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# DETERMINING THE FACTORS THAT AFFECT THE QUALITY OF TEST PRINTS AT FLEXOGRAPHIC PRINTING

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***Інтенсивне використання флексографічного друку для оздоблення упаковки та підвищені вимоги споживачів до неї вимагають поглибленого вивчення факторів впливу на якість друкарських відбитків. У роботі було досліджено пробні відбитки, отримані на пробо-друкарському станку для флексографічного друку. Друкування зображень на картоні здійснювалось екологічними фарбами українського виробника. Показано вплив поверхневого шару картону на мікрогеометрію відбитків, утворених голубою, жовтою, чорною і пурпурною фарбою. Встановлено, що параметр шорсткості Ra для картону з двошаровим крейдованим покриттям у порівнянні з картоном без крейдування зменшується у 3 рази. Фотографії мікроструктури поверхні відбитків, їх профілю показують значний влив крейдованого покриття на якість зображень. Підтверджено, що фарбовий шар згладжує мікронерівності поверхні відбитку. Проте, при друкуванні на картоні без крейдованого покриття, частинки фарби проникають глибше у структуру і не згладжують повністю його мікронерівності. Якщо розмір друкуючого елементу менший за площу комірки на растровому валику, він провалюється в цю комірку і фарба наноситься поза межі границь зображення. В результаті на відбитку замість растрової крапки певного розміру утворюється пляма довільної форми, тобто відбувається так звана «інверсна тонопередача». Виміряні денситометричні показники відбитків (оптична густина, баланс по сірому), від яких суттєво залежить якість продукції. На підставі функції бажаності Харрінгтона обчислені гранично допустимі значення оптичної густини, рівномірності друкування, контрасту, розтискування растрових елементів, трепінгу. За узагальненим критерієм оптимізації визначено комплексний показник якості пробних відбитків, який забезпечить прогнозовану якість майбутньому тиражу друкованої продукції, дозволить при необхідності внести корективи в друкарський процес***

***Ключові слова: флексографічний друк, пробні відбитки, картон, топографія поверхні, денситометричні показники якості***

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## 1. Introduction

At present, there is a tendency in the market of printing production towards the intensive use of flexographic printing techniques. This relates to the rapid development pace of the packaging industry, the introduction of innovative technologies, the reduction in the costs of products printed in large numbers [1]. The market of printing flexographic presses is rather diverse, ranging from the planetary, tier (stack, balcony) to the linear-type machines. It is known that one of the main nodes in a flexographic ink apparatus is an anilox roller. Changing the anilox roller adjusts the dosage of the ink that is fed to the photopolymer printing plate and to the printed material from it [2]. The volume of cells is most important both for the magnitude of the optical density and evenness of the print in solid printing. The excessive volume can lead to the ink overflowing onto the walls of the printing elements of the printing plate that leads to the deformation of raster dots [3]. There is a wide range of printing inks for flexography, which affects the quality of a printed image on the print [4].

Flexography is traditionally considered a comparatively simple printing technology. However, as the requirements for the flexographic product quality increase, there emerge certain problems that need to be solved and explored. That is why defining the effect exerted by some factors on the technological process of printing plates manufacturing, as well as and printing, can resolve the issues related to ensuring the quality of prints made by flexographic printing. Often, there are problems related to the correct reproduction of elements in the image with different complexity of the pattern, which affects the stability of the printing process, as well as obtaining high-quality prints. The use of various materials for printing flexographic images requires the study into their surface structure before and after the application of the ink and is of paramount importance for obtaining prints with the appropriate optical and operational characteristics.

## 2. Literature review and problem statement

Paper [5] reports the results of studying the optimization of the process of applying ink to the printing elements of the printing plate when printing the products. It was shown that the choice of the screening method is important. The authors note that a major issue in flexographic printing is the high dot gain, an increase in the area of raster dots on a print compared to their area in the original document, predetermined, first of all, by the elasticity of a flexographic plate. Dot gain is compensated for by making changes to an image on the plate: the size of dots on the printing plate is reduced by the magnitude of the dot gain. To determine the magnitude of a dot gain compensation, the test scales are printed, followed by the densitometric control of the prints.

One of the problems in flexographic printing is the poor wetting of the surface of the printing elements, especially solids, by ink. There is a paradoxical situation: the thickness of the ink layer in the regions with a relative raster dot area of 95–98 % is larger than that on the solids. This issue was explored in [6]. The authors argue that the images containing the areas of a solid background, surrounded by shadow spots, are reproduced incorrectly: on the print, the areas of a solid background are surrounded by dark halos. The poor wetting of solids with ink on the plate is typically compensated for by increasing the ink supply and enhancing the printing pressure. However, large deformation of the flexible printing plate results in a considerable raster dot gain. The consequences of these measures are the high ink consumption and the gradation distortions on the print. This phenomenon is described in [7]. An analysis of the flexo printing process reveals that the choice of anilox rollers, with certain cell shape and coating, is crucial for the print quality. Based on the research results, the company Zeller+Gmelin recommends, when printing with UV inks UVAFLEX Y77, using the anilox rollers with a line number of 400 lin/cm and a volume of cells of 2.7 $cm^3/m^2$ for cyan ink, 4.0 $cm^3/m^2$ for magenta and yellow, and 4,5 $cm^3/m^2$ for black, which should improve the quality of the ink transfer [8]. The authors argue that in order to avoid the emergence of moiré, the raster structure, formed at the surface of the printing plate, must be rotated relative to the structure of the anilox roller at an angle of 15 and 45 degrees [8].

Paper [9] notes that the printing and technical properties of ink rollers exert a significant influence on the optical indicators of prints. There are studies into the influence of elevated temperature on flexographic printing. Increasing the temperature may accelerate the drying of ink on the prints, but can also cause the print to deteriorate. The too high temperature in a drying plant can cause the print to stretch, which is due to an increase in the ribbon tension. Under the same conditions, without a sufficient number of cooling rollers between the drying and the winding of the printed ribbon, there is a setting-off or sticking of a printing ink [10]. Given that at present flexo printing plays a significant role in arranging the packaging for the food and pharmaceutical industries, much attention is being paid to studying the low migration inks aimed at making the packaging safe, as described in [11]. The issues related to using the UV inks with cationic or radical polymerization for flexo printing on food packaging materials were considered in [12]. The possible mechanisms to slow a process of polymerization using oxygen are defined in [13]. The factors that affect the process of ink transfer to a printing material were addressed in [14]. However, these processes were investigated by modeling production situations while the actual printing conditions were not taken into consideration. The factors for predicting the quality of flexographic printing by using a set of linguistic variables were described in [15]. The authors considered the effect of the technological parameters of the printing process on the product quality indicators. However, they did not conduct any in-depth research into the print quality control that could determine the quality of would-be printed products. Under production conditions, a decision to print a run is made when the required level of quality is reached at the stage of obtaining test prints. It is at this stage that there is a possibility to adjust certain technological modes and parameters of printing. That is why it is an important process to obtain the test prints at proofing equipment in order to pre-define their densitometric parameters and ensure the quality of the future run of printed products.

