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The rapid development of digital printing and the popularity of corrugated packaging production encourages manufacturers to improve product quality. Therefore, research into the quality of digital prints, using modern procedures for determining the qualimetric indicators, is important for both consumers and manufacturers. We have studied the prints made by the inkjet printing machine Durst Rho 1312. The printing involved the inks CMYK+Light Cyan+Light Magenta (Austria)+Light Cyan+Light Magenta. The prints were obtained directly on five-layer corrugated cardboard using the post-print technology. In addition, the printing was performed on a liner, followed by its pinning to fluting (the preprint technology).

The paper describes a procedure for determining the qualimetric prints' indicators, in particular, optical density, the increase in the tonality of the raster image, color reproduction, resolution, print stability on prints, and in the printing process, and lightfastness. The imprints' quality was evaluated in accordance with the requirements set by the standard ISO/TS15311-2:2018. The quality of digital and offset prints has been compared. It has been established that the digital post-print technology on the five-layer corrugated cardboard BE and the pre-print technology on the cardboard GD180 ensure the same print quality parameters. This includes such a quality indicator as the reproduction of raster image tones, optical density, color difference, printing stability. The print resolution of the imprints has slight deviations.

It was found that the color transfer of offset prints is higher (by 10 %) than that of the digital prints based on the pre-print technology. Offset printing also provides higher resolution (by 93 lines/cm) than digital printing. However, in terms of print stability and color difference, the inkjet prints are inferior to the offset technology. Digital prints have good lightfastness (10–20 times better than offset samples)

Keywords: digital and offset printing, five-layer corrugated board, pre-print, post-print, prints' quality

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DEVISING A PROCEDURE FOR EXAMINING THE QUALITY OF PRINTS OF DIGITAL AND OFFSET PRINTING ON CORRUGATED CARDBOARD

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1. Introduction

Requirements for the design of printed packaging are constantly growing. Packaging is becoming more attractive while the requirements for reproducing multi-color images are constantly increasing. The modern market offers a wide range of different packaging materials but priority by both

producers and consumers is given to environmentally friendly materials. These include cardboard and corrugated cardboard. Based on data from the research institute Smithers Pira, the global needs in corrugated cardboard in recent years have exceeded 143 million tons. Experts predict an annual increase in the use of corrugated cardboard for the packaging manufacturing at the level of 3.7 % Packaging made from

corrugated cardboard, according to experts, ranks first in a series of environmentally friendly products, and it is easily recycled [1]. The labor-intensity of making packaging from these materials is relatively small. However, corrugated cardboard, due to its specific structure, is not the easiest material to print on. Its capability to be printed on largely depends on the properties of the papers used to produce it. As it is known, important elements of corrugated cardboard are fluting and liner. The surface structure of the liner, its roughness, and smoothness determine the printing properties of corrugated cardboard. It is the presence of the coated surface or its absence on the liner surface determines the quality level of the printed image [2].

Various printing methods are used to print on packaging. At present, digital technologies cover different various production industries, including printing on containers and packaging made from cardboard and corrugated cardboard [3]. One of the main benefits of digital printing is the possibility to print in small and medium runs that are cost-effective. The use of traditional printing presses is profitable for printing large runs. It should be noted that the productivity of digital printing is increasing. A distinctive feature of digital printing is the fact that the prints after the printing process are almost dry, which saves time on drying the print run, which allows starting the finishing operations immediately. High print quality allows the digital method to compete with offset printing. Digital printing is the only printing technique, which may personalize products. For small runs, digital printing is more cost-effective and popular [4].

However, the variety of digital printing machines and materials requires that consumers should analyze carefully the quality of printed products. At the same time, specifications, technical conditions, standards do not typically contain indicators that could predict the quality of printed products, the behavior of such materials during printing. Therefore, it is important to study the quality of inkjet prints, the testing of packaging materials, taking into consideration the technological processes of printing.

2. Literature review and problem statement

There are many current studies that assess the quality of digital prints. The market of digital printing on corrugated cardboard can be divided into two major segments: pre-print and post-print. The first implies printing on the liner, followed by pinning to the fluting. The second option is, accordingly, the direct printing on corrugated cardboard. Work [5] considers the range of equipment, the options for its selection for printing images on corrugated cardboard. The technical capabilities of digital printing machines are described. However, the issues faced by manufacturers when printing on corrugated cardboard are not covered, in particular, such as the appearance of a liner depression into the corrugation associated with the unevenness of the printing surface. As well as the presence of bubbles due to a large amount of glue applied to the fluting, which also interferes with the printing process. All these facts testify that the above defects of corrugated cardboard have an obvious negative impact on the quality of printed images and should be taken into consideration when choosing the technology and printing technique.

