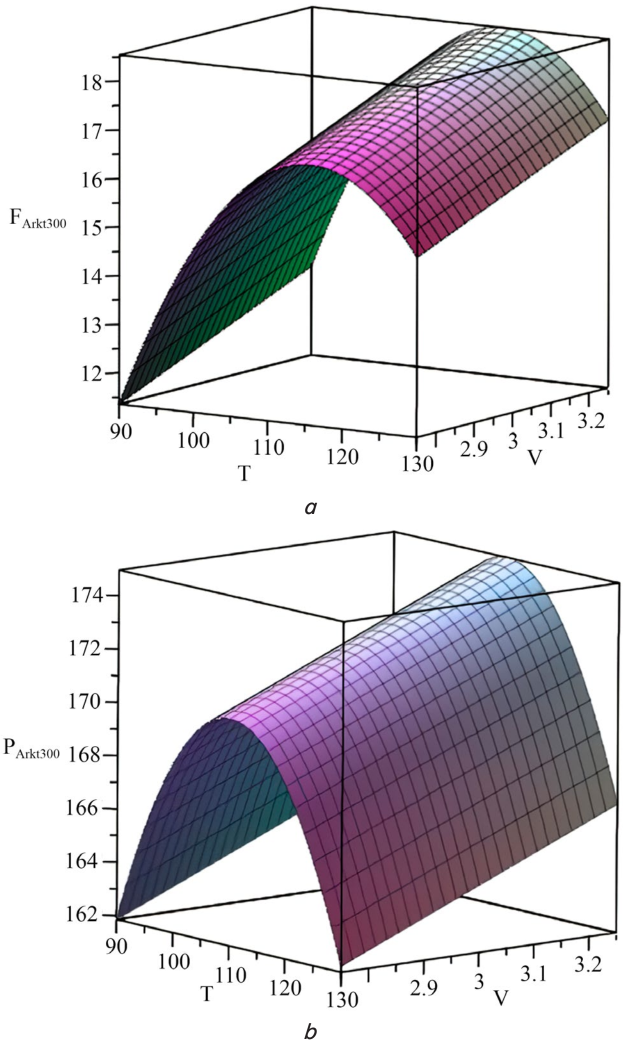

Fig. 7. The plots of models: $a-F_{Arkt300}(T,V)$; $b-P_{Arkt300}(T,V)$

From the plots shown in Fig. 7, it follows that the values of the tearing and punching forces of the laminate on the glossy surface of the Arktika 300 g/m^2 cardboard also increase with increasing lamination speed. Since the partial derivatives of the $F_{Arkt300}(T,V)$ and $P_{Arkt300}(P,V)$ models in terms of lamination speed are equal to constants, the coordinates of the local maxima of models (14), (15) can be specified by equating their partial derivatives with respect to temperature to zero:

$$\frac{\partial F_{Arkt\,300}\left(T,V\right)}{\partial T}=$$
$$=1.87663962305-0.0162218466682T=0, \qquad (16)$$

$$\frac{\partial P_{Arkt\,300}\left(T,V\right)}{\partial T}=$$
$$=4.62271798501-0.0419720820888T=0. \qquad (17)$$

After solving equation (16), the temperature value is $T=116$ °C, at which the largest value of the laminate breaking force is observed, and equation (17) – the temperature value is $T=110$ °C, at which the largest value of the laminate punching force is observed. The studied indicators of laminate strength on the glossy surface of Arktika 300 g/m^2

cardboard reach the highest values at the calculated temperatures and lamination speed of 3.25 rpm.

The breaking and punching forces of the laminate on the glossy surface of Arktika 300 g/m^2 cardboard, which correspond to the calculated optimal values of temperatures and laminating speed of 3.25 rpm, are given in Table 7.