## 3. The aim and objectives of the study

The aim of this study was to identify the factors affecting the surface topography of the printed material on the quality of flexographic prints and to verify a procedure for determining their sensitometric indicators.

To achieve this goal, the following tasks were set:

– to determine a change in the topography of the surface and structure of the printed material and the prints on it;

– to examine the densitometric quality indicators of flexographic prints (optical density, contrast, dot gain, gray balance, trapping); to optimize single indicators by using a Harrington desirability function.

## 4. Materials and methods to study the quality of test prints

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

The following materials were used for the study: the cardboard GD-2 with a grammage of 250 $g/m^2$ and the cardboard UD-3 with a grammage of 360 $g/m^2$, upon which we printed colored images at the flexographic proof printing press IGT F1 at a pressure of 150 N (Fig. 1).


Fig. 1. General view of the flexographic proof printing press IGT F1 (the Netherlands)

To obtain the flexographic prints, we used the organic soluble nitrocellulose-based inks (TU U 24.3.-30904372-002-2004) of different colors: yellow (the PNL code is 8201-F), magenta (the PNL code is 8101), black (the PNL code is 8501-F), cyan (the PNL code is 8301-F), designed for printing the food industry packaging.

Table 1 gives the parameters of inks, used for test printing on the cardboard applying a test printing plate.

Table 1

Parameters of inks for obtaining the test prints

| Indicators | Yellow (PNL code 8201-F) | Magenta (PNL code 8101) | Cyan (PNL code 8301-F) | Black (PNL code 8501-F) |
|---|---|---|---|---|
| Grinding degree (standard – not exceeding 5 μm) | 1 | 1 | 1 | 1 |
| Funnel viscosity at 20° for WZ-246 (nozzle diameter, 4 mm), (standard: 30–45 s) | 42 | 41 | 39 | 37 |
| Adhesion by the adhesive tape method (standard: not less than 4 points) | 4 | 4 | 4 | 4 |
| Volatile-matter content (standard: not less than 25 %) | 33 | 36 | 34 | 31 |
| Heat resistance of the print, °C | +200 | +200 | +200 | +200 |
| Resistance to a water alkali solution (standard: not less than 5 points) | 4 | 3 | 5 | 5 |
| Oil resistance (standard: not less than 3 points) | 3 | 3 | 3 | 3 |
| Water resistance (standard: not less than 5 points) | 5 | 5 | 5 | 5 |
| Resistance to lactic acid (standard: not less than 5 points) | 5 | 4 | 5 | 5 |

In flexographic printing, the ink viscosity is in the range of 0.05–0.5 Pa·s and the thickness of the layer on the print is 1 μm. Adjusting the viscosity of the ink is especially important to ensure the high-quality of a print. In this case, the ink should not be extruded beyond the boundaries of the printed image.

The ink should be of high density, well applied to the substrate, ensure that the cells of the anilox roller are filled. The type of a solvent for ink plays an important role because its evaporation following the application of the ink on the substrate results in a stable dry film on the print.

**4. 2. Studying the print surface structure**

To study the surface structure of cardboards and the prints on them, we used the AniCam measuring unit made by TROIKA Systems Limited, equipped with a 24-bit color camera with a resolution of 640×480 pixels and a view field of 1.25×0.92 mm (Fig. 2).

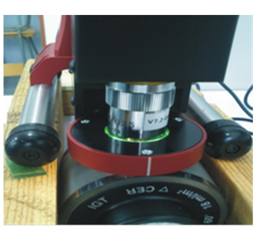


Fig. 2. Measuring the structure and profile of the print surface at the AniCam device (Great Britain)

The three-dimensional image of the surface structure was acquired from the analysis of digital photographs of the surface of the coated paper. The measurement accuracy is ±1 %. Two types of the image fragments were used to determine the ink thickness layer: a 4× magnification for the analysis employing the FlexoPlate QC v8.4 software and a 10× magnification for the analysis employing the Anilox QC v8.4 software. The lens was focused in such a way that the difference in the height of the printed and unprinted cardboard could be seen [2].

**4. 3. Procedure for studying the print optical properties**

The densitometric indicators of the prints were examined at the SPM 50 Spectro densitometer made by GRETAG, which operates under reflected light, determines the optical density of background and the solids, the dot gain (relative area) of raster elements, trapping, gray balance, the evenness and contrast of printing. The standardized viewing angles of 20 and 100 are used for colorimetric measurements of images observed from different distances. The standardized radiation sources D50, D65, A, B, C, etc., which have the corresponding spectral characteristics, are used to predict the colors of a would-be print edition under different illumination at a Spectro densitometer [16].

Considering the advantages and disadvantages of different mathematical methods for constructing the integrated indicators, a Harrington method for building a quality indicator should be used in order to evaluate quality based on a balanced system of indicators [17]. The main idea of the Harrington method for constructing an integrated indicator implies building a generalized desirability function and the partial desirability functions. The Harrington's desirability scale hosts the reference points that divide the entire scale into intervals, namely: (0–0.2) – very poor, (0.2–0.37) – poor, (0.37–0.63) – satisfactory, (0.63–0.80) – good, (0.80–1) – excellent. The desirability scale has a range of changes in the values from zero to unity [18]. The Harrington's conversion function is recommended by many scientists and possesses such prevailing properties as continuity, monotony, and smoothness. It is recommended to arrange the coded values symmetrically to zero along the abscissa. A value from 3 to 6 is typically selected on the coded scale. For instance, six intervals towards an ascend and six intervals towards a descend in the value of an attribute. The choice of the number of intervals determines the slope of the curve within the medium intervals. The desirability curve is typically used visually as a nomogram [19]. To determine the comprehensive quality indicator of the prints, 9 quality control indicators were selected as a quality criterion for the image obtained from the test flexo printing. These include the optical density of a background, the optical density of a print, the color difference, the magnitudes of trapping, contrast, dot gain, control of the ink combination, the "gray" balance.

A value for the integrated quality indicator of the printed image is calculated from the following formula:

$$O=\left(\prod_{i=1}^{n} d_i\right)^{1/n}, \tag{1}$$

where $d_i$ is the single desirability function based on the key indicators. For the two-sided and one-sided dependences, the Harrington's desirability functions take the following form:

– symmetrical two-sided:

$$d_i = \exp\left(-k\left(\frac{y_i - a_i}{b_i - a_i}\right)^2\right), \qquad (2)$$

– one-sided:

$$d_i = \frac{1}{1+\exp\left(-k\left(\frac{y_i - c_i}{a_i - c_i}\right)^2\right)}, \qquad (3)$$

where $y_i$ is the coded value of the indicators defined on the scale; $a_i$ is the optimal value of $y_i$, at which the two-sided desirability function is equal to 1 (100 % quality) and the one-sided function is not less than 0.95; $b_i$ is the value of indicator $y_i$, at which the quality is low, less than 0.05 (5 %); $c_i$ is the value of indicator $y_i$, at which a satisfactory quality value (0.37) for the one-sided desirability function is achieved.