The study of the digital printing properties on the example of electrographic technology is reported in paper [6]. The author shows a hierarchical tree of qualimetric indicators,

determines the weights of the properties of digital printing. Of interest is an algorithm of the procedure for determining the comprehensive indicator for assessing the quality of digital electrographic printing. However, the possibility of using this procedure to assess the quality of digital ink-jet prints is not proved.

Work [7] reports research into the effect of the quality of initial raw materials and glue on the operational properties of packing cardboard. The authors prove that the strength properties of corrugated cardboard can be significantly increased by using dry glue based on modified and natural corn starch diluted with cold water, which avoids a long boiling procedure, reduces energy consumption for the production of corrugated cardboard. However, there are no studies into the effect of the corrugated cardboard components and the structure of its surface on the quality of the printed images.

This issue is partially tackled in paper [8]. It is known that the quality of inkjet prints is affected by the technology of surface treatment of the printing material. The paper proves the positive effect of primers based on modified polyvinyl alcohol on the quality of digital prints. The authors of work [9] confirm the effect of the structure of the printed material on the quality of prints. A well-developed surface of the liner promotes better ink adhesion and the formation of a better printed image. However, there are no in-depth studies of the microgeometry of the substrate and its interaction with the printing ink. This issue is considered in detail in [10]. Researchers describe a procedure for assessing the integrity of the coating surface using atomic force microscopy. However, these studies apply to structurally integral materials while corrugated cardboard is a multilayer material (from 2 to 7 flat and corrugated layers joined by an adhesive composition). A procedure of the comprehensive assessment of the quality of digital printing using test prints is described in paper [11]. Based on the comparison of experimental and expert assessments of the prints' quality, the authors calculate their generalized comprehensive assessment. However, such a comprehensive assessment does not consider the specificity of the pre-print and post-print technology for obtaining the prints.

The problem of digital ink-jet printing quality is very important due to the growing pace of its use in the packaging industry. In [12], it is emphasized that the process of assessing the quality of printed products as an element of standardization in each printing shop requires determining individual indicators in each technological process. Based on the principles of qualimetry, the author of [13] proposes an algorithm for selecting a procedure for assessing the quality of prints and determining the priority of indicators considering the type and purpose of products. However, when using new materials and equipment, it is often necessary to predict the prints' quality. To this end, in [14], researchers recommend the use of simulation in order to optimize the printing process, thereby preventing defects. That could ensure a high level of product quality in accordance with international standards.

Testing the quality of prints obtained by digital printing is interesting in terms of the development of inkjet technology, as well as the growing popularity of corrugated cardboard as a material for the manufacture of environmentally friendly and energy-saving packaging. Compared to offset printing, digital printing is new, insufficiently studied, so it requires in-depth theoretical and experimental research.

3. The aim and objectives of the study

The aim of this study was to evaluate the prints' quality on five-layer corrugated cardboard obtained by ink-jet printing.

To achieve this goal, the following tasks were set:

- to investigate the quality indicators of test ink-jet prints (resolution, optical density, color coverage, the increment in a raster tone, print stability, gloss, resistance to light) and identify the impact of the pre-print and post-print technology on their values;

- to compare the quality of digital ink-jet and offset prints on corrugated cardboard.

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

4.1. The examined materials and equipment used in the experiment

Our study involved the prints on the BE five-layer corrugated cardboard with a liner made from the coated TLWC and uncoated TLW paper, obtained by the post-print technology. Printed images were applied to the corrugated cardboard on both the corrugation side B and the corrugation side E. The prints obtained by the pre-print method on the multilayer GD 180 corrugated cardboard with a weight of 180 g/m² were also examined (Table 1).

Color images were applied by the Durst Rho 1312 digital printing machine (Austria) using CMYK+Light Cyan+Light Magenta UV inks (Austria). The machine used a print head based on the Quadro Array technology, which ensures a small drop of ink – 12 picoliters and has more than 80,000 nozzles in the print carriage. This provides for high-quality printing with a resolution of 1,000 dpi.

The quality of digital printing was compared with the offset prints. Five identical prints were processed to validate the experimental studies.

4.2. Procedure for examining the prints' resolution

The resolution or the number of points contained in a length unit is central to assessing the prints' quality. The evaluation was performed using a Siemens star, which consists of 72 pairs of black and white lines arranged in a circle from one central junction point (Fig. 1).

