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DETECTION OF THE INFLUENCE OF FLEXOGRAPHIC PRINTING SPEED ON THE OCCURENCE OF THE BOUNCING EFFECT ON IMPRINTS

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The paper studies the influence of flexographic printing speed on the manifestation of the bouncing effect and imprint quality indicators. Printing was carried out on an Optima 2 flexographic machine (Soma Engineering, Czech Republic) on a white polypropylene film with a thickness of 20 μm. The study was carried out using a test printing form containing solid fills, raster areas (25%, 50%, 75%), linear elements and gradients. The geometric parameters of the lines were analyzed using an electron microscope. Spectrodensitometric studies of optical density and dot gain (TVI) in three zones across the width of the web were also conducted. The appearance of vibration defects in the form of banding and doubling of elements was observed at printing speeds of more than 400 m/min. It was found that with an increase in printing speed from 100 to 600 m/min, the TVI value decreases on average by 15–25% depending on the tone.

Based on the results obtained, second-order regression models were constructed that describe the dependence of TVI on printing speed and position on the web. Based on these models, the corresponding response surfaces were synthesized and analyzed. For a tone of 75%, a pronounced nonlinear nature of the process is observed ($R^2 = 0.93$), for 50% – moderate nonlinearity ($R^2 = 0.88$), for 25% – almost linear dependence ($R^2 = 0.81$). The adequacy of the models was confirmed by the Fisher criterion, and the homogeneity of the experimental data – by the Cochran criterion.

It was found that the position on the web is a significant factor determining the distribution of TVI, which indicates the spatial heterogeneity of the printing process. The results obtained can be used to optimize high-speed flexographic printing modes and reduce vibration defects during the manufacture of packaging products

Keywords: high-speed flexographic machines, vibration effects, imprints, tone value increment (TVI)

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1. Introduction

The packaging industry is characterized by a significant increase in the requirements for product quality and production speed. One of the dominant printing technologies in the production of flexible packaging is the flexographic printing method, due to a number of significant advantages in terms of productivity and versatility. The use of modern flexographic machines allows to achieve perfect color reproduction with a minimum of defects, automate complex processes such as drying or web registration, and reduce production times without losing quality [1]. However, an increase in printing speed is often accompanied by a complication of dynamic processes in the printing system. One of the characteristic defects associated with the dynamics of the printing process is the so-called bouncing effect, which manifests itself in the form of banding of solid fills, doubling of contours, and a general decrease in image sharpness. The occurrence of such a phenomenon is associated with periodic changes in contact pressure in the printing zone, caused by vibrations of the elements of the printing machine.

Therefore, the study of the influence of flexographic printing speed on the appearance of the bouncing effect on film materials is an urgent and critically important task for the packaging industry.

2. Literature review and problem statement

Existing studies of flexographic printing technology are mainly focused on the influence of individual technological parameters – pressure, ink properties or anilox roller characteristics – on the quality of prints. In this case, the printing speed is considered as an auxiliary factor or is studied in limited ranges that do not correspond to the operating conditions of modern high-speed equipment. In work [2] it is shown that with increasing speed, the stability of ink transfer deteriorates due to the reduction of the contact time between the form and the printed material. In the study [3] it was established that vibration phenomena, in particular resonant oscillations of cylinders, can cause printing defects that do not appear at low speeds, but become significant when they are increased.

In [4], it was found that the top geometry of halftone dots on a printing plate is a material parameter and does not depend on the image processing technology. This was the first case when a predominantly concave geometry was quantified. Concavity, together with new mechanisms of dot deformation, was considered as the cause of printing defects in the form of halos and partially unprinted areas in the halftone dot itself. However, the problem of the appearance of defects at different printing speeds on halftone materials remains unsolved. In addition, in most works, experimental studies are performed on laboratory devices, which does not allow taking into account vibration phenomena characteristic of industrial machines. In [5], factors affecting ink transfer during flexographic printing, including ink temperature and anilox roller, are studied. It was experimentally found that the ink temperature of 25°C and 30°C was suitable for flexographic printing, while the printing speed and anilox resolution did not affect the ink transfer from the anilox roller to the plate and from the plate to the printed substrates. However, these studies were conducted on a laboratory proofing machine, which cannot realistically reflect the printing conditions in production conditions.

An important feature of the real flexographic process is also the spatial heterogeneity of printing parameters across the width of the web, which is due to the design features of the machine and the distribution of loads in the printing system. However, this factor is practically not taken into account in known studies [6], where the authors consider ensuring the quality of flexographic printing on thin cardboard. The article considers some procedures specific to ensuring the quality of flexographic printing, which were implemented in a printing house, where a thematic study of process certification according to SR EN ISO 9001:2015 was conducted [7].

In [8], the effect of compression flexographic sleeve wear on print quality was investigated. It was found that with increasing sleeve wear, the unevenness of contact pressure increases and the densitometric performance of prints deteriorates. However, the study is limited to relatively low printing speeds and does not consider dynamic vibration phenomena characteristic of high-speed production.

The publication [9] describes methods for controlling and correcting the parameters of the flexographic process (pressure, ink transfer, color stability, control of printing parameters), but the exact numerical values of the printing speed are not given – the speed is considered only as one of the process parameters. The authors conducted experimental studies of the dependence of ink transfer on printing speed on a laboratory IGT device with a printing speed of 20–30 m/min. Therefore, such results cannot realistically reflect the printing process on high-speed machines.