## 5. Results of studying the quality indicators of the flexographic test prints

### 5. 1. Studying the surface structure of prints

The result of our study into the structure of the print has confirmed the significant effect exerted by the characteristics of cardboard surfaces on the process of ink absorption during printing. It was established that the roughness parameter of cardboards affects the quality of the prints. It is known that the smoothness (roughness) characterizes the microstructure of the cardboard surface and the evenness that determines the secondary structure of the cardboard, that is, its volumetric macro homogeneity, as well as impacts the effectiveness of interaction with the ink. The limits for the values of micro irregularities for different types of cardboard are determined by the sizes of the reproduced elements of the image. Our study has shown that depending on the location of measurement the prints demonstrate different roughness of the cardboard (Table 2).

Table 2

Results of studying the cardboard surface morphology

| Cardboard grade | Coating | Weight, g/m$^2$ | *Ra*, µm | *Rz*, µm | *Sp*, µm$^2$ | *Str*, µm$^2$ |
|---|---|---|---|---|---|---|
| GD-2 | Two-layer coating | 250 | 0.426 | 4.5 | 874 | 860 |
| UD-3 | uncoated | 350 | 1.26 | 7.34 | 1,034 | 2,475 |

An analysis of the tabular data shows that the UD-3 cardboard, uncoated, with the addition of cellulose fibers, is characterized by a large degree of surface irregularities, from –5.76 to +6.37 µm, which indicates the uneven distribution of the surface structure elements. This is also confirmed by the roughness parameter *Ra*=1.26 µm. The examined GD-2 cardboard has an average degree of surface irregularities from –3.1 to +2.02 µm, which indicates a more uniform distribution of the elements of the bleached cellulose fiber structure, the absence of large macro irregularities. Two layers of the chalked coating were applied onto the cardboard surface, the roughness parameter *Ra*=0.426 µm, which indicates a highly developed micro- and sub-microstructure of the surface. It is obvious that such surfaces can reproduce the fine-screen raster images well.

Therefore, our study has confirmed that the presence of a chalked coating has a significant effect on surface microgeometry. This layer changes the roughness parameters and the areas of peaks and holes on the cardboard. The roughness parameter *Ra* for the cardboard without chalking to a two-layer chalked coating is reduced by 3 times. The results of studying the cardboard prints morphology are given in Table 3.

Table 3

Results of studying the morphology of prints obtained at proofing equipment

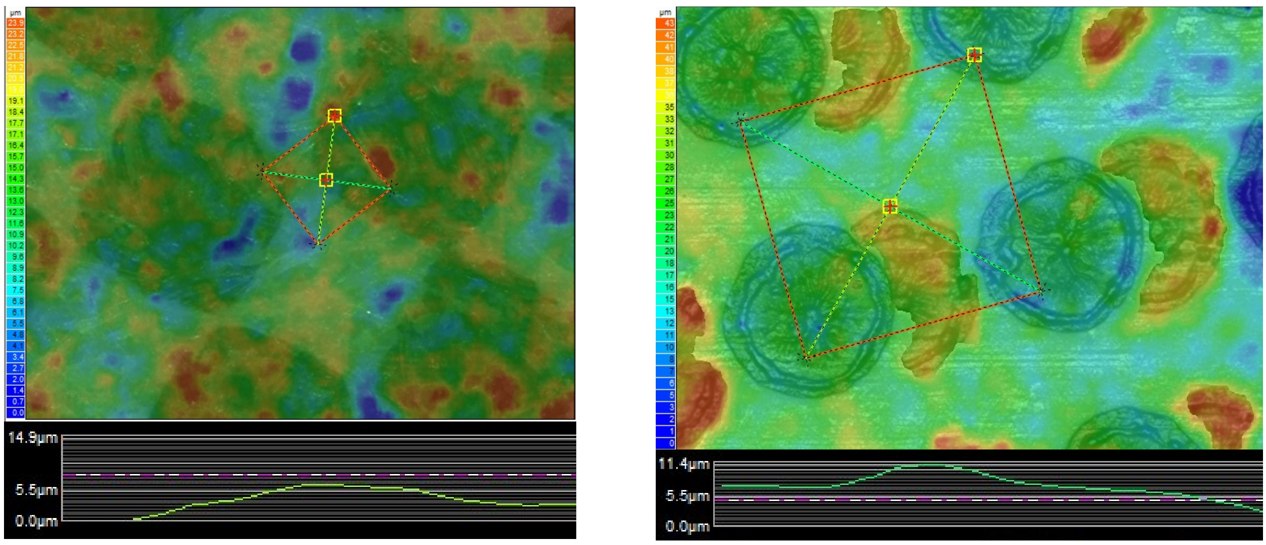
| Cardboard prints | Weight, g/m$^2$ | *Ra*, µm | *Rz*, µm | *Sp*, µm$^2$ | *Str*, µm$^2$ |
|---|---|---|---|---|---|
| GD-2 | 250 | 0.415 | 5.92 | 896 | 812 |
| UD-3 | 350 | 1.2 | 7.89 | 1,410 | 1,890 |

When applying an ink layer to the UD-3 uncoated cardboard, the roughness parameter *Ra* (the arithmetic mean of the profile deviation) is reduced by 0.04 µm and is 1.2 µm, with the average roughness depth *Rz* increasing from 7.34 to 7.89 µm. The surface peak area *Sp* increases from 1,034 to 1,410 µm$^2$, and *Str* decreases from 2,475 to 1,685 µm$^2$. The surface after the application of the ink layer became more even (there are no macro irregularities) but the parameters *Rz* and *Str* changed, which is explained by that the ink is applied to these substrates in an uneven layer, has a raster structure where each dot has its own microrelief, which affects the magnitudes of peaks and holes. A similar pattern is observed for the GD-2 cardboard, with a two-layer chalked coating; the roughness parameter *Ra* decreases to 0.415 µm, with the peaks area *Sp* increasing to 896 µm$^2$ while the area of the holes *Str* decreases to 812 µm$^2$. This fact confirms again that the ink layer smooths out the micro irregularities on a print surface. The prints on the GD-2 cardboard are smoother than those on the UD-3 cardboard. Ink particles penetrate deeper into the cardboard without a chalked coating and do not completely smooth out its microroughness. Fig. 3–6 shows the microphotographs of the surface topography of flexographic prints made by inks of different colors, as well as their profiles.