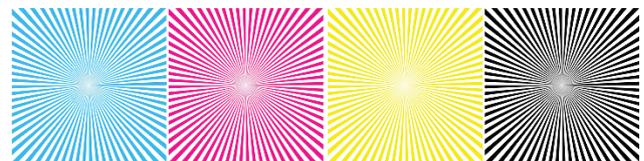


Fig. 1. A test to determine resolution using an example of TLWC-E print

When printing, the points that are close together merge into a spot in the center. The resolution of the printed image is determined by a magnifying glass with micrometric divisions and is calculated from the following formula:

$$R = \frac{\text{the number of line pairs}}{\pi d} \tag{1}$$

where *R* is the resolution (the number of line pairs/cm), *d* is the diameter of a field of merged lines (cm).

4.3. Procedure for determining the optical density of prints

The optical density of prints determines the degree of light absorption by the print and is a measure of its intensity.

Optical density is determined from the following formula:

$$D = \lg \frac{1}{\beta}$$

where β is the light reflection coefficient (2). Optical density was measured with the X-Rite 528 Spectro-densitometer, (measuring angle: 45°/0°; light with a temperature of 2,856 K; spectral head range: 400–700 nm; viewing angle: 2°).

4.4. Procedure for determining an increase in the tone of a raster image

The degree of surface coverage (raster tone) is determined for raster prints based on the percentage of the surface of the raster points to the entire surface of the print. The degree of coverage is determined from the Murray-Davis formula:

$$F(\%) = (1 - 10^{-DR}) \times (1 - 10^{-DV}) \cdot 100, \tag{3}$$

where *DR* is the optical density of the raster field; *DV* is the optical

Prints characteristics

Material-base	Characteristic	Image	
TLWC-E	Printing is performed on the liner from coated TLWC paper that is placed on the side of corrugation E of 5-layer BE corrugated cardboard		printing coated paper corrugation E corrugation B
TLW-B	Printing is performed on the liner from uncoated cardboard TLW that is placed on the side of corrugation B of 5-layer corrugated cardboard BE		coated paper corrugation E corrugation B printing
TLWC-B	Printing is performed on the liner from TLWC coated paper placed on the side of corrugation B of the 5-layer corrugated cardboard BE		corrugation E corrugation B coated paper printing
TLW-E	Printing is performed on the liner from uncoated TLWC paper placed on the side of corrugation E of 5-layer corrugated cardboard		printing corrugation E corrugation B coated paper
GD 180	Printing is performed on corrugated cardboard with the coated liner GD 180		printing coated paper

density of the field with a 100 % coverage. The X-Rite 528 Spectro-densitometer with a built-in print coverage function was used for the studies. The increase in the degree of surface coverage arises from the difference between the measurement on the print and the known value on the printing plate or data from the digital image. To determine this property, it is desirable to use midrange tones. Therefore, in experimental studies, the tone of the raster field was determined, which had a coverage of 50 % (Fig. 2).



Fig. 2. The field to measure an increase in the raster tone on the TLWC-E print

The increase in the degree of coverage of the imprint surface with the ink for the fields of the control scale was determined from the following formula:

$$\Delta P(\%) = Pod - 50\%, \tag{4}$$

where ΔP is the increase of tone in the field of 50 %; Pod is the tone of 50 % field on the print, %

4. 5. Procedure for determining the color coverage on a printed image

The color properties on a print depend on the surface, the degree of reflection or transmission of light through it. Therefore, the Lab color model, which is an instrument-independent model, is based on human perception of color. At the same intensity, the human eye perceives the green color of the rays as the brightest, slightly less bright – red, and even darker – blue. It should be borne in mind that brightness is a characteristic of perception, rather than the color itself. Any color in the Lab model is defined by brightness and two chromatic components: component «a» varies from green to red, component «b» varies from blue to yellow.

Any color in the Lab model is defined by the brightness and two chromatic components – parameter «a», which varies from green to red, and parameter «b», which varies from blue to yellow. Brightness in the Lab model is completely separated from color, which makes the model convenient for

adjusting the contrast, sharpness, and other tonal characteristics of the image. This model is three-channel. Its color coverage corresponds to the color coverage of the human eye and includes coverage of all other color models.

In order to determine the range of colors in the CIEL*a*b* system, the values of a^* , b^* of the measuring fields of primary colors (C, M, Y) and auxiliary colors (R, G, B) were determined. The coordinates a^* and b^* of the measured colors were plotted on a diagram, and the field of color coverage was constructed. The surface (G) of the constructed hexagon and color coverage was determined from the Green formula:

$$G \approx 12 \sum C \left\{ \begin{array}{l} a^*i+1+a^*i2 \times \\ \times (b^*i+1-b^*i) - \\ -b^*i+1+b^*i2 \times \\ \times (a^*i+1-a^*i) \end{array} \right\} \tag{5}$$

where a^*i+1+a^*i are the average values of a^* inks: Red, Yellow, Green, Cyan, Blue, Magenta, Red; b^*i+1+b^*i are the average from two values of b^* inks: Red, Yellow, Green, Cyan, Blue, Magenta, Red; a^*i+1-a^*i is the difference between values b^* in the inks range: Red, Yellow, Green, Cyan, Blue, Magenta, Red; $b^*i+1-b^*i-b^*$ is the difference between values b^* in the inks range: Red, Yellow, Green, Cyan, Blue, Magenta, Red.

