

UDC 655.326.1

## QUALITY ASSESSMENT OF VARNISH COATING APPLICATION BY FLEXOGRAPHIC PRINTING IN PACKAGING PRODUCTION

R. A. Khokhlova<sup>1</sup>

<sup>1</sup>National University of Food Technologies, 68 Volodymyrska St., 01601, Kyiv, Ukraine, <https://orcid.org/0000-0002-1545-9696>, [khokhlovarozalia@gmail.com](mailto:khokhlovarozalia@gmail.com)



*Creative Commons Attribution 4.0 (CC BY 4.0) License*

*This article investigates the technological conditions for applying functional varnish coatings — a barrier varnish and a heat seal adhesive — to paper substrates by flexographic printing for the manufacture of sustainable packaging. The study was conducted on a Soma Optima 2 flexographic press equipped with an auxiliary IPU (Intelligent Printing Unit) station. The optimum application parameters were established: sequential application of SunBar® OGR barrier varnish and SunFuse® Heat Seal thermosealable adhesive at a print speed of 100 m/min. The influence of anilox roller line count and cell geometry (hexagonal and GTT), pump type, and print speed on dry coat weight and grease resistance of the coatings was investigated. The dependence of heat-seal bond strength on jaw width and sealing temperature was determined. Based on the experimental results, a Pareto diagram was constructed to identify the principal factors influencing the quality of the functional coating.*

**Keywords:** *packaging, flexographic printing, anilox roller, printing press, printing speed, varnish coatings, barrier properties, heat seal, paper packaging.*

**Problem Statement.** Growing public concern about the environmental consequences of plastic packaging — in particular multi-layer polymer films that are virtually non-recyclable — is driving an active search for alternative solutions [1, 2]. At the same time, modern food logistics places ever-increasing demands on the barrier properties of packaging materials: protection against moisture, oxygen, fats, and mechanical damage. Paper packaging with functional varnish coatings represents a promising compromise between ecological sustainability and functional performance.

Paper is one of the oldest and most widely used packaging materials. According to market analysts, paper and board consistently hold leading positions among food-packaging materials owing to their renewability, biodegradability, and recyclability [3]. The key technological challenge in the production of such packaging is the application of functional layers that provide the requisite barrier properties and heat-sealability without materially compromising the ecological profile of the material.

Flexographic printing occupies a dominant position in flexible packaging production. According to Smithers, flexography accounts for more than 60% of global flexible

packaging output, a position attributable to its technological flexibility, compatibility with diverse substrates, and cost-effectiveness at short and medium run lengths [4]. In addition to image printing, flexographic equipment is widely employed for the application of functional coatings — primers, barrier varnishes, and heat seal adhesives.

**Analysis of Recent Research and Publications.** The application of functional coatings to paper substrates by printing methods has attracted considerable research interest in recent years. The influence of paper surface structure on the quality of water-based coating application was thoroughly investigated by Ozcan et al. [5]. The authors established that paper roughness and porosity directly affect the uniformity of water-borne varnish distribution: on more porous surfaces the varnish penetrates deeper into the fibre structure, which can reduce the effective dry coat weight at the surface and create non-uniformity of the barrier layer. These patterns are consistent with the results obtained in the present study for the 70 and 80 g/m<sup>2</sup> papers.

Aghamohammadi [6] analyses four key factors governing the functional properties of coatings on board packaging: the chemical composition of the varnish, the applied coating volume, the substrate grammage, and the parameters of the sealing equipment. The author concludes that increasing the number of varnish layers during flexographic printing improves water resistance and heat-sealability; however, the study does not examine in detail the influence of anilox roller parameters or pump-system type on the quality of varnish transfer.

The effect of anilox roller cell geometry on coating quality in the flexographic process was investigated by Theohari et al. [7]. The authors demonstrated that the selection of an anilox with an appropriate cell volume and geometry has a significant influence on the uniformity of ink lay-down and on the attainability of the target dry coat weight. The study shows that open-channel geometries (including the GTT type) deliver more stable transfer when applying higher-viscosity materials, whilst simultaneously reducing the tendency of the ink system towards foam formation.