The photographs of the microstructure of the prints' surface, their profile, and the three-dimensional models show a significant effect exerted by the chalked coating on the substrate on the quality of prints. The determined arithmetic mean values of the deviation of the *Ra* profile, the depth of roughness *Rz*, the changes in the peak area *Sp* and holes *Str* of the surface confirm the effect of the chalked coating on the depth of ink penetration and the densitometric indicators of the prints.

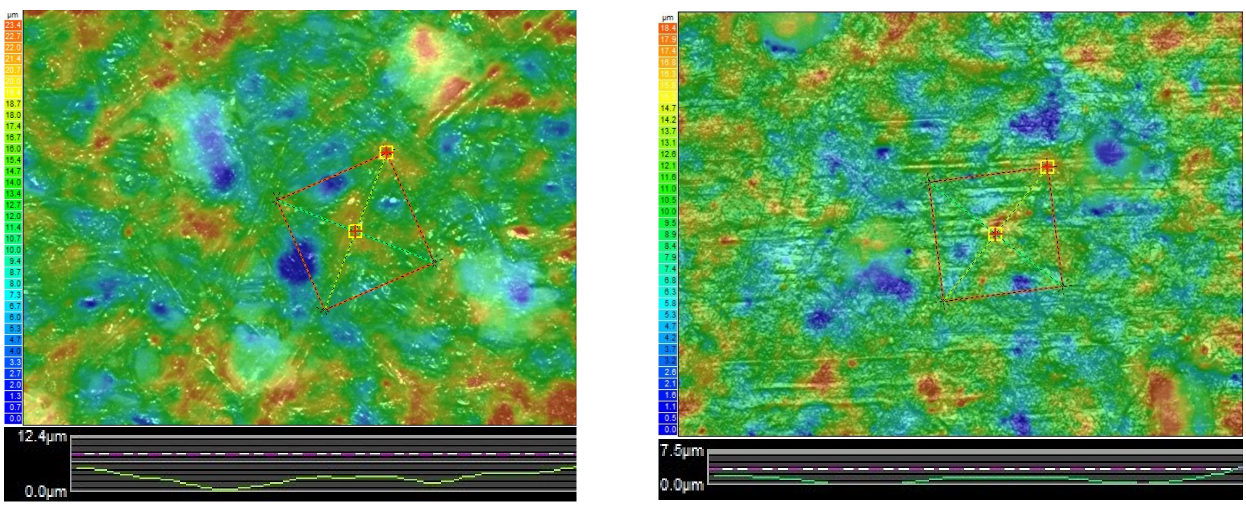
To obtain high-quality prints when reproducing the line and solid sections of images, certain technological modes must be adhered to. In particular, inks should have a viscosity in the range of 22–24 s and the large areas of a solid image should have a raster dot area not exceeding 97 %.

If the size of a printing element is smaller than the area of the cell on a roller, it falls into this cell and the ink is applied beyond the boundaries of the image. As a result, a spot of an arbitrary shape is formed on the print instead of a raster dot of a certain size, that is, the so-called "inverse tone transfer" occurs.



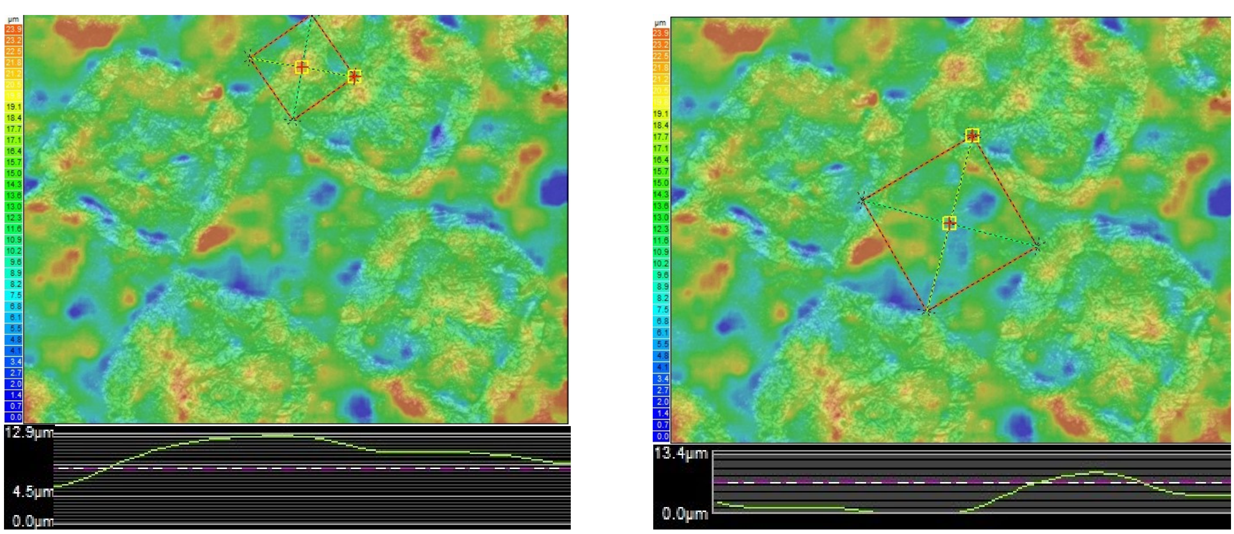

*a* *b*

Fig. 3. The surface topography and the profile of a flexographic print obtained on the cardboard using a cyan ink:
*a* – UD-3; *b* – GD-2




*a* *b*

Fig. 4. The surface topography and the profile of a flexographic print obtained on the cardboard using a magenta ink:
*a* – UD-3; *b* – GD-2




*a* *b*

Fig. 5. The surface topography and the profile of a flexographic print obtained on the cardboard using a yellow ink:
*a* – UD-3; *b* – GD-2