4. 6. Procedure for measuring the printing stability on the prints and during the printing process

Test samples were specially printed to determine the printing stability (Fig. 3).

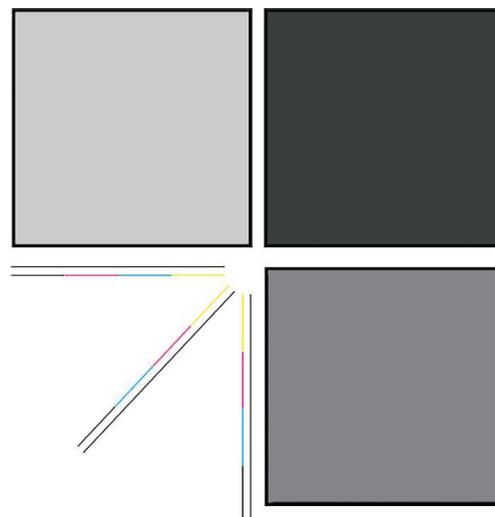


Fig. 3. An image fragment for determining the printing stability on the TLWC-E print

The test image consists of three fields with different degrees of coverage: dark (C65, M50, Y50, K50), gray (C40, M30, Y30, K30), and bright light (C20, M15, Y15, K15). The ink parameters L^* , a^* , b^* of these fields were determined using the Spectro-densitometer X-Rite 528 and the weight coefficients of the average value were calculated from four measurements for dark, gray, and light fields. Next, the weight ΔE^*ab was determined that quantifies the difference between colors (from the four corners of the sheet), and the color of a particular field. ΔE^*ab is determined from the following formula:

$$\Delta E^*ab = \sqrt{\Delta L^*2 + \Delta a^*2 + \Delta b^*2}, \tag{6}$$

where ΔL^* is the difference between a single and average value of the light field; Δa^* is the difference between a single and average value; Δb^* is the difference between the single b and average values.

The printing stability is characterized based on the standard color deviation value for all measurements. According to ISO 12647-7, the standard deviation of the values L^* , a^* , b^* should not exceed 0.5 but the value of ΔE^*ab between the three mean values and each field should not exceed 2.

To determine the printing stability in the printing process, 5 prints were used. The color difference for the three fields – light, gray, and dark – is determined in the specified places on the prints.

4. 7. Procedure for determining the lightfastness of prints

Lightfastness characterizes the color fastness of the printed image against light. The lightfastness assessment was determined based on the scale given in Table 2.

Table 2

Lightfastness value of printed images

Scale	ΔEab	Lightfastness parameter
I	Less than 4	Excellent
II	<4 and ≥ 8	Very good
III	<8 and ≥ 16	Good
IV	<16 and ≥ 24	Poor
V	More than 24	Bad

To determine this characteristic, samples with a 100 % print coverage printed with CMYK were prepared. From each type of the prints, 5 samples 25x25 mm were selected, and their ΔEab was determined using the X-Rite Spectro-densitometer. Next, these samples were exposed to light and their color characteristics were measured again.

5. Studying the effect of the post-print and pre-print technology on the quality of digitally printed samples

5. 1. Quality evaluation of the ink-jet printed samples on corrugated cardboard

The results of the tone transfer of the printed images on corrugated cardboard showed almost the same average CMYK values on the prints in dark and light areas, regardless of the choice of a pre-print or post-print technology. The lowest tone transfer is observed at points with a degree of coverage of 0.4 % in light areas of the image, and with a degree of coverage of 99 % – in dark areas of the image (the remaining raster field is 100 % covered with the ink).

Studies of the prints' resolution are illustrated in Table 3. As the tabular data show, the prints obtained by the pre-print technology on corrugated cardboard GD 180 have a slightly better resolution (10 % higher than the prints obtained by the post-print technology). Obviously, we can assume that this parameter influences the flat position of the sheet of corrugated cardboard during printing on it. In the post-print technology, the samples printed on the side of corrugation E (TLWC-E and TLW-E) showed slightly better resolution.

As evidenced by our studies of the optical density of printed images, given in Table 4, the prints obtained by the

post-print technology on coated surfaces, as well as the pre-print technology on cardboard GD 180, are characterized by the same values of optical density. The optical density on corrugated cardboard with a liner of uncoated paper is slightly lower.