Table 7

Values of the breaking and punching forces of the laminate on the glossy surface of the Arktika 300 g/m^2 cardboard

T, °C	$F_{Arkt300}(T,V)$, kg	$P_{Arkt300}(T,V)$, kPa
115.685942632	18.537683695	174.313843414
110.137923947	18.288025327	174.959804487
113	18.479169161	174.787897767

The third row of Table 7 shows values of the breaking and punching forces for a temperature of 113 °C, which corresponds to the average value of optimal temperatures according to models (16) and (17). The values of the breaking force of the laminate for a temperature of 113 °C deviate from the optimal value by 0.021 %, and the punching force – by 0.098 %. So, according to the $F_{Arkt300}(T,V)$ and $P_{Arkt300}(T,V)$ models, a satisfactory laminate on the glossy surface of Arktika 300 g/m^2 cardboard can be built at a temperature of 113 °C and a lamination speed of 3.25 rpm.

For the non-laminated print on Arktika 300 g/m^2 cardboard, the breaking force is 12 kg, and the punching force is 140 kPa.

Thus, based on the results of the analysis of the values of the strength indicators of the laminates for prints made on different materials, models were built that describe the expected values of the breaking and punching forces depending on the temperature and speed of the lamination process. Satisfactory laminate strength on the glossy surface of Arktika 300 g/m^2 cardboard and on UPM Digi Color 300 g/m^2 paper can be obtained at a temperature of 113 °C; for prints on the Arktika cardboard 200 g/m^2 and Fujifilm photo paper 200 g/m^2 – at a temperature of 111 °C and the same lamination speed of 3.25 rpm.

The parameters of these models were calculated using the Chebyshev approximation of functions of many variables, which ensures the achievement of the best accuracy of reproduction of observation results. The accuracy of reproducing the value of the breaking and punching forces of the laminate by the proposed models made it possible to determine the optimal lamination mode for the investigated prints.

6. Discussion of results of investigating the optimization of technological modes of lamination of prints

The results of experimental studies into the densitometric indicators of inkjet and laser prints before and after lamination, given in Table 2, confirm the research that we conducted earlier regarding the quality of lamination of digital prints [11]. In particular, the use of glossy film increases the brightness of printed images, both inkjet and laser printing, which is evidenced by the increase in optical density and color difference on laminates. Analysis of the optical density of printed prints shows that it varies depending on the technique of printing the surface of the substrate and the saturation of the control scale image. Thus, with an increase in image saturation from 50 % to 100 %, the optical density of printed images on all prints increases. However, the optical density indicators for laser prints on Digi Color paper are the largest and increase from 1.76 to 2.04. The lowest optical density values are typical for Arktika cardboard (1.38 – without lamination to 1.66 – after lamination). Jet prints are characterized by slightly lower values of densitometric characteristics compared to laser prints. However, after lamination, the tendency to increase the saturation of CMYK colors is characteristic of both laser and inkjet prints. So, our studies confirm that the densitometric indicators of laminates are influenced by the printing technique and the percentage of filling the print with printing elements.

Known studies into the influence of lamination modes, given in [4], concern the strengthening of only the paper itself and do not take into account the presence of a printed image on it. Therefore, the constructed models of tearing and punching forces of laminated prints, which take into account the ranges of temperatures and speeds of work processes on modern laminators, are an actual solution to the problem of ensuring the quality of laminated products. For the first time, the results of mathematical modeling using the Chebyshev approximation of functions of many variables were built for the optimization of lamination modes of inkjet and laser prints with BORR films on various materials.

The constructed graphic models (Fig. 3, 4) show the relationship between the temperature and speed of lamination and the breaking force of laminated prints on UPM Digi Color paper. It was determined that the maximum value (12 kg) of the tearing force of the laminate on the glossy surface of UPM Digi Color 300 g/m^2 paper and the punching force (81 kPa) is achieved at a temperature of T=113 °C and a lamination speed of 3.25 rpm.