The heat-sealing properties of water-dispersion-based coatings were studied in detail by Ilhan et al. [8]. The review highlights the decisive influence of jaw width, contact dwell time, and temperature on seal bond strength. It was established that the optimum sealing temperature depends on the chemical composition of the thermoplastic polymer within the coating and on the substrate grammage. The authors also emphasise the role of seam cooling: excessively prolonged cooling at elevated temperatures can cause thermal degradation of the coating and a reduction in seal strength.

Thus, notwithstanding the body of research in related fields, a comprehensive assessment of the combined influence of anilox roller parameters, pump type, print speed, and functional varnish combinations on coating quality under real production conditions on modern flexographic equipment remains a pertinent task.

**Aim of the Research.** The aim of the study is to determine the optimum technological parameters for the application of barrier and heat-seal varnish coatings by flexographic printing onto paper substrates for the manufacture of functional food packaging.

To achieve this aim, the following objectives were set:

- 1) to investigate the influence of functional varnish combinations and print speed on dry coat weight;

- 2) to evaluate the grease resistance of applied coatings as a function of varnish type and substrate grammage;
- 3) to determine the influence of sealing equipment parameters (jaw width, dwell time, cooling, and temperature) on heat-seal bond strength;
- 4) to identify the principal factors influencing coating quality by means of a Pareto diagram.

**Presentation of the Main Research Material.** The study was conducted on a Soma Optima 2 (Soma Engineering, Czech Republic) central-impression flexographic press. The machine is equipped with an auxiliary IPU (Intelligent Printing Unit) station comprising a small central impression cylinder and two flexographic units, intended for the application of functional coatings. The IPU station enables functional varnishes to be applied simultaneously to the reverse side of the web whilst a four-colour image is printed on the front side on the main press units — an arrangement that was employed throughout this investigation.

Two types of kraft paper for food packaging were used: Billerud Sack Kraft 70 g/m<sup>2</sup> (Billerud, Sweden) and Endura MG Kraft 80 g/m<sup>2</sup> (Stora Enso, Finland). The 70 g/m<sup>2</sup> paper exhibited higher porosity and lower surface smoothness compared with the 80 g/m<sup>2</sup> paper.

A water-based barrier varnish SunBar® OGR (Sun Chemical, United Kingdom) — a copolymer-dispersion formulation providing protection against the penetration of fats and oils (OGR), a degree of moisture vapour transmission resistance (MVTR), and low water absorption — was applied. The recommended dry coat weight is 2.0–3.5 g/m<sup>2</sup>. A water-based heat seal adhesive SunFuse® Heat Seal (Sun Chemical, United Kingdom), certified for direct food contact, was also used. The varnish is based on a copolymer dispersion and a stabilised vegetable-wax emulsion; it provides heat-sealing capability from 75°C under heat and pressure and is designed for application to paper and board substrates by flexographic or gravure printing.

To reduce the porosity of the 70 g/m<sup>2</sup> paper, a water-based primer SunBar® Barrier Primer (Sun Chemical) — an acrylate-dispersion material with a degree of grease and water resistance — was applied at the first IPU station prior to the heat seal layer.

Digital photopolymer printing plates XSYS nyloflex® FTM Digital, 1.14 mm thick, designed for solid-area imprints, were used throughout. Plates were mounted on 3M™ E1020 medium-hardness mounting tape.

At the first IPU station (cell volume 18 cm<sup>3</sup>/m<sup>2</sup>) and the second IPU station (cell volume 25 cm<sup>3</sup>/m<sup>2</sup>), conventional hexagonal-cell anilox rollers were used initially. In the second test series, one IPU station roller was replaced with a GTT (Gravure Trihelic Technology, Apex International) open-channel-geometry roller. A membrane pump was used initially; for comparison, a Verder peristaltic pump was substituted during testing.

The experiments were conducted in three series. In the first series (Table 1), functional varnish combinations and print speeds of 100 and 200 m/min were varied to assess the influence of these parameters on dry coat weight. In the second and third series (Tables 2 and 3), the print speed was 300 m/min — representative of typical industrial

high-speed production conditions — and grease resistance and heat-sealing properties of the resulting coatings were investigated.