Table 3

Prints' resolution on corrugated cardboard

Technology	Type of printed surface	Resolution (lines/cm)				
		C	M	Y	K	Average CMYK value
Post-print	TLWC-E	40	37	32	46	39
	TLW-B	33	32	27	36	32
	TLWC-B	34	29	28	27	30
	TLW-E	39	35	32	40	35
Pre-print	GD 180	47	43	38	49	44

Table 4

Results of studying the optical density of prints

Liner printed at the side of corrugation	Optical density of solid printing (D), [-]				
	C	M	Y	K	Average CMYK value
Ink-jet post-print technology					
TLWC-E	1.21	1.42	1.37	1.70	1.43
TLW-B	1.31	1.41	1.44	1.70	1.47
TLWC-B	1.04	1.22	1.13	1.31	1.17
TLW-E	1.04	1.24	1.12	1.33	1.18
Ink-jet pre-print technology					
GD 180	1.15	1.41	1.29	1.75	1.4

The magnitudes of the increase in the tonality of raster images are given in Table 5. As one can see, the print made by the pre-print technology on cardboard GD 180 is characterized by the smaller increments in tones (about 50 % on the field with a degree of coverage of 50 %). Significant fluctuations of this indicator are observed for all CMYK colors on each printed image.

Table 5

Values of an increase in the raster image tone on prints

Liner	Increase in the tone of a raster image in the field with a 50 % coverage degree (ΔP), %				
	C	M	Y	K	Average CMYK value
Ink-jet post-print					
TLWC-E	14.3	21.0	13.6	19.0	17.0
TLW-B	21.0	21.0	20.0	20.0	20.5
TLWC-B	21.6	23.6	23.4	20.6	22.5
TLW-E	20.3	20.6	21.3	18.6	20.2
Ink-jet pre-print					
GD 180	6.67	14.33	5.33	14.67	10.25

Gloss is an important indicator of print quality. Fig. 4 shows that the gloss is affected by the structure of the printing surface (liner), in particular the presence of a coated surface layer.

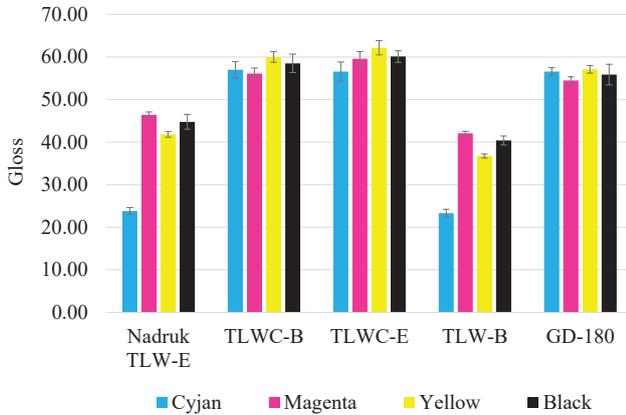


Fig. 4. The gloss of digital prints made by the pre-print technology on GD 180 cardboard and the post-print technology on the liners (TLWC-E, TLWC-B, TLW-B, TLW-E)

Studies have shown that the coated liner surface (TLWC-E and TLWC-B) based on the post-print technology and cardboard GD 180 (the pre-print technology) has a higher gloss (40–50 %) of the printed images than on the prints without a coated layer (TLW-B and TLW-C).

5.2. Comparing the quality of the digital and offset prints in the pre-print technology

Our studies have shown that the color range of offset prints is slightly higher, by 10 %, compared with the prints from digital printing (Table 6, Fig. 5). The color coverage parameter is affected by the structure of the printed base, in particular its absorbency, so offset prints coated with varnish have a lower color range than the prints without varnish. On all prints, the Magenta ink has the same color coverage. The exception was the digital print obtained with a Green ink, which had a higher color strength than that on the offset samples.

Table 6

Difference in colors of the digital and offset prints

Printing technology	Varnish coating on the print surface	Color characteristics [-]
Offset pre-print	With varnish	11439
Offset pre-print	Without varnish	12026
Ink-jet pre-print (GD 180)	Without varnish	10772

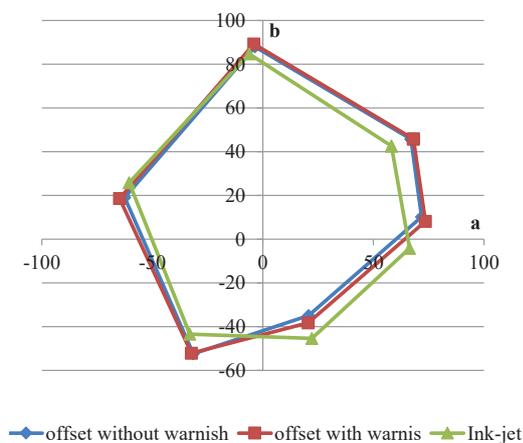


Fig. 5. Diagram of color coverage of digital prints made by the pre-print technology (GD 180) and offset prints (with and without varnish) on cardboard GD-180

Fig. 5 shows the saturation diagram of the primary colors of the image on the prints made by the digital procedure. The images were reproduced on GD 180 cardboard by the pre-print technology, as well as by offset technique (with or without varnish).