In work [10], an analysis of the gain of the raster dot caused by the interaction of the engraving frequencies of the flexographic form and the anilox roller was carried out. This work revealed that the interference between the rule lines of the form and the anilox can cause a significant undesirable increase in the raster dot. However, the study focuses exclusively on the frequency effects of the form-anilox interaction and does not cover the influence of printing speed and related vibrations on the quality of the print.

The influence of flexographic printing process conditions on optical density and tone gain (TVI) when printing polymer films was studied in [11]. It was found that an increase in pressure and ink viscosity leads to an increase in TVI, and the nature of the dependence is nonlinear. The study was performed at relatively low speeds (up to 100 m/min) on laboratory equipment, so its results cannot be directly transferred to the operating conditions of modern industrial machines with speeds of 400–800 m/min, where the vibration bouncing effect is the determining factor in quality destabilization. In [12], the authors studied the influence of the pressure and characteristics of the anilox roller on the optical density of solid and raster areas of prints. It was shown that an increase in pressure above the optimal value leads to a deterioration in quality due to excessive gain of the raster dot and instability of ink transfer. Despite a thorough analysis of static printing conditions, the study does not cover dynamic operating modes at high speeds and does not consider the influence of vibrations of the machine's structural components on the quality of prints.

Analysis of scientific publications [2–12] showed that for the most part, the authors investigate the problem of ink transfer to film materials by modeling the printing process on proofing devices. However, these results do not reflect real printing processes on high-speed flexographic machines, do not take into account the spatial heterogeneity of the process and vibration phenomena that cannot be adequately assessed in laboratory research conditions.

Thus, the problem of quantitatively determining the influence of flexographic printing speed in high-speed production conditions on print quality parameters remains unresolved.

3. The aim and objectives of the study

The aim of this study is to determine the influence of flexographic printing speed on the manifestation of the bouncing effect. This will make it possible to scientifically substantiate the choice of optimal technological modes of flexographic printing on large-format high-speed machines and reduce the number of production defects caused by vibration defects in the production of packaging products.

To achieve the aim, the following objectives were set:

– to develop a test printing form with a set of elements (solid fills, raster areas, lines, texts, gradients) for the identification and quantitative assessment of vibration defects in flexographic printing;

– to carry out experimental printing of prints on an Optima 2 flexographic machine in the speed range of 100–600 m/min on polypropylene film and conduct a visual analysis of the prints;

– to determine the optical density and dot gain (TVI) in three zones across the width of the web (left, center, right) for 25%, 50%, and 75% bitmap tones at each print speed;

– to conduct a microscopic analysis of the geometric parameters of the lines and the sharpness of the edges of the printing elements to assess the change in the shape of the dot depending on the print speed; the geometry of the printing elements and the deformation of the dot;

– to analyze the dependence of the dot gain on the prints on the print speed and determine the speed ranges with minimal impact of vibrations on the quality of the prints.

4. Materials and methods

The object of the study was prints obtained on the Optima 2 flexographic machine (Soma Engineering, Czech Republic) on a white polypropylene film with a thickness of 20 microns.

The hypothesis of the study was that an increase in the speed of flexographic printing leads to an increase in the amplitude of mechanical vibrations in the printing section, and when critical values are reached, it causes resonance and becomes the main cause of the appearance of the "bouncing effect", which manifests itself in the form of uneven optical density or banding on the prints.

The following assumptions were taken into account in the process of the study:

– the condition of the machine and all mechanisms are in good condition, the shafts are within the passport wear standards and do not have critical defects that could distort the effect of speed; the printing form is mounted without distortions, and the pressure between the anilox, the form cylinder and the printing cylinder are set at the level of "minimum contact";

– the rheological properties of the ink (viscosity and temperature) remain stable throughout the test, and their change due to heating at high speeds is insignificant;

– the thickness and surface tension of the film are identical along the entire length of the roll;

– the compression mounting tape has the same elasticity over the entire area and does not lose its properties during a short-term experiment;

– the location of the printing elements on the form is a critical factor.

– the external sources of vibrations do not affect the amplitude of vibrations of the printing section.

In this study, certain theoretical simplifications were adopted for building models: the anilox roller and the form cylinder are considered as ideal rigid cylinders without taking into account their microgeometry and radial runout, which allows to focus exclusively on the dynamic vibrations caused by the speed regime.

During the test, the same runs were printed at different speeds: 100, 200, 300, 400, 500, 600 m/min. Printing was carried out on an Optima 2 flexographic printing machine manufactured by Soma Engineering on a white polypropylene film with a thickness of 20 microns. Single-color printing was carried out using black ink manufactured by Sun Chemical, Soliflex series. The printing form was made using crystal quartz technology on an XSYS plate. The printing form was mounted using 3M series 1320 mounting tape. The parameters of the anilox roller were: lineature 300 lines/cm, cell volume 6 cm^3/m^2, manufactured by Simec. The Nano 1 doctor blade manufactured by Primeblade (Sweden) was used as a doctor blade.