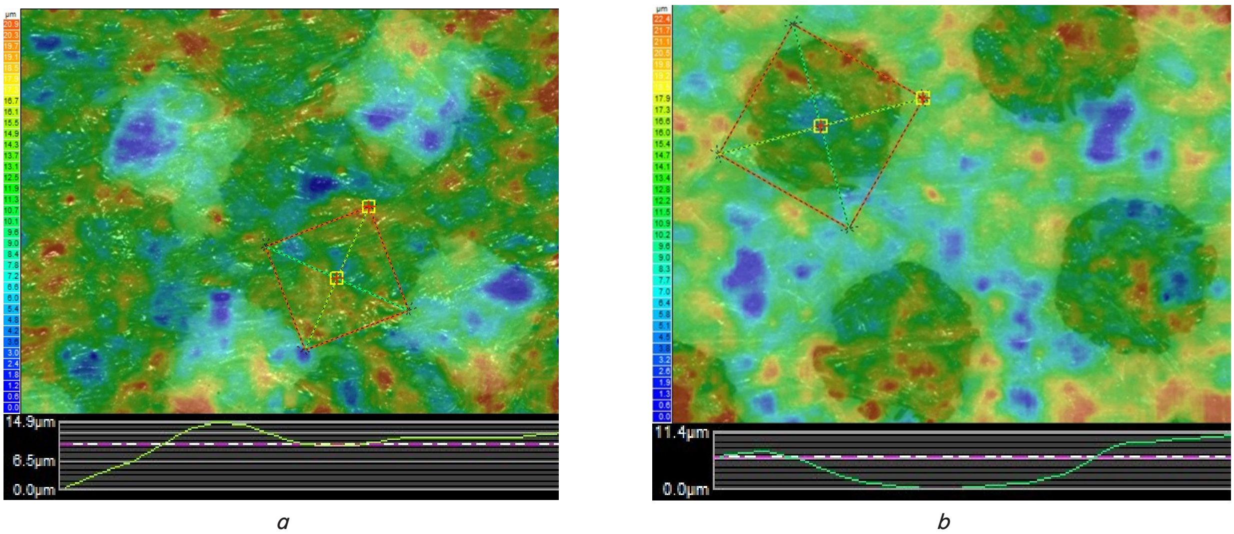



Fig. 6. The surface topography and the profile of a flexographic print obtained on the cardboard using a black ink: *a* – UD-3; *b* – GD-2

**5. 2. Studying the densitometric indicators of prints**

The optical characteristics of the printed images determine the quality of the prints. Fig. 7 shows the graphical dependences of the optical density of prints formed by cyan, black, magenta, and yellow inks. As can be seen from Fig. 7, *a*, the upper limit of the optical density for a cyan ink is 1.64, the lower is 1.42. For the print formed by a magenta ink, the upper limit of optical density is 1.98, the lower one is 1.72 (Fig. 7, *b*).

The upper limit of optical density for the print formed by a yellow ink (Fig. 7, *c*) drops slightly to 1.52 and the lower – to 1.38. The maximum value of the upper (1.99) and lower (1.76) boundaries of optical density is observed on the print formed by black ink (Fig. 7, *d*). For the GD-2 cardboard prints, the optical density of cyan, magenta, yellow, and black inks varies from 0.2 (at saturation of –20 %) to 2.0 (at an image saturation of 90 %). The optical density of the prints on the UD-3 cardboard is much smaller. At a 90 % saturation, the optical density of a print is 1.24 for cyan, magenta, and black inks, and –1.15 for yellow ink. These values of the densitometric indicators of the prints once again confirm the effect of the surface structure of the cardboard on the quality of the printed images.

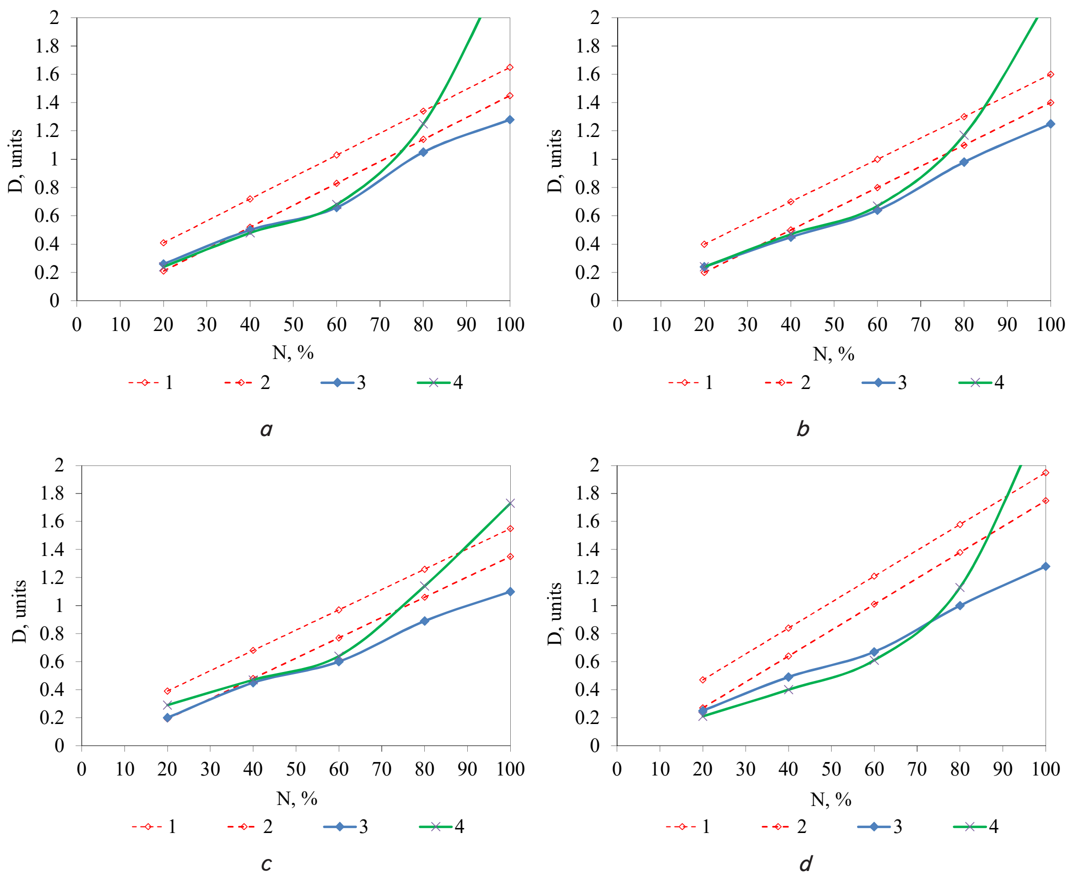



Fig. 7. Dependence of the optical density of the cardboard prints formed by: *a* – cyan; *b* – magenta; *c* – yellow; *d* – black ink; D – optical density (units); N – saturation (%); 1 – upper acceptable limit; 2 – lower acceptable limit; 3 – cardboard GD-2; 4 –cardboard UD-3

A calibration scale was developed to calibrate the Harrington-based optical background density on the print and the coded values for the indicators were determined (Fig. 8).