The stability of printing on sheets, and the values of their standard deviations, are within the range from 0.4 to 1.1 for digital prints, and within the range from 0.4 to 0.8 for offset prints (Table 7). On this basis, it can be argued that the stability of printing based on both technologies is high but in digital printing technology, it is better than in the offset technology.

Table 7

Comparison of the maximum values of standard deviation (OS) for L, a, and b coefficients

Prints	Maximal values of standard deviation for the average values L, a, and b								
	C20M15Y15K15			C40M30Y30K30			C65M50Y50K50		
	L*	a*	b*	L*	a*	b*	L*	a*	b*
SRP offset – TL	0.71	0.38	0.79	1.07	0.54	0.5	1.02	0.59	0.77
Ink-jet (GD 180)	0.55	0.56	0.37	0.76	0.72	0.39	0.65	0.84	0.47
Maximal values of color difference (ΔE_{ab} max)									
SRP offset – TL	1.18			1.29			1.83		
Ink-jet (GD 180)	1.05			1.32			1.33		

As our studies show (Fig. 6), the quality of the printed images on offset prints has a much better resolution compared to the ink-jet prints. It is known that the resolution of digital prints primarily depends on the resolution of the printing system. Thus, the plotter Durst Rho 1312 has a resolution of 800 dpi. Offset printing allows one to reproduce images with a resolution of about 2,500 dpi. This explains the lower resolution of digital prints (44 lines/cm).

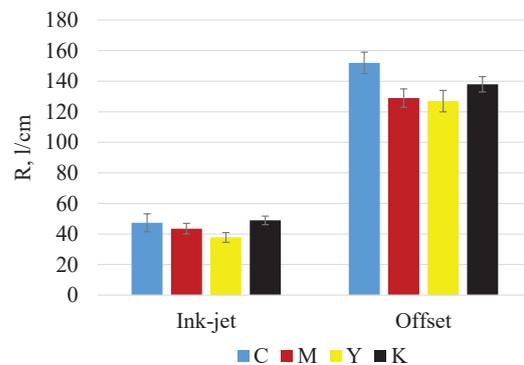


Fig. 6. Resolution diagrams of the digital and offset prints based on the pre-print technology

For printed products, the prints' daylight resistance is important. The results of studying the lightfastness of the digital and offset prints after exposure to sunlight for 12 months are given in Table 8. The digital prints based on the pre-print and post-print methods have 10 times better resistance to light than offset prints.

As Table 8 shows, the presence of varnish on the surface of the offset prints did not have a significant effect on their lightfastness.

Table 8

The prints' lightfastness after 12 months of light exposure

Lightfastness – a difference in the ΔE_{ab} colors of prints			
Printing technology	Offset		Ink-jet
Printed base	GD 180	GD 180+L	GD 180
C	0.00	2.25	6.0
M	52.86	75.05	4.75
Y	90.91	89.89	6.70
K	1.61	1.00	7.95

The visual evaluation and analysis of the research results demonstrated that the offset prints with Yellow ink (with and without varnish) completely faded while the prints with Magenta ink changed color (ΔE_{ab} about 60–70). In the digital prints after twelve months of exposure to sunlight, there is almost no change in the color of the printed images (ΔE_{ab} below 8).

6. Discussion of the results of studying the prints' quality of digital and offset printing

Our experimental studies confirmed that in general the prints' quality is determined by individual qualimetric indicators. The chosen procedure for assessing the quality of the printed images involved modern control and measuring devices with mathematical and statistical data processing. This has allowed determining the factors affecting the quality of the prints, in particular printing techniques, the pre-print and post-print technologies, the microgeometry of the printed surface, the presence of a varnish coating. An analysis of the digital prints' quality indicators revealed that the post-print technology on the five-layer corrugated cardboard BE is not inferior to the quality of the pre-print technology on the cardboard GD 180. The prints obtained by the pre-print technology on corrugated cardboard have a 10 % higher resolution than those based on the post-print technology (Table 3). The height of the corrugation also affects the quality of the print. The post-print samples printed on the corrugated E side (TLWC-E and TLW-E) showed better resolution. The optical densities of the prints (Table 4) on the coated surfaces GD 180 (pre-print) and the prints on corrugated cardboard (post-print), made on a liner of coated paper (TLWC-E and TLWC-B), have the same values (1, 4).