Tests were conducted in four varnish combination configurations. In all tests, dry coat weight was measured gravimetrically (ISO 287) [9]. Grease resistance was evaluated using the OGR (oil and grease resistance) criterion with sunflower oil, assessed after 1, 4, and 24 h contact, scored from 0 (no protection) to 5 (excellent protection). Heat sealing was carried out on a laboratory sealer with controlled jaw width, temperature (70–210°C), dwell time, and cooling parameters. For evaluation of heat-sealing properties, 70 g/m<sup>2</sup> paper samples were selected as the more demanding substrate: its higher porosity and lower surface smoothness create more challenging conditions for seam formation, thereby yielding a conservative assessment of the minimum permissible sealing parameters. Seal strength was rated from 0 (no seal) to 5 (complete fibre tear).

The results of the four tests varying functional varnish combinations are presented in Table 1. A comparison of tests 2 and 3 (both IPU stations applying heat seal, at 100 and 200 m/min respectively) showed a reduction in dry coat weight from 5.9 to 4.9 g/m<sup>2</sup> when speed was doubled. This confirms the expected effect: shorter contact time between the anilox roller, the printing plate, and the substrate at higher speeds reduces the volume of varnish transferred.

Table 1

**Test matrix: varnish combinations and print speeds**

Test No.	Dry residue (g/m <sup>2</sup> )	Varnish — Station 1 (anilox 18 cm <sup>3</sup> /m <sup>2</sup> )	Varnish — Station 2 (anilox 25 cm <sup>3</sup> /m <sup>2</sup> )	Print speed (m/min)
1	2.6	SunFuse® Heat Seal	—	100
2	5.9	SunFuse® Heat Seal	SunFuse® Heat Seal	100
3	4.9	SunFuse® Heat Seal	SunFuse® Heat Seal	200
4	5.9	SunBar® OGR	SunFuse® Heat Seal	100

Note: “—” denotes no varnish applied at that station.

Test 4 (barrier varnish + heat seal at 100 m/min) achieved the same total dry coat weight of 5.9 g/m<sup>2</sup> as test 2 (two layers of heat seal), but differed qualitatively: the lower barrier-varnish layer effectively sealed the paper pores, providing a more uniform substrate for the heat seal layer.

During the tests it was established that replacing the membrane pump with a peristaltic pump and replacing the hexagonal-cell anilox with a GTT-geometry roller substantially reduced foam formation in the ink reservoir and stabilised varnish delivery, thereby improving the uniformity of dry coat weight across the width of the printed web.

The results of the grease-resistance evaluation as a function of substrate type and varnish are presented in Table 2. Unprinted samples of both papers exhibited no protection against oil (score 0 at all time points).

Table 2

**Results of functional varnish application at different print speeds**

No.	Substrate	Coating	Speed (m/min)	Dry residue (g/m <sup>2</sup> )	OGR 1 h	OGR 4 h	OGR 24 h
1	Paper 70 g/m <sup>2</sup>	Uncoated	—	—	0	0	0
2	Paper 80 g/m <sup>2</sup>	Uncoated	—	—	0	0	0
3	Paper 70 g/m <sup>2</sup>	SunBar® OGR	100	2.8	5	4	3
4	Paper 80 g/m <sup>2</sup>	SunBar® OGR	100	2.3	3	2	2
5	Paper 70 g/m <sup>2</sup>	SunFuse® Heat Seal	300	5.9	1	1	1
6	Paper 80 g/m <sup>2</sup>	SunFuse® Heat Seal	300	5.4	1	1	1

Note: 0 — no grease protection; 5 — excellent grease resistance (OGR score).