The graphic models shown in Fig. 5 determine the optimal lamination modes for printing on Fujifilm photo paper 200 g/m^2. It was found that at a temperature of T=110 °C, the maximum value of the laminate breaking force (14 kg) is observed, and at a temperature of T=111 °C, the highest value of the laminate punching force (202 kPa), the numerical values of which are given in Table 5. As can be seen from Fig. 6, the formation of a high-quality laminate on the print made of Arktika cardboard 200 g/m^2 is possible at a temperature of T=111 °C, which provides the maximum breaking force (15 kg), and the punching force is 182 kPa (Table 6). According to the $F_{Arkt300}(T,V)$ and $P_{Arkt300}(T,V)$ mathematical models, a satisfactory laminate on a glossy surface of Arktika 300 g/m^2 cardboard can be built at a temperature of 113 °C and a lamination speed of 3.25 rpm, which is shown by graphic interpretation in Fig. 7. Data analysis (Table 7) reveals that for a laminated print on the Arktika 300 g/m^2 cardboard, the breaking force is 18 kg, and the punching force is 175 kPa.

In comparison with the studies of the strength characteristics of prints with a pressed film given in [8], our results make it possible to correctly select the speed and temperature of lamination of prints, to obtain satisfactory quality and appropriate performance indicators.

Since the lamination of digital prints on appropriate paper substrates was carried out on professional equipment under industrial conditions, the results of the experiments can be realistically reproduced.

The disadvantage of this study is the need to introduce correction factors for calculating models associated with a change in the type of film, for which other temperature regimes for laminating prints are regulated by the manufacturer.

Our research has limitations as it concerns the optimization of lamination modes of inkjet and laser prints on glossy paper, photo paper, and cardboard with a grammage of 300 and 200 g/m^2 with a film based on bio-oriented polypropylene. It is obvious that the use of a different film for laminating prints built on the same substrates can make corrections in the selection of lamination process modes. Changing the laminator could have a significant impact on the optimal lamination modes, especially the choice of lamination speed.

However, the proposed technique can be used to predict the strength of laminated prints created by other printing methods and when using other types of films.

The development of this research is the advancement of the information technology of the multidimensional Chebyshev approximation to the determined experimental quality indicators and the construction of the quality function of the product lamination process based on them.

7. Conclusions

1. As a result of experimental studies, a positive effect of the process of lamination with a glossy film on densitometric and colorimetric indicators of digital prints was revealed. The quality of laminated prints of laser and jet printing increases according to the studied indicators of optical density, and for prints of laser printing, these indicators are somewhat higher. Thus, for prints on Digi Color paper, the optical density is the highest and increases by 0.28 units after lamination. The lowest values of optical density are typical for prints on Arktika cardboard, but after lamination the values also increase (from 1.38 – without lamination to 1.66 – after lamination).

2. A close connection was established between the temperature and speed of lamination and the tensile strength of laminates. As the speed of lamination increases, the amount of punching force increases. This tendency is characteristic of all prints, regardless of the type of paper and the technique of obtaining the print. The smallest punching forces are in laminated prints on UPM Digi Color 300 g/m^2 paper. Laminated prints on Fujifilm 200 g/m^2 photo paper have the highest punching and tearing forces.

3. It was established that the most significant effect on the strength of laminated prints on paper substrates is exerted by the temperature of lamination, which depends on the type and properties of the film for lamination, as well as the speed of lamination and the technique of obtaining a print. Owing to the selection of values of the input variables (temperature – from 90 to 130 °C and speed – from 2.75 to 3.25 rpm), it is possible to achieve satisfactory strength of laminates. In particular, at the optimal temperature $T=111$°C, the highest value of punching force (202 kPa) is achieved for a laminated print on Fujifilm photo paper 200 g/m^2, a slightly smaller value of the indicator (182 kPa) in a laminate made of Arktika cardboard 200 g/m^2. The lowest value of punching force (81 kPa) is in a laminated print on UPM Digi Color 300 paper. The maximum breaking force is demonstrated by a laminated print on the Arktika 300 g/m^2 cardboard (18 kg), the lowest breaking force (12 kg) in a laminated print on UPM Digi paper Color 300 at temperature $T=113$ °C. The optimal lamination speed for all prints is 3.25 rpm.

Conflicts of interest

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

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Data availability

All data are available in the main text of the manuscript.

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