It was found that the post-print technology on the coated surface of the liner (TLWC-E and TLWC-B) and the pre-print technology on the cardboard GD 180 ensures a higher gloss (by 40–50 %) of the printed images than on the prints without coating (TLW-B and TLW-C).

The difference between the colors of the images on the prints of GD 180 cardboard (pre-print) and corrugated cardboard (post-print) is on average 11,000. The exception was the prints on the corrugated cardboard with a liner of uncoated paper (the color difference is about 25 %) (Table 6, Fig. 5).

The stability of printing on GD 180 cardboard (pre-print) and on coated liner (TLWC-E and TLWC-B) of corrugated cardboard (post-print) is close and high. The standard deviation of the color coefficients $L^*a^*b^*$ is about 0.5, the maximum values of the color difference on the prints equal 1. The exception was the prints on corru-

gated cardboard TLW-E. They revealed significantly lower values of the standard deviation for the average values of $L^*a^*b^*$ and the maximum color difference of the studied fields (Table 7).

It was established that the color range of offset prints is 11,700. The color difference in the samples of offset printing varies from 1.18 to 1.83, and inkjet printing is from 1.05 to 1.33. The image resolution of offset prints is 137 lines/cm as opposed to the inkjet prints (44 lines/cm). In general, the quality of offset printing exceeded digital printing on corrugated cardboard in terms of the color range of images (by 10 %) and resolution (by 94 lines/cm) (Fig. 6).

However, the stability of digital printing is much better than that of offset printing. This is confirmed by the values of a standard deviation, which are in the range from 0.4 to 0.8 for digital prints, and for offset copies – from 0.4 to 1.1 (Table 7). The effect of daylight for twelve months on the prints (Table 8) showed that the lightfastness of digital prints is 10 % higher than that of offset printing.

The results of our research are of practical value as the procedure for determining the quality of digital prints on corrugated cardboard could be used by manufacturers of packaging products. The tested procedure has the potential to be used to assess the quality of digital printing on corrugated cardboard with a honeycomb structure.

- the reproduction of tones of raster images in the maximum segment is from 0.4 % to 99 % for all prints;
- the optical density of prints on GD 180 averaged from 1.4 (pre-print) and prints on corrugated cardboard (post-print), made on a liner of coated paper (TLWC-E and TLWC-B);
- the color difference averaged about 11,000 for GD 180 (pre-print) and corrugated (post-print) prints on a liner made from coated paper (TLWC-E and TLWC-B). The exceptions were the prints on corrugated cardboard with a liner of uncoated paper (the color difference is about 25 %);
- the stability of printing on a sheet for prints on cardboard GD 180 (pre-print) and prints on corrugated cardboard (post-print), made on liners of coated cardboard (TLWC-E and TLWC-B), is close and high. The standard deviation of the color coefficients $L^*a^*b^*$ is about 0.5, and the maximum values of the color difference on the prints equal 1. The exception was the prints on corrugated cardboard TLW-E. They showed significantly lower values of standard deviation for the average values of $L^*a^*b^*$ and the maximum color difference for the studied fields.

A slight difference in the quality of prints was found for the following indicators:

- the quality of offset prints based on the pre-print technology is better than the digital ones;
- the color range for offset prints is 10 % higher than that of the inkjet prints;
- the resolution of printing on inkjet prints is 44 lines/cm, which is much less than this indicator in offset printing (137 lines/cm).

In general, the stability of digital printing is much better than that of offset printing. The standard deviation value of the print stability indicator for offset prints is in the range from 0.4 to 1.1, and for digital prints – from 0.4 to 0.8. However, the color difference on offset prints is higher (from 1.18 to 1.83) than that on inkjet prints (from 1.05 to 1.33).

Our studies of the prints' resistance to light have shown that the lightfastness indicator in inkjet printing is 10 % higher than that in offset printing.

These parameters include the following:

- the reproduction of the tones of raster images in the maximum segment from 0.4 % to 99 % for all prints;
 - the optical density of prints on GD 180 averaged from 1.4 (pre-print) and prints on corrugated cardboard (post-print), made on a liner of coated paper (TLWC-E and TLWC-B);
 - the color difference averaged about 11,000 for prints on GD 180 (pre-print) and prints on corrugated cardboard (post-print), made on a liner of coated paper (TLWC-E and TLWC-B). The exception was the prints on corrugated cardboard with a liner of uncoated paper (the color difference is about 25 %);
 - the stability of printing on the sheet and in the printing process for prints on cardboard GD 180 (pre-print) and prints on corrugated cardboard (post-print), made on liners of coated cardboard (TLWC-E and TLWC-B), is close and at a high level. The standard deviation of the color coefficients $L^*a^*b^*$ is about 0.5, and the maximum values of the color difference on the prints were 1. The exception was the prints on corrugated cardboard TLW-E, which revealed slightly lower values of the standard deviation for the average values of $L^*a^*b^*$ and the maximum color difference for the studied fields on the prints.
- A slight difference was observed in the prints' quality for the following indicators:
- the printing resolution is slightly worse (30–39 lines/cm) for prints on corrugated cardboard (post-print) compared to (44 lines/cm) prints on GD 180 (pre-print);
 - the comparison of the quality of inkjet and offset printing, based on the pre-print technology, showed that the quality of offset printing is better in terms of the following indicators:
 - the color range for offset prints is 11,700, which is 10 % higher than that for inkjet prints;
 - the resolution of printing on inkjet prints is 44 lines/cm, which is much less than this indicator in offset printing (137 lines/cm).