SunBar® OGR barrier varnish demonstrated significantly higher grease resistance compared with the heat seal varnish. On 70 g/m<sup>2</sup> paper with a dry coat weight of 2.8 g/m<sup>2</sup>, the initial OGR score was 5 (excellent), declining to 3 after 24 h. On 80 g/m<sup>2</sup> paper (dry coat weight 2.3 g/m<sup>2</sup>), the corresponding scores were 3 and 2. This indicates that the higher porosity of the 70 g/m<sup>2</sup> paper enables a greater quantity of varnish to be absorbed, though the uniformity of distribution is lower. Notably, the grease resistance of the heat seal varnish remained at a minimum level (score 1), which is expected, as heat seal is not designed to provide oil-resistance functionality.

These data highlight an important practical conclusion: for packaging of fat-containing food products, application of a barrier underlayer prior to the heat seal is essential. The combination in test 4 (barrier varnish + heat seal) is optimum from the standpoint of achieving both grease resistance and heat-sealability.

The results of the dependence of heat-seal bond strength on sealing conditions for 70 g/m<sup>2</sup> paper samples with applied heat seal varnish (at 300 m/min) are presented in Table 3.

Table 3

**Dependence of fibre-tear bond strength on sealing conditions**

Sample	Sealing conditions	70°C	90°C	110°C	130°C	150°C	170°C	190°C	210°C
Paper 70 g/m <sup>2</sup> , SunFuse® Heat Seal, 300 m/min	Jaw 25 mm, dwell 0.5 s	0	1	3	4	5	5	5	5
	Jaw 5 mm, dwell 0.2 s, cooling 0.5 s	0	0	0	2	3	3	2	2
	Jaw 25 mm, dwell 0.5 s, cooling 0.3 s	0	2	3	3	3	2	0	0

Note: 0 — no seal formed; 5 — maximum seal strength (complete fibre tear).

Analysis of the results shows that the best heat sealing (score 5 at 150–210°C) is achieved with a wide 25 mm jaw and a 0.5 s dwell time without forced cooling. Use of a narrow 5 mm jaw with a short dwell time (0.2 s) and 0.5 s cooling reduces the maximum score to 3 and shifts the optimum temperature range towards 150–170°C. Forced cooling with a 25 mm jaw and a 0.3 s hold leads to thermal degradation of the seal above 150°C — the score drops sharply to 0, which constitutes a critical defect for hermetically sealed packaging.

It was established that in all positive cases, failure occurred through the paper fibres rather than through the seam, indicating adequate adhesion of the heat seal varnish to the substrate. Consequently, the bond strength of the seal is limited by the strength of the paper itself rather than by the adhesive properties of the varnish.

To systematise the influence of the various technological parameters on the quality of the functional coating, a Pareto diagram was constructed (Fig. 1). The parameters analysed were: choice of varnish combination, print speed, anilox cell geometry (GTT vs. hexagonal), pump type, substrate grammage, and sealing conditions.