The methodology of the study was based on the use of test printing plates recommended for assessing print quality defects in flexographic processes [7, 13]. A similar approach to the analysis of vibration defects was used in [11], which emphasizes the influence of design on the occurrence of the bouncing effect and the feasibility of using solid fills, gradients and lines of different thicknesses. Optical density measurements and dot gain were performed in accordance with the requirements of ISO 12647-6 and ISO 13655 standards, which ensures reproducibility and correctness of the results. The obtained print samples were subjected to quantitative analysis using an eXact spectrodensitometer manufactured by X-Rite (Fig. 1). Measurements were carried out in three zones across the width of the web (left, center and right) on prints obtained at each of the six studied print speed values. This allowed to ensure the representativeness of the sample and to identify both general trends and local deviations of quality indicators. To assess the clarity of edges and geometric parameters of lines, microscopic analysis methods were used [14].

To build mathematical models for determining the dependence of TVI on printing speed and position on the film material for different tonal ranges, the response surface method (RSM) was used. To process the results of experimental studies, Excel 2021 and Statistica 12 (USA) programs were used.

Fig. 1. Illustration of the optical density measurement process with an eXact spectrodensitometer

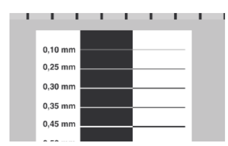
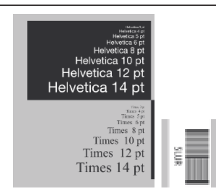
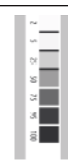
5. Results of studies of the influence of printing speed on the quality of flexographic prints

5. 1. Development and justification of the structure of a test printing plate for identifying vibration defects

A test printing plate was developed for experimental studies, containing a set of special elements for detecting defects caused by vibrations during printing. The test plate included lines of different thicknesses, positive and negative text, solid fill areas, gradient transitions and raster areas with coverage of 25%, 50% and 75% (Table 1). Test elements were placed both at the edges and in the center of the plate to evaluate the rebound effect across the entire width of the web (Fig. 2).

Table 1

Test plate composition and purpose of its elements

No.	Test design elements		Purpose of the test element
1	Lines of varying thickness (0.5–3 mm)		To assess edge contrast (thickness change) in the longitudinal direction at different speeds
2	Lines of positive and negative text and thin horizontal and vertical lines (slur)		To detect "doubling" and edge blurring
3	Solid fill areas (100% coverage) as horizontal stripes		To observe streaks and uneven paint coverage and enhance the bounce effect
4	Gradients (0 to 100%)		To analyze the smoothness and stability of the transition, control the stability of the halftone dot gain
5	Large solid areas of 25% raster		To visually assess vibration effects

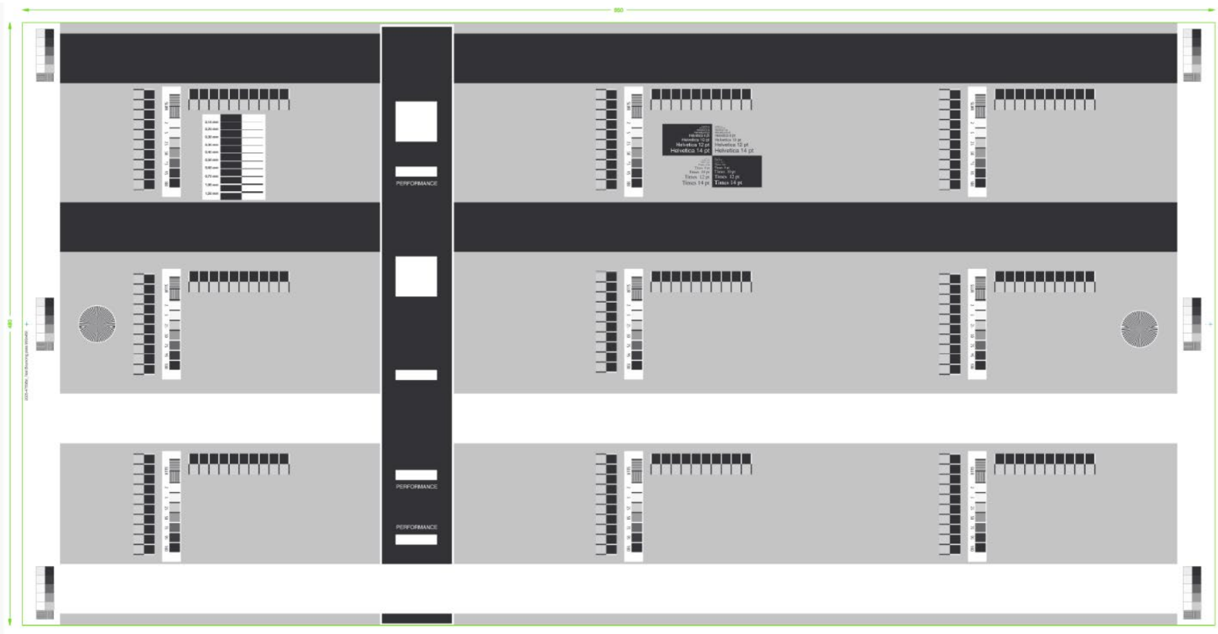


Fig. 2. Placement of test elements on the printing plate along the width of the print (left, center and right zones)

This configuration of the test plate allows not only to visually identify the zones of dynamic impacts, but also to obtain quantitative data on the geometric distortions of the printing elements. The use of raster sections in combination with linear objects of different orientations provides the possibility of a comprehensive analysis of the influence of vibrations on the tone growth (TVI) and the clarity of reproduction of small details. In particular, the duplication of identical elements in three zones of the canvas (left, center, right) is critically important for detecting distortions or uneven pressure in the printing apparatus, which can be amplified when the machine reaches resonant frequencies. Thus, the developed test plate serves as a tool for objectively assessing the stability of the process in the entire studied speed range.

