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# Influence of Halftone Dot Geometry on Dot Gain and Tone Reproduction in Flexographic Printing on Aluminium Foil

**ABSTRACT**

*This study investigates the influence of halftone dot geometry on dot gain and tone reproduction in UV flexographic printing on non-absorbent aluminium foil 20 µm thick. Two screening technologies were compared — conventional regular round dots (AM) and a fractal structure. The microstructure of the imprints was examined by optical microscopy (150× magnification), followed by analysis of dot perimeter and area in the DinoCapture 2.0 software environment; the effective dot area was determined densitometrically for nominal tone values from 1 to 99%. The fractal screen was found to exhibit substantially higher dot gain in the midtone region (a maximum of ΔA = +23.8% at the 50% tint, compared with +6.1% for the round screen), whereas in the highlight region (1–5%) the fractal structure provided better isolation of individual dots and lower dot gain. Regression models of the dot-gain curves were developed; the best fit to the experimental data ($R^2$ = 0.93–0.99) was achieved by a third-degree polynomial and a smoothing spline. The results confirm the perimeter-driven ink-squeeze mechanism as the dominant factor in dot gain on metallised non-absorbent substrates and indicate the need to construct separate dot-gain compensation curves (DGC) for fractal screening in foil flexography.*

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**KEY WORDS**
Flexographic printing, aluminium foil, screening, dot gain, tone reproduction, fractal geometry, optical density, regression modelling

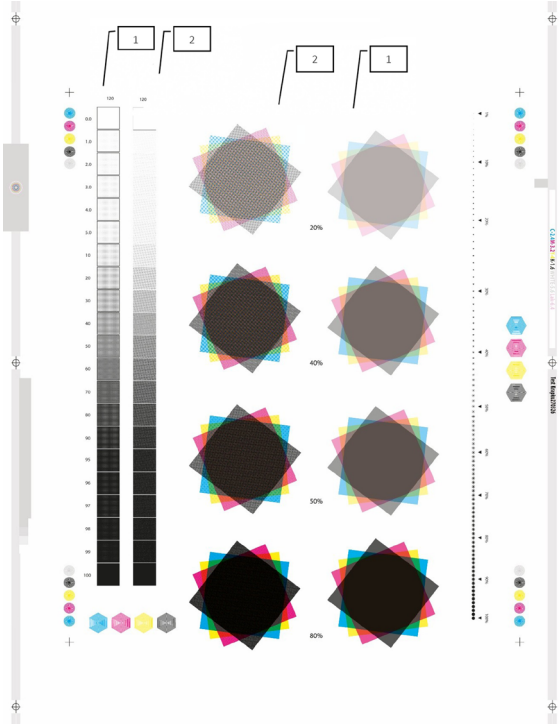
## 1. Introduction

Flexographic printing is being increasingly used to apply images to non-absorbent and metallised substrates, in particular aluminium foil, which is widely used in the manufacture of flexible food and pharmaceutical packaging, as well as in advanced metallisation processes such as photovoltaic front-side contact printing (Lorenz et al., 2016). A distinctive feature of printing on such materials is the absence of ink absorption into the substrate, as a result of which the entire excess volume of the ink layer is squeezed onto the surface and spreads along the edges of the halftone dot, causing pronounced mechanical dot gain. Ink formulations developed specifically for printing on non-absorbent flexible foil substrates have also been the subject of recent research (Várza, Joóbné Preklet & Horváth, 2021).

The quality of flexographic imprints on metallised and polymer films has repeatedly been addressed in the literature: the influence of printing-process parameters on optical density and tonal value increase on printed films has been studied (Żołek-Tryznowska et al., 2020), as has the deformation of halftone dots in flexography in general (Valdec et al., 2021). It has been shown that ISO-defined substrate properties substantially determine colour reproduction in the flexographic process (Valdec, Miljković & Augustštin, 2017), and that a geometric dot-gain model allows AM and FM screening technologies to be compared quantitatively (Valdec et al., 2026).

A separate direction in screening improvement is the use of irregular and fractal structures, which, unlike the classical regular (AM) screen, make it possible to reduce visual moiré and increase the subjective smoothness of tonal transitions. At the same time, the fractal geometry of the dot contour is characterised by a considerably greater total perimeter for the same nominal area, which potentially reinforces the perimeter-driven ink-squeeze mechanism and, correspondingly, dot gain. Studies of flexographic imprints by optical and electron microscopy confirm the value of microstructural analysis of halftone dots for establishing the physical causes of tonal distortions (Havenko, Labetska & Telehina, 2024), while the influence of printing speed on the occurrence of the 'bouncing effect' further demonstrates the sensitivity of the flexographic process to the mechanical parameters of plate-to-substrate contact (Havenko, Telegina & Labetska, 2026).