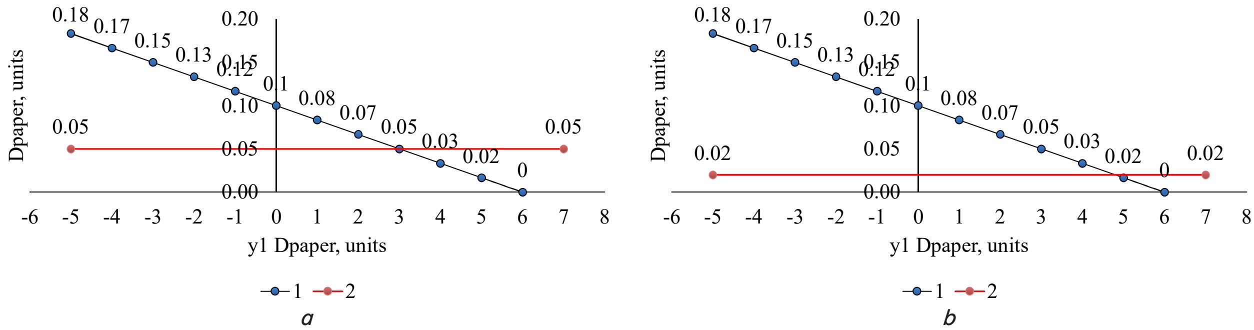



Fig. 8. Determining the coded value of an optical density indicator of the cardboard background: *a* — cardboard GD-2; *b* — cardboard UD-3; Dpaper — optical density of the background (units); y1 Dpaper — coded value of an optical density indicator for the background (units); 1 — calibrated value scale; 2 — measured value of the quality indicator

Accordingly, the Harrington's scale was used to determine the coded values for the indicators of the optical density of the background in an image printed by cyan, yellow, magenta, and black inks. These values are given in Table 4.

Table 4

Coded values of the optical density indicator for the prints, determined based on the Harrington's scale

| Image on prints | Coded values of the optical density indicator | | | |
|---|---|---|---|---|
| Printed material | Cyan | Magenta | Yellow | Black |
| Cardboard GD-2 | | | | |
| max | 0.54 | 0.49 | 0.44 | 0.66 |
| min | 1,64 | 1.59 | 1.54 | 1.96 |
| mean | 1.0 | 0.95 | 0.9 | 1.2 |
| Cardboard UD-3 | | | | |
| max | 0.49 | 0.47 | 0.47 | 0.64 |
| min | 1.60 | 1.62 | 1.56 | 1.93 |
| mean | 0.98 | 0.94 | 0.92 | 1.17 |

An experimental study shows that the value of the optical density indicator varies from 0.54 to 1.64 for cyan ink, from 0.49 to 1.59 – for magenta ink, from 0.44 to 1.54 – for yellow ink, from 0.66 to 1.96 – for black ink.

In terms of the quality of prints, the indicator of printing evenness is very important. Fig. 9 shows the chart of determining the coded value of the printing evenness indicator when using a cyan ink on the examined cardboards, based on Harrington's scale.

Fig. 9 shows that the coded value of the printing evenness indicator when using a cyan ink for printing, based on Harrington's scale, changes from 0 to 0.37. Moreover, the identical values of this indicator are observed when printing using other CMYK colors. It is obvious that this is due to the identical printing conditions and the same technical characteristics of the inks.

The trapping indicator, based on the Harrington's scale, on prints for all inks is 1.

The coded value of the gray balance indicator was also determined. It is established that for different areas of the print filling (75 %, 50 %, 25 % of the field) this indicator based on Harrington's scale is equal to 1.

The contrast value of the printed image is rather important for evaluating print operational performance. The coded values of the contrast indicator when printing using black ink on the cardboard GD-2 and UD-3 are shown in Fig. 10.

Table 5 gives the coded values of the contrast indicator on the print created by cyan, magenta, yellow, and black inks.

Table 5

Coded values of the contrast indicator on a print

| Print | Coded value of the contrast indicator on a print | | | |
|---|---|---|---|---|
| Ink | Cyan | Magenta | Yellow | Black |
| cardboard GD-2 | 54.5 | 54.5 | 53.7 | 21 |
| cardboard UD-3 | 52.1 | 53.5 | 49.8 | 52 |

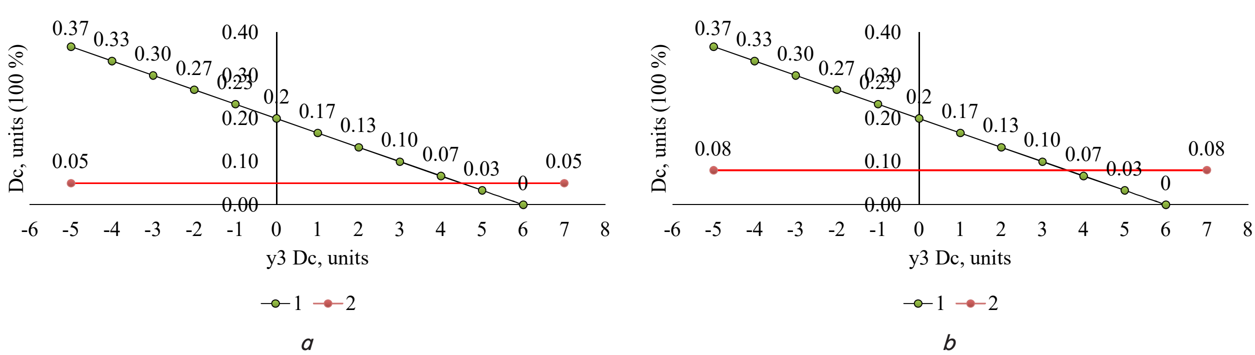



Fig. 9. Determining the coded value of the evenness printing indicator using a cyan ink, based on the Harrington's scale: *a* — cardboard GD-2; *b* — cardboard UD-3; Dc — optical density of a cyan ink solid (units); y3 Dc — coded value of the optical density indicator of a cyan ink solid (units); 1 — calibrated value scale; 2 — measured value of the quality indicator

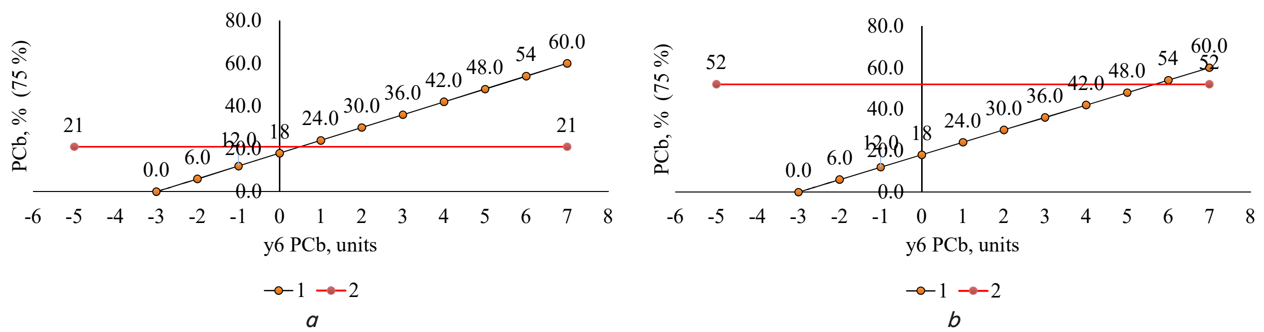



Fig. 10. Determining the coded value of contrast indicator when printing using a black ink: *a* – cardboard GD-2; *b* – cardboard UD-3; PCb – a contrast of black ink (%); y6 PCb – coded value of the contrast indicator for black ink (units); 1 – calibrated value scale; 2 – measured value of contrast indicator

The coded value of the contrast indicator when printing on the cardboard GD-2 using the cyan and magenta inks varies, based on the Harrington's scale, from 0.5 to 54.5. When printing using yellow ink, this indicator is –2.3 to 53.7. When printing using black ink, the contrast indicator changes from –12 to 60.