5. 2. Visual analysis of prints on polypropylene film obtained by experimental printing on the Optima 2 flexographic machine in the speed range of 100–600 m/min

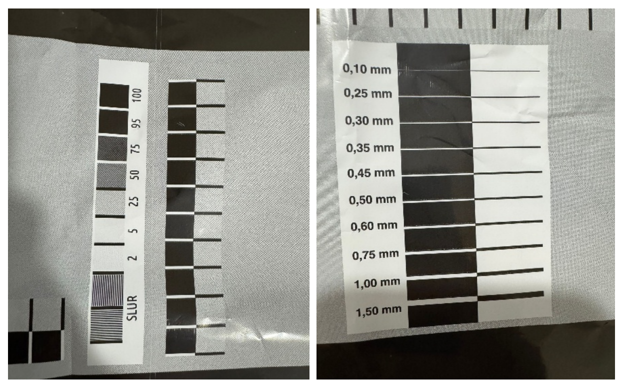
Experimental printing on the Optima 2 flexographic machine allowed to record changes in image quality with an increase in speed from 100 to 600 m/min. Analysis of the prints obtained confirmed that the selected configuration of test elements is quite sensitive to vibration oscillations of the printing system.

Visual inspection of the samples (Fig. 3) allowed to highlight the following features:

– at speeds of 100–300 m/min, the prints are characterized by high print clarity, the absence of visible deformations of raster dots and uniform coverage on solid areas of the fill (plates);

– starting from a speed of 400 m/min, the first signs of the "bouncing effect" appear on the prints: barely noticeable transverse stripes on the plates and gradient transitions. Moreover, the intensity of these manifestations is asymmetrical: in the central zone of the printed substrate, the stability of the print is higher than at the edges;

– at speeds of 500–600 m/min, vibration defects become more pronounced. The phenomenon of "doubling" of thin lines and blurring of the edges of raster dots in the direction of printing is observed.



a *b*

Fig. 3. Samples of flexographic printing prints on polypropylene film: a – sample of print at a speed of 100 m/min; b – sample of print at a speed of 600 m/min

Thus, the visual analysis of the obtained prints indicates the nonlinear nature of the influence of speed on the quality of flexographic printing. This prompts further quantitative assessment of densitometric indicators and dot gain.

5. 3. Assessment of optical density and dot gain (TVI) depending on the printing speed

Based on the statistical processing of the results of experimental studies, a graphical dependence of the change in the optical density of the ink image on the printing speed in different areas of the canvas was constructed. As can be seen from Fig. 4. in the studied speed range of 100–600 m/min, the optical density indicators have insignificant changes: for all zones of the printed web, the optical density values are within 1.40–1.50 D. This indicates the relative stability of the ink transfer process according to this indicator.

However, with increasing printing speed, there is a tendency to a slight decrease in optical density indicators. For example, for the left zone of the web, the optical density decreases from 1.45 at 100 m/min to 1.40 at 600 m/min. A similar situation is observed in the central and right zones, although with less pronounced changes.

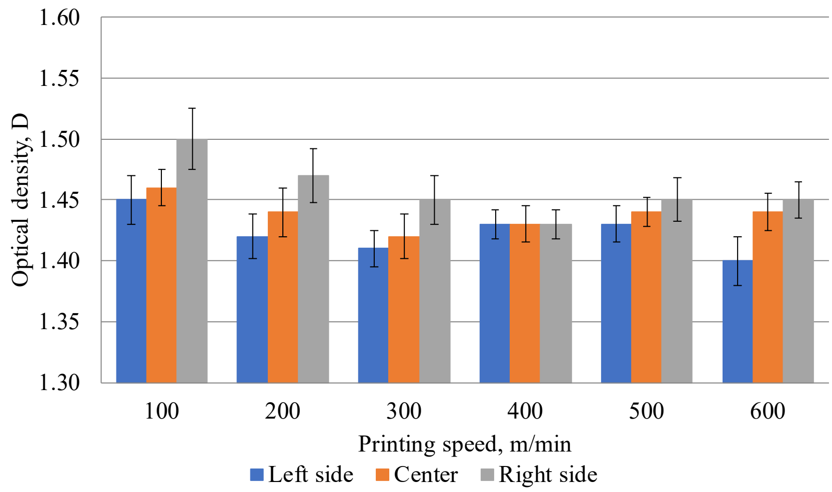


Fig. 4. Dependence of optical density on printing speed in different zones of the printing bed

The obtained results are consistent with the physical nature of the printing process and can be explained by the reduction of the contact time between the printing form and the printed material with increasing speed, which leads to a decrease in the volume of transferred ink. At the same time, it was found that the position on the bed significantly affects the level of optical density. For most speed modes, the highest values are observed in the right zone (up to 1.50 at 100 m/min), while in the left zone they are minimal. The difference between the zones is up to 0.05 D, which exceeds the measurement error and indicates spatial heterogeneity of the printing process.