Despite the considerable number of studies devoted separately to dot gain on films and to the moiré-suppression advantages of fractal screening, a quantitative comparison of round and fractal screens specifically for aluminium foil, together with the construction of mathematical models of tonal shift for both technologies, has to date been practically absent from the literature. This defines the aim of the present study.




» **Figure 1:** *Digital layout of the test form for flexographic printing on aluminium foil with control elements (a Siemens-star-type target, a microelement scale, and round (1) and fractal (2) screening fields)*

## 2. Materials and Methods

To reduce moiré interference effects and improve tone reproduction in critical tonal ranges, a new type of halftone dot with a multi-ray, star-like geometry was proposed. As the basic geometric prototype, a dot analogous to a snowflake-like structure with four main rays positioned at angles of 0°, 45°, 90° and 135° was chosen.

The general appearance of the digital layout of the test form with the control scale elements is shown in Figure 1. In the round (AM) screening zone, a regular structure of ink overlap and a periodic grid are clearly visible at the 40–50% tints, whereas for fractal screening the boundaries of the tonal zones appear more diffuse and the transition smoother, which is consistent with the well-known ability of irregular structures to suppress moiré.

The experimental samples were printed on a Varyflex V2 670 flexographic printing press equipped with a web-tension control system and UV curing. Aluminium foil 20 µm thick was used as the substrate. Printing was carried out with UV flexographic inks at a speed of 80 m/min, using corona treatment before printing and instant UV curing after each ink station, in line with the general process-control requirements for flexographic printing (International Organization for Standardization, 2020). Microstructural analysis of the imprints of the test scales was performed by reflected-light optical microscopy using a Dino-Lite Edge AM7915MZTL digital microscope with a built-in polarising filter that minimises specular reflection from the foil surface. The geometry of the round and fractal halftone dots was studied at 150× optical magnification; the perimeter, dot area and the zone of edge ink squeeze-out (halo) were determined in the DinoCapture 2.0 software environment. The optical density of the imprints was measured spectrodensitometrically in accordance with the ISO 13656 procedure (International Organization for Standardization, 2021) for nominal tone values from 1 to 99%.

The effective halftone dot area was determined from the optical density of the imprint on the basis of a modified Yule–Nielsen equation:

$$A_{eff} = \frac{1-10^{-Dt/n}}{1-10^{-Ds/n}} \quad (1)$$

where Dt is the optical density of the halftone field; Ds is the density of the solid (full-tone) element; and n is the light-scattering coefficient at the ink–foil interface, which for the specular metallic surface was determined by residual-minimisation separately for the round and fractal screens.

The absolute and relative dot gain were calculated as:

$$\Delta A = A_{eff} - A_{nom}, \quad DG = \frac{A_{eff}-A_{nom}}{A_{nom}} \times 100\% \quad (2)$$

where Anom is the nominal halftone dot area.

To quantify the contribution of the dot contour to dot gain, a perimeter-influence coefficient was used:

$$PI = \frac{P}{\sqrt{A}} \quad (3)$$

where P is the perimeter of the halftone dot and A is its area; an increase in PI corresponds to an increase in the relative length of the contour along which ink squeeze-out occurs.

The dot-gain curves were approximated by a third-degree polynomial:

$$\Delta A(x) = a \cdot x^3 + b \cdot x^2 + c \cdot x + d \quad (4)$$

and the quality of the fit was assessed using the coefficient of determination $R^2$ and the root-mean-square error:

$$RMSE = \sqrt{\frac{1}{n}\sum_{i=1}^{n}(y_i - \hat{y}_i)} \quad (5)$$

For each nominal tone value, the mean, standard deviation and coefficient of variation of the measured dot area were calculated, and the 95% confidence interval was used to assess the reliability of the differences between the screens. The significance of the differences in mean ΔA values between the round and fractal screens within each tonal zone was tested using Student's t-test; the coefficient of determination $R^2$ and RMSE were used to compare the quality of the linear, polynomial and spline models.