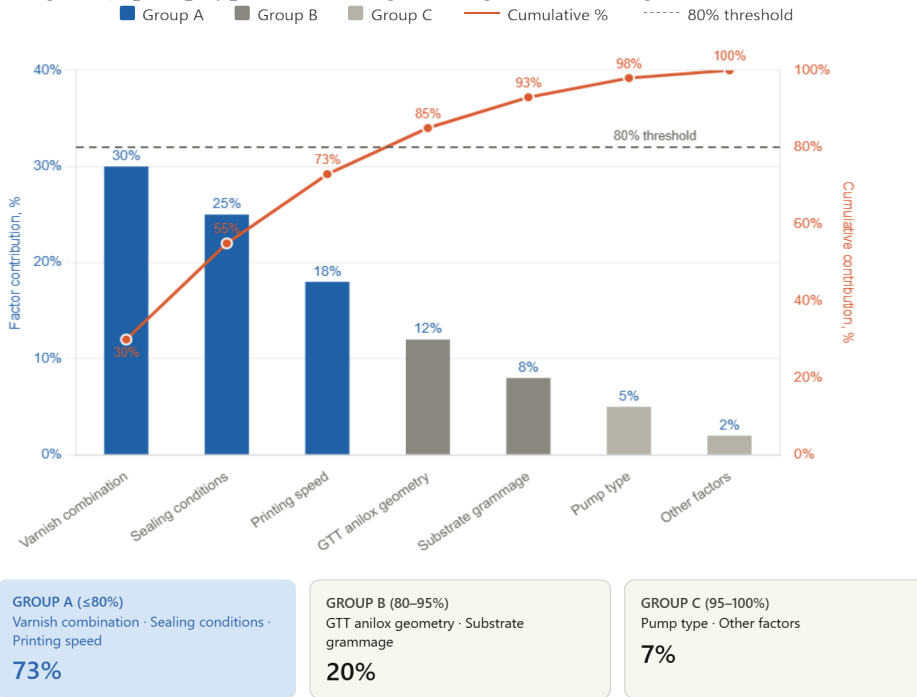


Fig. 1. Pareto diagram of the principal factors influencing varnish coating quality in flexographic application

Analysis results show that three key factors account for the greatest influence on functional coating quality (73% of combined contribution): choice and sequence of varnish application (30%), sealing equipment parameters (25%), and print speed (18%). These factors form Group A in the Pareto framework and are the priority targets for process optimisation. GTT anilox roller technology and paper grammage are Group B factors (combined 20%), whilst pump type and other parameters constitute Group C (7%).

**Conclusions.** As a result of the experimental investigation, the following conclusions were drawn:

1. The optimum technological solution for the production of functional paper packaging is the sequential application of two varnish layers: SunBar® OGR barrier varnish (IPU Station 1, anilox 18 cm<sup>3</sup>/m<sup>2</sup>) followed by SunFuse® Heat Seal thermosealable adhesive (IPU Station 2, anilox 25 cm<sup>3</sup>/m<sup>2</sup>), applied at a print speed of 100 m/min. This combination provides a dry coat weight of 5.9 g/m<sup>2</sup>, grease resistance OGR ≥ 4, and reliable heat sealing.

2. Increasing the print speed from 100 to 200 m/min reduces dry coat weight by approximately 17% (from 5.9 to 4.9 g/m<sup>2</sup>) as a result of the reduced varnish transfer time from the anilox roller to the substrate.

3. Replacing a membrane pump with a peristaltic pump and adopting a GTT-geometry anilox roller in place of a hexagonal-cell roller substantially reduces foam formation in the ink reservoir and improves the stability of varnish delivery, with a positive effect on coating uniformity.

4. Paper with a lower grammage (70 g/m<sup>2</sup>) and higher porosity absorbs a greater quantity of varnish, yielding a higher initial grease-resistance score (OGR 5); however, protection declines to a score of 3 after 24 h, compared with a score of 2 for the 80 g/m<sup>2</sup> paper.

5. Maximum heat-seal bond strength (score 5, complete fibre tear) is achieved with a jaw width of 25 mm, a dwell time of 0.5 s, and a sealing temperature of 150–210°C without forced cooling. Prolonged post-seal cooling at elevated temperatures adversely affects seal strength.

6. Pareto analysis reveals that three factors — varnish combination and sequence, sealing equipment parameters, and print speed — account for 73% of the combined influence on functional coating quality and are the priority targets for process optimisation.

#### СПИСОК ВИКОРИСТАНИХ ДЖЕРЕЛ

1. The influence of packaging attributes on recycling and food waste behaviour — an environmental comparison of two packaging alternatives / F. Wikström, H. Williams, G. Venkatesh. *Journal of Cleaner Production*. 2016. Vol. 137. P. 895–902. DOI: 10.1016/j.jclepro.2016.07.097.
2. Bertling J., Hamann L., Bertling R. *Kunststoffe in der Umwelt: Mikro- und Makroplastik*. Fraunhofer UMSICHT, 2018. 128 p. DOI: 10.24406/UMSICHT-N-497117.
3. Europe Paper Packaging Market. URL: <https://www.marketdataforecast.com/market-reports/europe-paper-packaging-market> (дата звернення: 12.05.2026).
4. The Future of Flexographic Printing to 2029. *Leatherhead : Smithers Pira*, 2025. 187 p. URL: <https://www.smithers.com/services/market-reports/printing/the-future-of-flexographic-printing-to-2029> (дата звернення: 12.05.2026).
5. Ozcan A., Sonmez S., Tutak D. Effect of coating pigment type on paper printability with water-based inks. *Journal of Coatings Technology and Research*. 2022. Vol. 19. P. 1149–1157. DOI: 10.1007/s11998-021-00593-8.
6. Aghamohammadi G. The functional properties of the coating lacquers in disposable cup-making : Lappeenranta–Lahti University of Technology LUT. 2023. 97 p. URL: [https://lutpub.lut.fi/bitstream/handle/10024/165944/Aghamohammadi\\_Golnoosh.pdf](https://lutpub.lut.fi/bitstream/handle/10024/165944/Aghamohammadi_Golnoosh.pdf) (дата звернення: 12.05.2026).