To quantitatively assess the influence of factors, an analysis of variance (two-factor ANOVA without repetitions) was performed, where the factors were printing speed and position on the bed.

Detailed results of the analysis of variance are presented in Table 2.

The results of the calculations show that:

– the printing speed factor has a limited effect on the optical density

$$F_{speed} = 2.36 < F_{crit} = 3.11,$$

$$p = 0.09;$$

– the position factor on the web is statistically significant

$$F_{position} = 6.42 > F_{crit} = 3.11,$$

$$p = 0.012;$$

– the interaction of factors is not statistically significant

$$F_{interaction} = 1.87 < F_{crit} = 2.68,$$

$$p = 0.15$$

Table 2 shows the results of the analysis of variance (ANOVA) of the optical density of flexographic prints.

Thus, the primary analysis of the results confirms that the variations in optical density are primarily due to the spatial heterogeneity of the process (position on the web).

Table 2

Results of the analysis of variance (ANOVA) of the optical density

Source of variation	Sum of squares (SS)	df	Mean square (MS)	F	p-value
Printing speed	0.0032	5	0.00064	2.36	0.090
Web position	0.0035	2	0.00175	6.42	0.012
Interaction	0.0025	10	0.00025	1.87	0.150
Error	0.0049	18	0.00027	–	–
Total	0.0141	35	–	–	–

5. 4. Results of microscopic analysis of the geometry of printing elements and deformation of raster dots

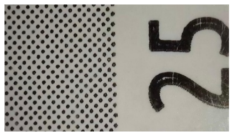
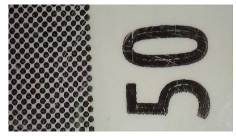
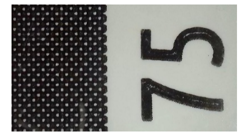
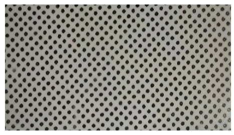
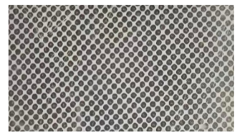
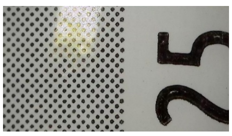
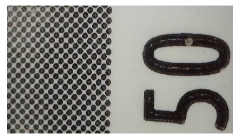
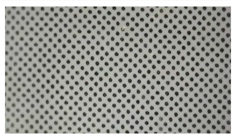
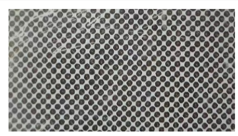
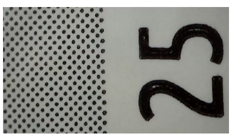
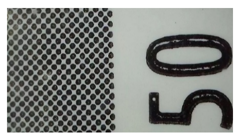
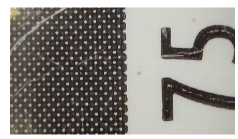
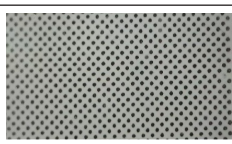
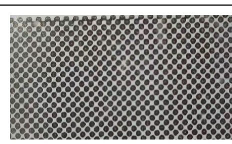
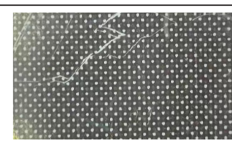
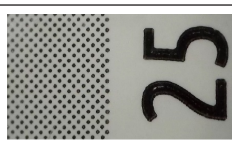
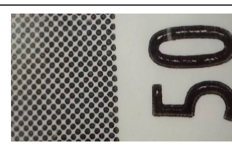
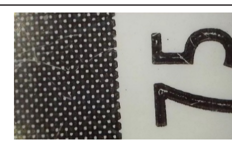
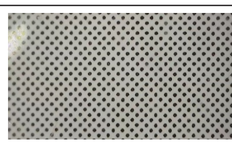
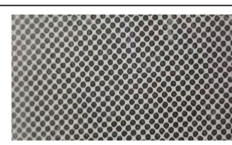
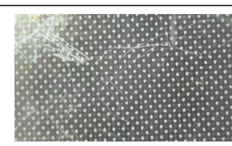
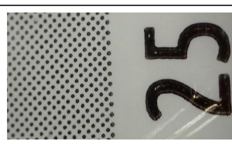
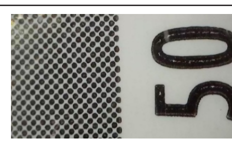
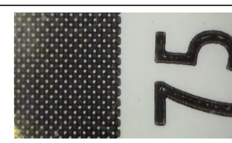
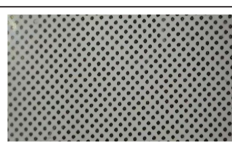
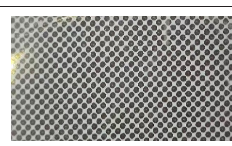
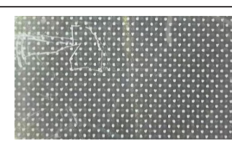
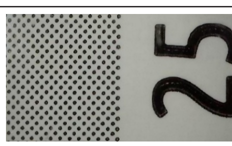
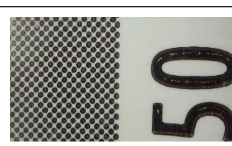
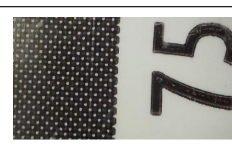
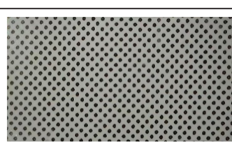
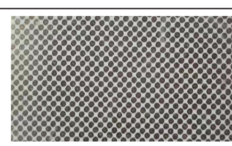
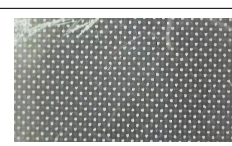
The transition to high printing speeds on the Optima 2 machine is accompanied not only by a change in the intensity of the color, but also by a transformation of the microgeometry of the printing elements. Since densitometric measurements record only averaged light absorption indicators, a microscopic study of the prints was conducted to better understand the nature of the "bouncing effect".