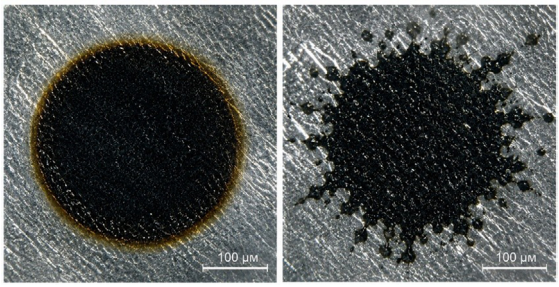
## 3. Results

In the course of the experiment, a comparative analysis of halftone dot gain in flexographic printing on aluminium foil was carried out for round (conventional) and fractal screening. Measurements were performed for nominal tone levels from 1 to 99%; the results are summarised graphically and in a table of raw data, and a physical interpretation is provided on the basis of microstructural analysis of the imprints.

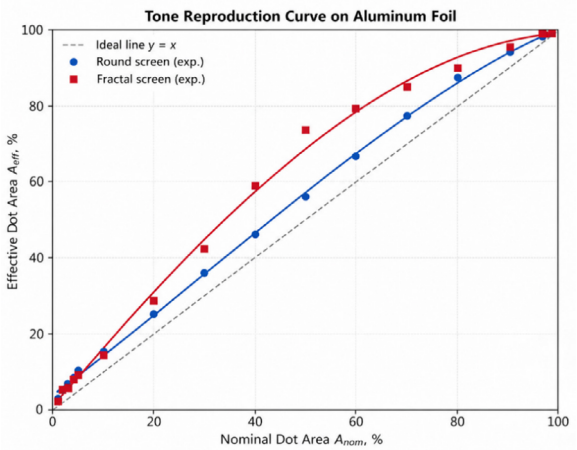
Micrographs of the halftone dots at the 50% tint (Figure 2) demonstrate a fundamental difference in the contour of the two screening technologies. The classical round dot has a clear Euclidean shape with a slight elliptical deformation caused by pressure in the printing-contact zone; a characteristic narrow dark halo forms along its perimeter, caused by ink squeeze-out on the non-absorbent foil. The fractal dot, in contrast, is characterised by a branched contour of fractional dimension: the disproportionately large perimeter length causes the excess ink to be distributed along numerous micro-branches, resulting in a diffuse edge-spreading zone forming around each micro-vertex.

On the basis of the experimental values obtained for the effective area and dot gain of both screening technologies across the entire tonal range, a tone-reproduction curve was plotted (Figure 3). The data analysis shows that both screening technologies provide relatively stable reproduction in the highlights and shadows, while the most pronounced differences are observed in the midtone zone (20–70%). For round screening, the measured area increases almost linearly with nominal coverage, indicating moderate and uniform mechanical dot gain (ΔA within +5...+8%). Fractal screening, by contrast, shows a considerably greater increase in effective area in the midtone zone: the maximum deviation was recorded at the 50% tint, where the measured area reached 73.8% (ΔA = +23.8% versus +6.1% for the round screen — a difference of more than 17 percentage points).

At the same time, in the critical-highlight zone (1–3% tints), the fractal screen shows somewhat lower effective-area values than the round screen (for example,




» **Figure 2:** *Micrographs of halftone dots on aluminium foil (nominal area 50%, magnification 150×): left — regular round screen; right — fractal screen*




» **Figure 3:** *Tone-reproduction curve on aluminium foil: measured (effective) halftone dot area as a function of nominal area for round and fractal screening (the dashed line shows the ideal line y = x)*

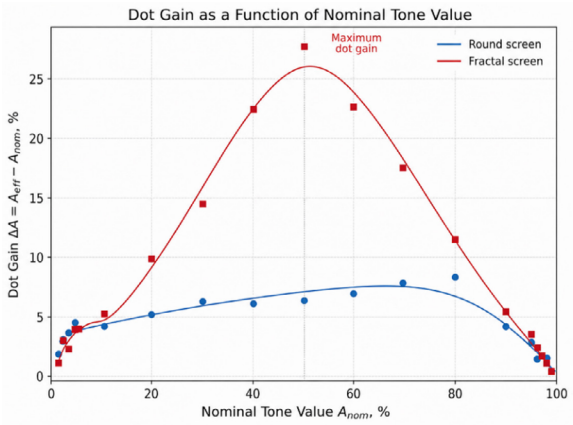
2.4% versus 3.2% at the 1% tint), indicating better isolation of individual microelements and the absence of premature dot 'closing-up' in this region.