7. Theohari I., Politis I., Gkikas D. Effect of paper properties on print quality by flexographic method. *Proceedings of the International Circle of Educational Institutes for Graphic Arts Technology and Management*. 2022. P. 1–10. URL: [https://www.internationalcircle.net/wp-content/uploads/2022/02/06-theohari\\_Effect-of-paper-properties-on-print-quality-by-flexographic-method-1.pdf](https://www.internationalcircle.net/wp-content/uploads/2022/02/06-theohari_Effect-of-paper-properties-on-print-quality-by-flexographic-method-1.pdf) (дата звернення: 12.05.2026).
8. Understanding the factors affecting the seal integrity in heat sealed flexible food packages: A review / I. Ilhan, D. Turan, I. Gibson, R. ten Klooster. *Packaging Technology and Science*. 2021. Vol. 34, No. 6. P. 321–337. DOI: 10.1002/pts.2564.
9. Папір та картон. Визначення вологості. Метод висушування в сушильній шафі (EN ISO 287:2009; ISO 287:2009, IDT) : ДСТУ EN ISO 287:2017. [Чинний від 2017-01-01]. Київ : ДП «УкрНДНЦ», 2017. 18 с.

### REFERENCES

1. Wikström, F., Williams, H., & Venkatesh, G. (2016). The influence of packaging attributes on recycling and food waste behaviour — an environmental comparison of two packaging alternatives. *Journal of Cleaner Production*, 137, 895–902. <https://doi.org/10.1016/j.jclepro.2016.07.097>.
2. Bertling, J., Hamann, L., & Bertling, R. (2018). *Kunststoffe in der Umwelt: Mikro- und Makroplastik*. Fraunhofer UMSICHT. <https://doi.org/10.24406/UMSICHT-N-497117>.
3. Europe Paper Packaging Market. (n.d.). MarketDataForecast. <https://www.marketdataforecast.com/market-reports/europe-paper-packaging-market>.
4. Smithers. (2025). *The Future of Flexographic Printing to 2029*. Smithers. <https://www.smithers.com/services/market-reports/printing/the-future-of-flexographic-printing-to-2029>.
5. Ozcan, A., Sonmez, S., & Tutak, D. (2022). Effect of coating pigment type on paper printability with water-based inks. *Journal of Coatings Technology and Research*, 19, 1149–1157. <https://doi.org/10.1007/s11998-021-00593-8>.
6. Aghamohammadi, G. (2023). *The functional properties of the coating lacquers in disposable cup-making* [Bachelor thesis, LUT University]. LUT Institutional Repository. [https://lutpub.lut.fi/bitstream/handle/10024/165944/Aghamohammadi\\_Golnoosh.pdf](https://lutpub.lut.fi/bitstream/handle/10024/165944/Aghamohammadi_Golnoosh.pdf).
7. Theohari, I., Politis, I., & Gkikas, D. (2022). Effect of paper properties on print quality by flexographic method. *Proceedings of the International Circle of Educational Institutes for Graphic Arts Technology and Management*, 1–10. [https://www.internationalcircle.net/wp-content/uploads/2022/02/06-theohari\\_Effect-of-paper-properties-on-print-quality-by-flexographic-method-1.pdf](https://www.internationalcircle.net/wp-content/uploads/2022/02/06-theohari_Effect-of-paper-properties-on-print-quality-by-flexographic-method-1.pdf).
8. Ilhan, I., Turan, D., Gibson, I., & ten Klooster, R. (2021). Understanding the factors affecting the seal integrity in heat sealed flexible food packages: A review. *Packaging Technology and Science*, 34(6), 321–337. <https://doi.org/10.1002/pts.2564>.
9. DSTU EN ISO 287:2017 *Paper and Board. Determination of Moisture Content. Oven-Drying Method* (EN ISO 287:2009; ISO 287:2009, IDT).