The analysis of the micrographs (Table 3) allows to establish the relationship between the speed of movement of the printed web and the degree of mechanical smearing of the image, which is critical for maintaining the clarity and readability of small text elements, barcodes and QR codes, which are usually present in the labeling of packaging products. For each combination of print speed and tone, two images are presented to compare print stability across the width of the printed material.

Summarizing the results of microscopic studies, it can be stated that the microgeometry of printing elements is the most sensitive indicator of the "bouncing effect". The blurring of contours and the appearance of a characteristic "edging" of the paint recorded at high speeds (500–600 m/min) indicate that vibration shocks cause an instantaneous increase in the specific pressure in the contact zone, which significantly exceeds technologically permissible limits. This leads to the displacement of the paint beyond the boundaries of the printing element and distortion of its area, which is the root cause of the deterioration of image sharpness. The obtained data of the visual analysis of the microstructure of the prints correlate with the results of densitometric measurements and become the basis for further quantitative calculation of the dot gain (TVI), which will allow mathematically describing the effect of speed on the quality of tone reproduction.

Table 3

Micrographs of raster elements of prints obtained at different print speeds for tones of 25%, 50% and 75%

Speed, m/min	Tone 25%	Tone 50%	Tone 75%
100			
			
200			
			
300			
			
400			
			
500			
			
600			
			

5. 5. Results of the analysis of the dependence of the dot gain on prints on the printing speed

The final stage of the study was the establishment of a mathematical dependence between the speed of the Optima 2 machine and the total dot gain (TVI), which made it possible to determine the critical limits of printing stability.

The input variables were the printing speed (x_1, m/min) in the range of 100–600 m/min and the position on the canvas (x_2, discrete factor), which was coded for calculations as follows: –1 (left zone), 0 (center), +1 (right zone). The response function (Y) determined the increment in the size of the raster dot (TVI, %), measured in accordance with the requirements of the ISO 12647-6 and ISO 13655 standards.

The implementation of the active experiment was carried out according to the scheme of a full factorial design with elements of central compositional design (18 experimental points). To minimize random errors and estimate the variance of reproducibility at each point of the plan, three parallel measurements were performed.

Before building regression models, the homogeneity of variances was checked using the Cochrane criterion. The obtained value $G_{exp} = 0.21$ does not exceed the critical $G_{crit} = 0.35$ at the significance level $p = 0.05$, which confirms the homogeneity of the sample. The average variance of reproducibility was $S_y^2 = 0.42$.

Based on the obtained experimental data, mathematical models in the form of second-order polynomials for different tone gradations (25%, 50%, 75%) were constructed. The regression equations in natural variables have the following form:

– for 75% tone

$$TVI_{75} = 18.6 - 0.012\upsilon + {}$$
$$+1.35z + 1.8\cdot10^{-5}\upsilon^2 - 0.92z^2 - 0.0021\upsilon z \; (R^2 = 0.93); \quad (1)$$

– for 50% tone

$$TVI_{50} = 14.2 - 0.009\upsilon + {}$$
$$+ 0.82z + 1.2\cdot10^{-5}\upsilon^2 - 0.55z^2 - 0.0013\upsilon z \; (R^2 = 0.88); \quad (2)$$

– for 25% tone

$$TVI_{25} = 9.8 - 0.004\upsilon + {}$$
$$+ 0.31z + 0.6\cdot10^{-5}\upsilon^2 - 0.21z^2 - 0.0006\upsilon z \; (R^2 = 0.81), \quad (3)$$

where υ – printing speed (m/min); z – position of the control zone on the web.

The adequacy of the models is confirmed by the Fisher criterion. The calculated value $F_{exp} = 2.14$ is less than the critical $F_{crit} = 3.05$ ($f_1 = 12$, $f_2 = 36$, $p = 0.05$), which indicates a high convergence of the theoretical models with experimental data. The variance of inadequacy is $S_{ad}^2 = 0.67$.

The analysis of the obtained equations indicates a different nature of the influence of factors depending on the relative area filling of the raster elements. The greatest sensitivity to changes in technological parameters is observed in the deep shadow zone (75%), which is confirmed by high values of the coefficients for linear and quadratic terms. The negative coefficient for speed (a_1) indicates a tendency to decrease TVI with increasing printing speed, which is explained by the reduction of the contact time of the form with the printed material and the dynamics of ink transfer.

The presence of a significant interaction term υ_z indicates spatial heterogeneity of the process: the effect of speed on gain is manifested differently in the central and peripheral zones of the web, which is probably due to the structural rigidity of the form roller and the features of the dynamic load in the printing contact zone.

This approach allows not only to assess the individual influence of factors, but also to identify their interaction and nonlinear effects.