The tone-reproduction curve clearly illustrates that for round screening the deviation from the ideal line y = x is smooth and almost symmetrical about the midpoint of the scale, whereas for fractal screening the curve deviates sharply upward as early as after 20% nominal coverage, reaching a maximum at approximately 50–55%, after which the deviation gradually decreases in the shadow region.

The dot-gain diagram (Figure 4) confirms the fundamentally different behaviour of the two screening technologies. For the round screen, the dot-gain value remains relatively stable, within approximately 5–8%, over most of the scale, which is characteristic of a mechanically predictable flexographic process. The fractal screen, in contrast, shows a pronounced non-linear, near-parabolic dependence with a clear maximum in the 50–55% zone and a subsequent decline towards the shadows, consistent with the dominance of the perimeter-driven ink-squeeze mechanism for dots of complex geometry.

Particular attention should be paid to the local inversion of values for the round screen at the 95–96% tints (98.3% → 97.8%), which should be interpreted not as a measurement error but as a manifestation of a mechanical artefact — micro-creases and local folds of the thin 20 µm foil in the printing-contact zone, causing a short-term redistribution of pressure. The fractal screen in this same zone shows a monotonic increase (98.7% → 98.8%), indicating its greater resistance to such mechanical defects owing to its more diffuse contact geometry.

Since aluminium foil scatters practically no light within the substrate (unlike paper), the effective scattering coefficient n in the Yule–Nielsen equation for the round screen was found to be close to 1.0, whereas for the fractal screen it increases statistically significantly owing to additional light scattering at the developed microrelief of the ink–air interface along the numerous micro-branches of the contour.




» **Figure 4:** *Dot gain ΔA as a function of nominal tone value for round and fractal screening*

For a quantitative comparison of approximation models for the dot-gain curve ΔA(Anom), linear, polynomial (2nd- and 3rd-degree) and spline regressions were constructed separately for each screen type (Table 1).

**Table 1**

Goodness of fit of experimental dot-gain curves by different regression models

| Model | Round $R^2$ | Round RMSE | Fractal $R^2$ | Fractal RMSE |
|---|---|---|---|---|
| Linear | 0.060 | 1.96 | 0.000 | 6.85 |
| 2nd-degree polynomial | 0.742 | 1.03 | 0.921 | 1.92 |
| 3rd-degree polynomial | 0.828 | 0.84 | 0.929 | 1.83 |
| Smoothing spline | 0.878 | 0.71 | 0.989 | 0.71 |

The linear model proved unsuitable for describing dot gain of the fractal screen ($R^2 \approx 0$) owing to the pronounced non-linearity of the curve with an extremum in the midtones, while for the round screen it also gives an unsatisfactory result ($R^2 = 0.06$). The third-degree polynomial substantially improves the fit for both screens ($R^2 = 0.83$ and 0.93, respectively), and the best fit to the experimental points is provided by the smoothing spline ($R^2 = 0.88$ for the round screen and $R^2 = 0.99$ for the fractal screen), which is recommended as the basis for constructing dot-gain compensation curves (DGC) during pre-press calibration.

# 4. Discussion

## 4.1. Physical mechanism of dot gain

The results obtained confirm that the decisive factor behind the differences in dot gain between round and fractal screens on aluminium foil is the perimeter-driven ink-squeeze mechanism. The round dot has the minimum possible perimeter for a given area, so the zone of edge ink spreading is limited, and dot gain remains moderate and stable over a wide tonal range. The fractal dot has a substantially greater length of contact boundary, as a result of which the ink spreads more intensively along the numerous micro-branches of the contour. Since aluminium foil is a practically non-absorbent substrate, the entire excess volume of ink remains on the surface and is redistributed precisely along the perimeter, which explains the sharp increase in the effective area of the fractal screen in

the midtones, where the density of dot placement and the total length of their contours are at a maximum.

## 4.2. Mathematical interpretation

In general form, dot gain can be regarded as a multifactor function of geometric and technological parameters:

$$\Delta A = f(P/A, \eta, v, p, \gamma) \quad (6)$$

where P/A is the perimeter-to-area ratio of the dot (the PI coefficient), η is the ink viscosity, v is the printing speed, p is the process pressure, and γ is the surface tension of the ink at the interface with the metal. The experimental data obtained are consistent with this representation: for fixed technological parameters (η, v, p, γ), it is precisely the increase in the P/A ratio for the fractal screen that determines its systematically higher dot gain compared with a round screen of the same nominal area. This confirms that dot gain on a non-absorbent metal substrate is not a purely geometric characteristic of screening, but the result of the interaction of contour geometry with the hydrodynamics of the thin ink layer.