When printing on the UD-3 cardboard, the coded value of the contrast indicator changes slightly for the worse, which is probably related to the surface structure of the substrate, that is, the absence of a chalked coating.

One of the problems of flexo printing is the poor wetting of the printing elements of the printing plate by ink, in particular, solids. There is a paradoxical situation where the thickness of the ink layer in the regions with a relative raster element area of 95–98 % is larger than that on the solids. This distorts the print with the shadows appearing around the outlines of the image. It is recommended to compensate for the poor wetting of solids by ink by increasing the ink supply and by increasing the printing pressure. However, it should be noted that this leads to the over-consumption of inks and distorts the image on the print due to an increase in the dot gain indicator of raster elements.

Therefore, we determined the coded values of the dot gain indicator of raster elements (an increase in the area of raster elements), which are shown in Fig. 11.

Fig. 11 shows that the dot gain indicator of raster elements varies from (for an 80 % field) when printing by the cyan, magenta, and yellow inks on the cardboard GD-2 and is 14. At the same time, when printing on the same cardboard using black ink, the dot gain indicator is 17 (for an 80 % field) and 20 (for a 40 % field). Our analysis of the dot gain indicator when printing on the cardboard UD-3 shows the increase in its value by up to 21 units when printing by the cyan, magenta, yellow, and black inks (for a 40 % field). When printing with these inks (for an 80 % field) the dot gain indicator of raster elements drops to 16 units. When printing using black ink, this indicator drops to 13 (for an 80 % field).

In flexographic printing, the ink viscosity is in the range of 0.05–0.5 Pa·s and the thickness of the ink layer on a print is up to 1 μm. Adjusting the viscosity of the ink is especially important to ensure the high quality of a print. The ink, in this case, should not be extruded beyond the boundaries of the printed image.

The ink should be of high density, applied properly on the substrate, ensure that the cells of the anilox roller are filled. The type of a solvent for the ink plays an important role because its evaporation following the application of the ink on the substrate leaves a stable dry film on the print.

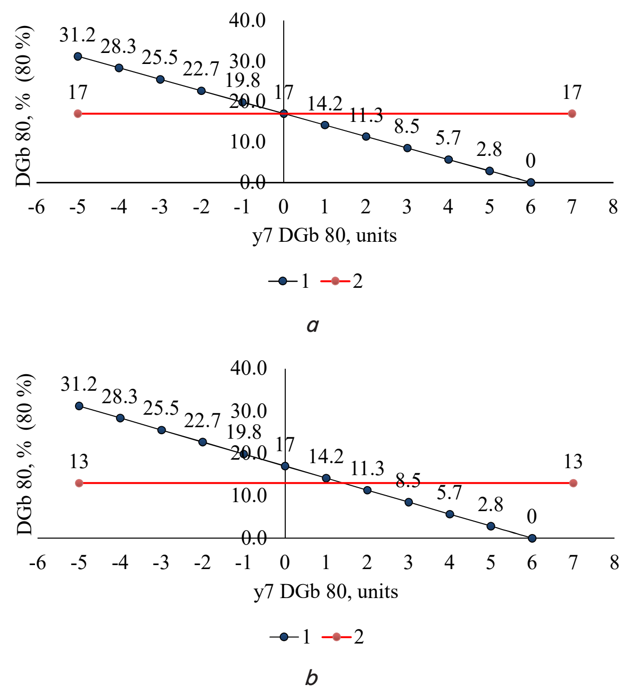



Fig. 11. Determining the coded value of the dot gain indicator of raster elements of 100 % field of black ink: *a* – cardboard GD-2; *b* – cardboard UD-3; DGb 80 – dot gain of raster elements of black ink (%); y7 DGb 80 – the coded value of the dot gain indicator of raster elements of black ink (units); 1 – calibrated value scale; 2 – measured value of the quality indicator

We have determined the coded value of a slip indicator when printing by the cyan, black, magenta, and yellow inks on cardboard. Based on the Harrington's scale, the slip indicator is 1 point.

At printing, the optimization process of the print quality indicators mentioned above is rather important. Fig. 12 shows the diagrams of the single desirability functions of the optical image densities on the prints.

Fig. 12 shows that the single values for the desirability function of the optical density indicators of the solid's background and the evenness of printing on cardboards are in the range from 0.95 to 0.99.

Fig. 13 shows the diagrams of the single Harrington's desirability functions for the indicators of gray balance, contrast, dot gain (an increase in the area of a raster dot) when printing on the UD-3 and GD-2 cardboards.

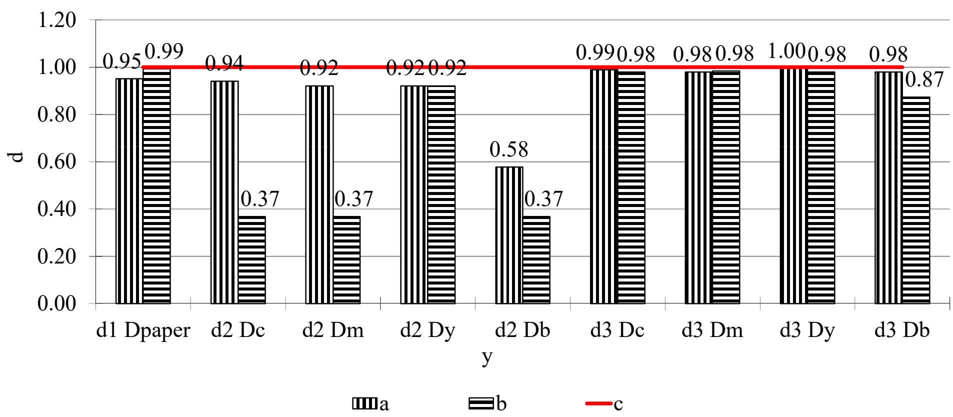



Fig. 12. Diagrams of the single Harrington desirability functions (d) for the optical density indicator of the solid's background and the printing evenness on cardboard: *a* – UD-3; *b* – GD-2; *c* – the level of desirability; y – coded values of quality indicators of the print