The data shown in Fig. 5 indicate a decrease in TVI values with increasing printing speed, which may be associated with a decrease in the contact time of the printing form with the material. A similar trend, although less pronounced, is observed for tones of 50% and 25% (Fig. 6, 7). To quantitatively describe the identified dependencies and assess the contribution of individual factors – printing speed and position on the web – the Response Surface Methodology (RSM) was applied using a second-order quadratic regression model.

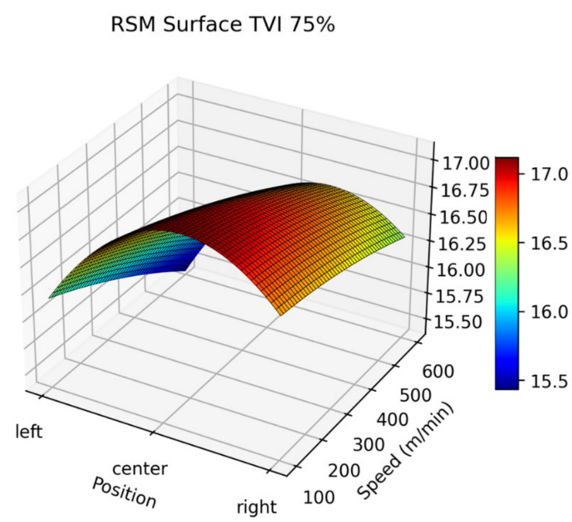


Fig. 5. 3D model of the response surface of the halftone dot gain (Tone Value Increase TVI) for a tone of 75% depending on the printing speed and position on the film

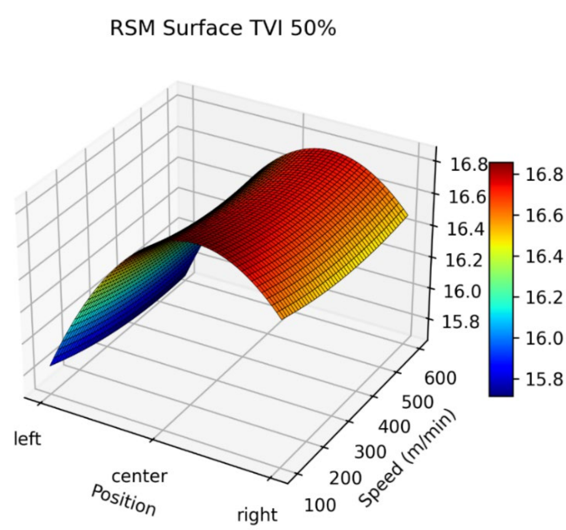


Fig. 6. 3D model of the response surface of the halftone dot gain (Tone Value Increase TVI) for a tone of 50% depending on the printing speed and position on the film

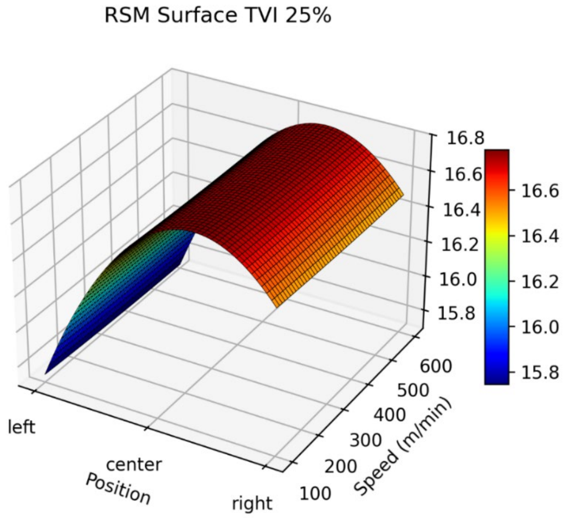


Fig. 7. 3D model of the response surface of the halftone dot gain (Tone Value Increase TVI) for a tone of 25% depending on the printing speed and position on the film

The constructed 3D model of the response surface of the halftone dot gain for the 75% tone has a pronounced nonlinear character with the presence of a local maximum of TVI in the central zone of the film, which is preserved in a wide range of speeds.

The response surface for the middle tone (50%) has a less pronounced curvature, which indicates partial linearity of the process. There is a decrease in the intensity of the positional factor compared to the 75% tone. The gain indicator changes quite smoothly over the entire speed range. This indicates that when printing middle tones, the system is less vulnerable to changes in operating parameters.

The highest stability is recorded for areas of light tones (25%), where the response surface is almost flat, which indicates the absence of significant nonlinear effects.

6. Discussion of the results of the study of the influence of printing speed on the manifestation of the bouncing effect

Analysis of the obtained results of experimental studies and constructed regression models allows to establish a quantitative relationship between the dynamics of the printing machine and the stability of image reproduction.

The recorded decrease in TVI values by 15–25% at a speed of 600 m/min (Fig. 2, 3) can be explained by the reduction in the contact time between the printing form and the substrate. The results obtained in this study indicate a pronounced nonlinear nature of the process depending on the tonality. In particular, the most significant changes were recorded for the tone of 75% ($R^2 = 0.93$), which are visualized by a rapid decline when passing beyond the limit of 400 m/min on the corresponding 3D response surface (Fig. 6).