## 4.3. Technological implications

- fractal screening is advisable for applications where the priority is maximum optical density, saturation and contrast in the midtones, as well as moiré suppression
- round screening remains the better choice where precise and predictable differentiation of highlight gradations and ease of process calibration are critical
- for fractal screening on aluminium foil, the application of separate dot-gain compensation curves (DGC), constructed on the basis of a spline or third-degree polynomial model, is mandatory
- a further reduction in dot gain can be achieved by optimising UV ink viscosity, process pressure and anilox roll line screen, taking into account the increased P/A value for fractal dots (Xue et al., 2026)

# 5. Conclusions

The geometry of the halftone dot substantially affects dot gain and tone reproduction in flexographic printing on non-absorbent aluminium foil: the dominant physical factor is the perimeter-to-area ratio of the dot (the PI coefficient).

The fractal screen shows substantially higher dot gain in the midtone zone (a maximum of ΔA = +23.8% at the 50% tint) compared with the round screen (ΔA = +6.1% at the same tint), which is attributable to the considerably greater perimeter length of the fractal dots.

The round screen provides more stable and almost linear dot-gain behaviour (5–8%) over a wide tonal range, which simplifies its calibration, whereas in the critical-highlight region (1–3%) the fractal screen shows better dot isolation and lower dot gain.

The experimental dot-gain curves are well described by non-linear models: the third-degree polynomial and the smoothing spline provide $R^2$ values of 0.83–0.99, making it possible to use them for constructing compensation curves.

For the practical implementation of fractal screening in flexographic printing on aluminium foil, technological compensation of dot gain (DGC) in the midtone zone is required, together with optimisation of ink viscosity and printing pressure.

# 6. References


Havenko, S., Labetska, M. and Telehina, T. (2024) 'Study of flexographic imprints using the methods of optical and electron microscopy', *Sixteenth International Conference on Correlation Optics. Proceedings of SPIE*, 12938, 129380W. DOI: 10.1117/12.3012269

Havenko, S., Telegina, T. and Labetska, M. (2026) 'Detection of the influence of flexographic printing speed on the occurrence of the bouncing effect on imprints', *Eastern-European Journal of Enterprise Technologies*, 2(1/140), pp. 115–124. DOI: 10.15587/1729-4061.2026.359494

International Organization for Standardization. (2020) *ISO 12647-6: Graphic technology — Process control for the production of half-tone colour separations, proof and production prints — Part 6: Flexographic printing*. Geneva: ISO.

International Organization for Standardization. (2021) *ISO 13656: Graphic technology — Application of reflection densitometry and colorimetry to process control or evaluation of prints and proofs*. Geneva: ISO.

Lorenz, A., Gredy, C., Beyer, S., Yao, Y., Papet, P. and Ufheil, J. (2016) 'Flexographic printing — towards an advanced front side metallization approach with high throughput and low silver consumption', *Solar Energy Materials and Solar Cells*, 157, pp. 550–557.

Valdec, D., Hajdek, K., Vragović, L. and Geček, R. (2021) 'Determining the print quality due to deformation of the halftone dots in flexography', *Applied Sciences*, 11(22), p. 10601.

Valdec, D., Miljković, P. and Augustštin, B. (2017) 'The influence of printing substrate properties on color characterization in flexography according to the ISO specifications', *Tehnički glasnik*, 11(3), pp. 73–77.

Valdec, D., Štumerger, M., Majnarić, I. and Valdec, L. (2026) 'Analytical modeling of geometrical dot gain relationship between AM and FM halftone screening technologies', *Applied Sciences*, 16(7), p. 3413.

Várza, F., Joóbné Preklet, E. and Horváth, C. (2021) Application analysis of white flexographic printing inks on biodegradable flexible foils. In: *Proceedings of the 2nd International Conference on Circular Packaging CPC*, pp. 311–320.

Xue, B., Liu, X., Liu, Y., Xu, Q., Ke, J. and Jiang, M. (2026) 'Mussel-inspired multi-functional adhesive for metal flexographic printing plates: superior metal and polymer adhesion, strength, toughness, and long-lasting durability', *Progress in Organic Coatings*, 212, p. 109913.

Żołek-Tryznowska, Z., Rombel, M., Petriaszwili, G., Dedijer, S. and Kašiković, N. (2020) 'Influence of some flexographic printing process conditions on the optical density and tonal value increase of overprinted plastic films', *Coatings*, 10(9), p. 816.



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