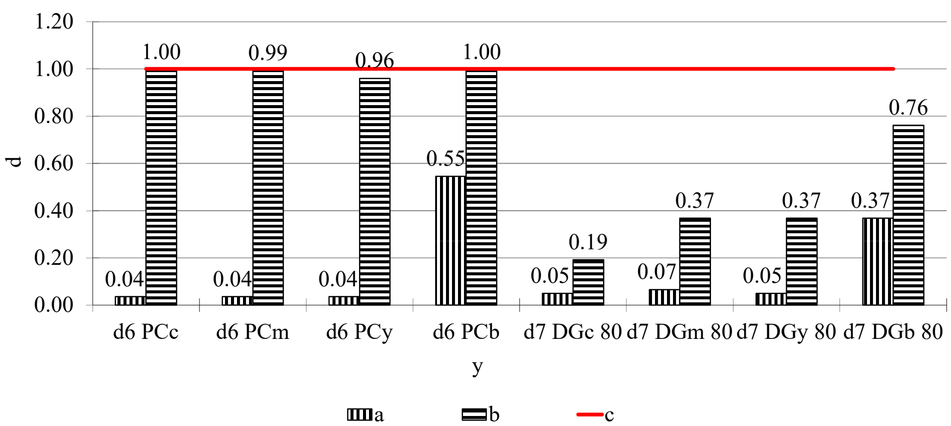



Fig. 13. Diagrams of the single Harrington's desirability functions (d) for the indicators of gray balance, contrast, the raster dot gain when printing on cardboard: *a* – UD-3; *b* – GD-2; *c* – the level of desirability; *y* – coded values for the print quality indicators

The values of the desirability functions for the indicators of gray balance, contrast, and a raster dot gain when printing on the GD-2 cardboard are approaching 1. At the same time, when printing on the UD-3 cardboard, these indicators are significantly lower and are in the range from 0.04 to 0.55.

## 6. Discussion of results of studying the optical indicators of the flexographic prints

The results of our theoretical and experimental studies have confirmed that a comprehensive quality indicator of flexographic prints is made up of evaluating the separate elements in the printed image. Taking into consideration the increased requirements of consumers for the quality of the prints, the expediency of making test prints at the proofing equipment before printing the run has been confirmed. That would make it possible to properly select the technological modes of printing, to test the ink properties, their interaction with substrates, and to save consumables.

The study of the surface profiles has shown that the presence of a chalked coating affects the decrease in the cardboard roughness indicator and smooths out its micro-roughness. Such a highly developed micro- and sub-microstructure enables the reproduction of fine screen raster images on the print. The topography of the print surface replicates the micro-geometry of the substrate. It has been proven that the UD-3 cardboard is characterized by a large degree of surface irregularities, which is explained by the absence of a chalked coating. The microphotographs of the prints clearly show the holes, micro-holes, which, even after the application of the ink layer, remain unsmoothed. The examined GD-2 cardboard demonstrates a uniform distribution of the structural elements. The absence of large macro irregularities is due to the presence of two chalked coating layers on the cardboard surface. Our analysis of the cardboard surface profiles and the microphotographs of the structure shows that the presence of a double chalked coating reduces the roughness parameter by three times. The uneven surface of the substrate promotes the deep penetration of ink inside the cardboard structure and reduces the saturation of the prints. The smooth surface of the coated cardboard promotes the bonding of the ink to the pulp fibers in the paper base, ensuring its uniform distribution across the print and the high quality of the printed images.

Our study of the test flexographic prints has confirmed that failing to comply with the optimum pressure at printing leads to the raster dot gain, changes the image contrast, its optical density, regardless of the ink it was printed with.

An analysis of the densitometric study has demonstrated that the optical densities of prints depend on the structure of the cardboard surface. At an image saturation of 90 %, the optical density of the prints on the UD-3 cardboard without a chalked coating decreases by 0.75 relative units compared to the prints on the coated GD-2 cardboard. The lowest values of the optical density indicator are characteristic of the prints made with yellow ink (1.52) and the highest values (1.99) – of the prints made with black ink, which is consistent with the theoretical principles of printing processes. The quality of the test prints is determined by the print evenness indicator, which was the same for all images, which is explained by the use of inks with the same properties and our adherence to the norms of the printing process. The value of the dot gain indicator of raster elements on the prints on the cardboard UD-3 is 7 units higher than that on the cardboard GD-2. Increasing the area of the raster images distorts them and, therefore, causes defects. The most contrasting prints are those made by the black and magenta inks, the least contrasting ones are the prints of yellow ink.

The constructed desirability functions of the print quality indicators, specifically the contrast and raster dot gain, have shown that when printing, using different inks, on the GD-2 cardboard, their values are close to unity. The values of these indicators are twice lower for the prints on the UD-3 cardboard.

Our verification of the procedure for determining the comprehensive indicator of print quality based on the generalized criterion of optimization of single indicators based on Harrington's desirability function has shown the expediency of its use for evaluating the quality of test prints. A given procedure could be advanced for predicting the quality indicators of the flexographic images printed on cardboard used for packaging.

## 7. Conclusions

1. The effect of the substrate surface topography on the quality of the prints has been identified. The presence of a chalked coating on cardboard helps reduce the roughness indicator and apply the ink more evenly (regardless of color) on the print. The studied GD-2 cardboard with a double chalked coating has an average degree of surface irregularities from –3.1 to +2.02 μm, the absence of large macro irregularities. The roughness parameter $Ra$=0.426 μm, which indicates the highly developed micro- and sub-microstructure of the surface and the high-quality reproduction of images on the print. The UD-3 cardboard, without a chalked coating, is characterized by a large degree of surface roughness, from –5.76 to +6.37 μm, by an increase in the roughness parameter $Ra$=1.26 μm. The quality of the printed images is much lower.

2. The densitometric study of the prints' quality has shown the coded values of the indicators based on the Harrington's scale:

– the optical density of prints for a cyan ink varies from 0.54 to 1.64; for a magenta ink – from 0.49 to 1.59; for a yellow ink – from 0.44 to 1.54, for black ink – from 0.66 to 1.96;

– the printing evenness varies from 0 to 0.37, regardless of an ink color because the technical characteristics of the inks are the same and they are applied on cardboard under the same conditions;

– the trapping on the prints over a 100 % field across the entire printed area is equal to one;

– the contrast when printing on the GD-2 cardboard by the cyan and magenta inks changes from 0.5 to 54.5 (when printing with yellow ink, this indicator is –2.3 to 53.7, when printing with black ink, the contrast indicator changes from –12 to 60);

– the dot gain (increasing the area of raster elements) (for an 80 % field) when printing by the cyan, magenta, and yellow inks on the GD-2 cardboard is 14 units, for black ink – 17 (for an 80 % field) and 20 (for a 40 % field); the dot gain indicator when printing with CMYK on the UD-3 cardboard increases to 21 units (a 40 % field);

– the single values for the desirability function of the optical density indicators of the solid's background and the printing evenness on cardboards are in the range from 0.95 to 0.99;

– the values for desirability functions of the gray balance indicator for a different area of the print filling (75 %, 50 %, 25 % field), the slip indicator at printing using different inks, the indicators of contrast and raster dot gain at printing on the GD-2 cardboard using different inks are close to 1. At the same time, when printing on the UD-3 cardboard, these indicators are much lower and vary in the range from 0.04 to 0.55.

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