doi: 10.32403/2411-3611-2026-1-49-92-100

### ОЦІНЮВАННЯ ЯКОСТІ НАНЕСЕННЯ ЛАКОВИХ ПОКРИТТІВ МЕТОДОМ ФЛЕКСОГРАФІЧНОГО ДРУКУ ПРИ ВИГОТОВЛЕННІ ПАКОВАНЬ

Р. А. Хохлова<sup>1</sup>

<sup>1</sup>Національний університет харчових технологій, вул. Володимирська 68, 01601, м. Київ-33, Україна, <https://orcid.org/0000-0002-1545-9696>, [khokhlovarozalia@gmail.com](mailto:khokhlovarozalia@gmail.com)

У статті досліджено технологічні умови нанесення функціональних лакових покриттів — бар'єрного лаку та термозварювального адгезиву (*heat seal*) — на паперові субстрати методом флексографічного друку для виготовлення екологічного харчового пакування. Дослідження виконано на флексографічній машині *Soma Optima 2* із центральним друкарським циліндром (*Soma Engineering*, Чеська Республіка), оснащений допоміжною секцією IPU (*Intelligent Printing Unit*), що складається з двох флексографічних секцій і забезпечує одночасне нанесення функціональних лаків зі зворотного боку субстрату під час чотирьохфарбового друку. Для досліджень використано два крафт-папери граматурою 70 г/м<sup>2</sup> та 80 г/м<sup>2</sup>. Застосовано водний бар'єрний лак *SunBar® OGR* та водний термозварювальний адгезив *SunFuse® Heat Seal* (обидва виробництва *Sun Chemical*, Великобританія). Досліджено вплив комбінацій лаків (тільки бар'єрний лак; тільки *heat seal*; два шари *heat seal*; бар'єрний лак + *heat seal*), геометрії комірки анілоксого валика (гексагональна та ГТТ з відкритим каналом), типу насосу (мембранний і перистальтичний) та швидкості друку (100–300 м/хв) на масу сухого залишку покриття, жиростійкість і міцність термозварювального шва у діапазоні температур зварювання 70–210°C. Встановлено, що оптимальними параметрами є послідовне нанесення *SunBar® OGR* (секція 1 IPU, анілокс 18 см<sup>3</sup>/м<sup>2</sup>) з наступним нанесенням *SunFuse® Heat Seal* (секція 2 IPU, анілокс 25 см<sup>3</sup>/м<sup>2</sup>) на швидкості 100 м/хв, що забезпечує загальну масу сухого залишку 5,9 г/м<sup>2</sup>, жиростійкість  $OGR \geq 4$  та надійне термозварювання. Заміна гексагонального анілоксу на ГТТ-валик, а мембранного насосу — на перистальтичний суттєво знизила піноутворення у фарбовому резервуарі та покращила рівномірність покриття. Максимальна міцність зварного шва досягається при ширині затискача 25 мм, часі затиску 0,5 с і температурах зварювання 150–210°C без примусового охолодження. Аналіз діаграми Парето підтвердив, що три чинники — комбінація та послідовність нанесення лаків (30%), параметри зварювального обладнання (25%) та швидкість друку (18%) — визначають 73% сукупного впливу на якість функціонального покриття.

**Ключові слова:** пакування, флексографічний друк, анілоксний валик, друкарська машина, швидкість друку, лакові покриття.

Стаття надійшла до редакції: 12.05.2026.

Submitted: 12.05.2026.

Прийнято до друку: 15.05.2026.

Accepted: 15.05.2026.

Опубліковано: 20.05.2026.

Published: 20.05.2026.