The spatial heterogeneity of prints discovered, which received clear statistical confirmation (Table 2), deserves special attention. The calculations show that the position factor on the web is critically important ($F = 6.42$ with a much smaller F_{crit}) and is manifested in the discrepancies in the optical density values between the left and right edges, which is seen in Fig. 4.

It was found that the "bouncing effect" is not limited only to longitudinal vibrations, as previously thought. It also provokes a transverse skew of dynamic pressure. This observation allows to clarify and expand the conclusions of colleagues [10, 11] regarding the physical nature of contact in the printing zone. It becomes obvious that the dynamics of the printing machine at high speeds is much more complex and multi-vector.

A detailed analysis of micrographs (Fig. 5) allowed to identify visual manifestations of the "bouncing effect", such as banding and doubling of small elements. The nature of these defects is consistent with the constructed regression levels (1)–(3), which clearly indicate a rapid increase in system instability with an increase in printing speed above 450 m/min.

The constructed 3D surfaces (Fig. 6–8) allowed to clearly distinguish the operating modes for different gradation areas. At printing speeds of 100–350 m/min (the zone of "technological calm"), the process remains maximally controlled, and the print quality is stable. When the speed increases above 500 m/min (the critical risk zone), a mode appears in which vibration oscillations become the dominant factor, which requires special attention to the settings or correction of printing parameters. Such localization allows not only to fix the defect, but also to consciously choose the appropriate operating modes of the equipment to obtain a high-quality result.

The significance of the obtained results of the study lies in proving that when switching to ultra-high speeds, the dominant influence factor changes. If in normal modes the quality of the print is mainly influenced by the rheological properties of the ink or the adhesive properties of the substrate, then in extreme speed ranges the vibration component comes to the fore. It is it that becomes the main cause of the deformation of the raster structure.

The developed regression models can be integrated into prepress systems for dynamic adjustment of TVI compensation curves. This will allow adapting the release parameters directly to the target printing speed, ensuring stable print quality.

However, it is worth considering certain limitations of this stage, which relate to the use of ideal geometry of printing cylinders. Therefore, further study can be focused on studying radial runout and its interference with the frequency of the form "bounce". It is also important to build complex multifactor models that will take into account not only the speed, but also the operating pressure, rheological characteristics of the inks and specifications of the anilox rollers. Such an approach will allow creating a comprehensive digital model of the dynamic stability of the flexographic printing process.

7. Conclusions

1. For experimental study, a special test printing form was developed, which contains a combination of different types of elements: dies, raster fields (25%, 50%, 75%), microtexts and lines. The diversity of test objects allowed for a deep quantitative assessment of defects: to analyze geometric distortions and changes in optical parameters in each tonal zone – from the lightest areas to deep shadows. This made it possible to establish how the dynamics of the machine affect image reproduction in the entire range of tonal reproduction.

2. Analysis of flexographic printing impressions obtained on the Optima 2 machine on polypropylene film allowed to identify defects that occur at speeds above 400 m/min and are caused by the "bouncing effect". The appearance of clearly

pronounced banding and doubling of small elements indicates that at high speeds the system goes beyond the limits of technological stability. Such a critical mode is unacceptable for the production of high-quality packaging products, where the accuracy of reproduction of small elements is a key requirement.

3. It was established that the increase in tone value (TVI) is distributed unevenly across the width of the web. The left and right edge zones were the most vulnerable, where, when the printing speed increased to 500–600 m/min, a sharp decrease in TVI by 15–25% was recorded relative to the speed of 100 m/min. The optical density indicators at this moment remained almost unchanged within 1.40–1.50 D. This proves that dynamic vibrations primarily affect the microstructure of the raster, while the total amount of ink on the print does not change significantly. Thus, control only over the optical density at high printing speeds may be uninformative, since it does not reflect the real degradation of the raster dot.

4. Microscopic analysis confirmed significant deformation of the geometry of printing elements with increasing speed. Dynamic vibrations of the system cause not only distortion of the shape of the raster dot itself, but also a noticeable blurring of its contours. These visual observations were mathematically substantiated by constructing second-order regression models. In the range of 75% of the tone ($R^2 = 0.93$), the maximum degree of nonlinear deformation was recorded. The "bouncing effect" becomes so intense that it provokes a specific "merger" of dots in the direction of printing. This indicates that at high speeds the dynamics of the printing apparatus completely violates the stability of the microcontact.

5. Based on the analysis of the constructed response surfaces, the operation of the printing system is clearly delimited into the following optimal technological ranges: a zone of stable printing at a speed of 100–350 m/min with minimal vibration; a transitional printing zone at speeds of 400–500 m/min, which requires preventive correction of compensation curves to eliminate the first manifestations of dynamic instability; a critical risk zone at printing speeds of more than 550 m/min, which leads to uncontrolled loss of quality due to significant deformation of raster structures. Such zoning allows technologists to consciously balance between machine performance and quality requirements of a specific order.

Conflict of interest

The authors declare that they have no conflict of interest in this study, including financial, personal, authorship or other, which could affect the study and its results presented in this article.

Financing

The study was conducted without financial support.

Data availability

The manuscript has no related data.

Use of artificial intelligence

The authors confirm that they did not use artificial intelligence technologies when creating the presented work.

Authors' contributions

Svitlana Havenko: Conceptualization; **Tetiana Telegina**: Methodology, Investigation; **Marta Labetska**: Formal analysis.

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