In general, the printing stability in digital printing is much better than that in offset printing. Accordingly, the standard deviation value for offset prints is in the range from 0.4 to 1.1, and for digital prints is from 0.4 to 0.8. The color difference on offset prints is higher (from 1.18 to 1.83) than that in inkjet prints (from 1.05 to 1.33).

Our studies of the prints' lightfastness have shown that this indicator in inkjet printing is 10 % higher than that in offset printing.

7. Conclusions

1. A procedure for studying the qualitative characteristics of digital prints has shown that ink-jet printing can be an alternative to offset printing on five-layer corrugated cardboard. This is confirmed by the values of the densitometric and colorimetric indicators of print quality. There is almost the same optical density and color difference of the prints (the post-print technology on coated surfaces and the pre-print technology on cardboard GD 180). The exception was the prints on uncoated corrugated cardboard liner (the color difference is about 25 %).

2. The comparison of prints' quality has shown that the pre-print technology provided better performance in offset printing (the color range is 10 % higher and the resolution is 94 lines/cm higher) than that in inkjet printing. The color difference of offset prints is much higher (from 1.18 to 1.83) compared to inkjet printing (from 1.05 to 1.33). However, the stability of digital printing is higher (from 0.4 to 0.8) and the lightfastness of the prints is larger (by 10 %).

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This paper addresses the identified issue of the inefficient use of post-consumer wood (PCW) in the technological wood processing due to its surface contamination. An option to resolve this issue by cleaning PCW in a mechanized manner has been proposed, specifically by using a needle milling tool and selecting the tension value and feed rate. The impact of the tension of needle milling tools before processing on the cleaning depth of the contaminated surfaces of workpieces made from the PCW has been determined. The constructed model of the contact between a needle milling tool and the contaminated PCW surface has made it possible to describe the essence of the cleaning technique involving this tool. It was found that the depth of the layer removed by the needle milling tool's wire is reduced in proportion to an increase in the distance before cutting is completed. A nomogram has been built to determine a change in the front angle depending on the needle milling tool's tension value. Knowing the front angle at a certain point of the needle touch on the contact arc enables determining the thickness of cleaning, which is important for practical application, specifically, at a tension of 4.5 mm the thickness of the removed material can equal 3.46 mm. An adequate regression model was derived, the analysis of the coefficients of which showed a significant impact of tension (+0.895) on the depth of cleaning over the feed speed (+0.256). The devised model makes it possible to forecast the thickness of the removed layer to ensure the required cleanliness of the PCW wooden. Practical recommendations on the operational modes of a needle milling machine have been formulated: the feed rate should equal 10–12 m/min, the tension – 0.5–5.0 mm, which could ensure, depending on the material's type, hardness, and the kind of PCW surface contamination, the removal of the surface layer with a thickness of 0.4–4.0 mm. A rational tension of the needle milling tool of 2.5 mm has been proposed for industrial application, which ensures the cleaning depth of contaminated surfaces within the range of 1.8–2.2 mm

Keywords: *post-consumer wood, wood processing, wood science and technology, needle milling tools, wood residues, waste recycling*

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DETERMINING THE REGIME PARAMETERS FOR THE SURFACE CLEANING OF POST-CONSUMER WOOD BY A NEEDLE MILLING TOOL

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1. Introduction

A potential resource and an underutilized base of wood raw materials, whose reserves increase in proportion to the development of the country's industry and economy in general, are the stocks of post-consumer wood (PCW). While being an additional resource of timber mass [1, 2–7], this raw material, due to the lack of technological advancements

and recommendations (from collection to the manufacture of size-quality blanks and products), is not involved in processing at the furniture and woodworking enterprises.

It is a relevant task to develop highly efficient mechanical techniques to clean PCW, which would maximally take into consideration the physical-mechanical properties of recycled materials. That is why this scientific study is aimed at determining the regime parameters for the surface cleaning of post-con-