

Quantifying dot gain mechanisms in flexographic highlight tones

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Short abstract

Reproducing small dots is essential for smooth highlight tones in flexographic printing, but both mechanical and optical dot gain influence how dark these tones appear. Most earlier work focuses on offset printing and does not separate the contributions in flexography, where deformation of the raster dot on the print form and substrate compressibility play a key role. In this study we use high resolution scanning and histogram-based dot area estimation together with standard and modified Murray Davies calculations to account for internal dot reflectance and separate physical and optical dot gain. The method is applied to a full scale printed 4% tone on three coated liquid packaging paperboards differing in baseboard and top layer structure. The results show that all three mechanisms contribute to the apparent tone value in highlight tones. Differences between the paperboards were mainly reflected in the physical gain for the baseboards and in the optical effects for the top layers. The method provides a practical tool for identifying the dominant mechanism for a given substrate.

Keywords: Dot gain, Optical dot gain, Mechanical dot gain, Internal dot reflectance, Flexography

1. Introduction and background

Reproducing small dots is essential for printing highlights and creating smooth tonal transitions as the print fades to zero. In flexographic printing this is particularly challenging as a compliant relief print form and the applied nip pressure enlarge dots and limit how small they can be made.

The reflectance of a screened area depends on three factors: the area of the dots, the reflectance inside the dots, and the reflectance of the unprinted substrate between the dots. The apparent tone value from spectrophotometry of the halftone, the solid tone and the unprinted substrate can then be calculated using the Murray–Davies equation, as described for example by Nyström (2008). The tone-value increase (referred to here as dot gain) is the difference between the apparent and the nominal tone value in digital file. This approach does not account for reflectance differences between the solid tone and the interior of the dots. Such differences may arise from deviations in ink layer thickness and from light scattering within the material, which can make dots appear brighter than the solid tone. Furthermore, the Murray–Davies approach does not account for light-scattering effects that make the unprinted area around the dots appear optically darker. Although this industry-standard measurement provides the apparent tone value, the contributions of the separate mechanisms remain hidden. While this aligns with visual perception, separating the factors is essential to enable improvements of both the substrate and the printing process, since they originate from different mechanisms.

Mechanical dot gain, also referred to as physical dot gain, arises from plate deformation and ink spreading that increase the physical dot area. The possible impact of physical dot gain is especially pertinent to flexography with its deformable raster dots. The physical dot area can be estimated from micro-scale reflectance images by applying a histogram threshold at the minimum between the ink and paper peaks (Nemedian et al., 2013), or from edge-based methods that set the

boundary at the point of maximum slope (Nyström, 2008) or at the inflection point (Yuasa, Kakumoto and Aizu, 2011) in the reflectance profile. Light transmission imaging or spectrophotometric measurement have also been used to suppress the impact of optical spreading (Nyström, 2008). However, these still capture some optical gain and exhibit lateral non-uniformities on thin papers (Namedanian and Gooran, 2011; Namedanian et al., 2013), and they are not applicable to thick coated boards. Nyström (2008) also proposed simulating the physical area using Murray–Davies and the internal reflectance of dots and internal reflectance between dots, both obtained from micro-scale images of the halftone area. This approach estimates physical dot gain while accounting for optical dot gain and the internal ink layer inside the dots.

Optical dot gain originates from lateral light scatter in the substrate and is described by the paper's point spread function (PSF) or, equivalently, its modulation transfer function (MTF). The PSF or MTF can be quantified using measurement or modelling. Quantification can be achieved, for example, by knife-edge and bar-target techniques, or by series-expansion analysis of a single low-frequency bar pattern (Rogers, 1998; Atanassova and Jung, 2007). These measurements are sensitive to the measurement set-up (Atanassova and Jung, 2007) and do not provide a straightforward understanding of the contribution from optical dot gain to the darkening of halftone areas. Optical dot gain can be obtained as the total apparent dot area (from Murray–Davies estimates on measured reflectance) minus the physical area (Nyström, 2008; Namedanian et al., 2014), or it can be inferred via MTF fitting so that a simulated effective coverage matches measurements (Namedanian et al., 2013). As an alternative, optical and mechanical contributions can be separated from line-based measurements by fitting the line spread function with several peak functions that attribute physical and optical dot gain respectively (Ivanda et al., 2025).

While literature on dot gain is plentiful, most research has focused on effects in offset printing (Nyström, 2008; Namedanian and Gooran, 2010, 2011; Namedanian et al., 2013, 2014). Mechanical dot gain has typically been related to the printing process, whereas optical dot gain is often treated as a purely material-related factor (Namedanian et al., 2014; Ivanda et al., 2025). To our knowledge, there is a lack of studies addressing the highlight tones (i.e. halftones of low tone values) in flexography in terms of separating optical dot gain, physical dot gain, and internal dot reflectance. Although deformation of the print form (the polymer plate with its relief pattern) has been shown to directly affect the physical dot area (Bould et al., 2004; Olsson et al., 2006), the appearance depends on all three mechanisms. Furthermore, ink layer thickness can differ between flexographic solid tones and screened areas, due to changes in contact area and pressure, which makes it particularly important to account for internal dot reflectance.

The aim of this work is to establish a practical method for separating physical and optical dot gain. The method should account for how the reflectance inside halftone dots differ from the reflectance in the solid tone. Thereby the method will provide a first indication of the importance of each of the three mechanisms for the apparent tone value of highlight tones in flexographic printing on coated liquid packaging boards. By applying high-resolution scanning, histogram-based physical area and internal dot reflectance estimates, and Murray–Davies calculations, we evaluate three paperboards differing in baseboard and top-layer structure to indicate how material properties govern mechanical and optical contributions in flexographic highlight reproduction. The results show that all three mechanisms significantly influence the apparent tone value. Physical dot gain accounted for the largest differences between the baseboards, while optical effects related to optical dot gain and reflectance inside the dots accounted for the largest differences between the top-layer structures.

2. Materials and methods

Three liquid packaging substrates were full-scale printed in a production flexographic press. Materials and settings are described in the following section.

2.1 Materials and printing

Three coated liquid packaging paperboards were used. All are multiply duplex paperboards referred to as 260 mN CLC/C+ qualities and they are intended to give comparable quality. One pair differed in the baseboard construction (Base 1 and Base 2), and one pair differed in the top layer formulation (Top A and Top B).

A standard flexographic cyan ink for coated liquid packaging grades was used, taken from the same batch for all trial points. Flat-top dot polymer plates were produced in the same converting factory as the printing, with screening and processing optimised for CLC/C+ grades. Print settings were adjusted for each grade according to routine practice. Five parallel lanes were printed on a 1.5 m web, and analyses were performed on lane 1.

2.2 Print characterisations

Print density was measured using a flatbed scanner (Creo II). The RGB channels were calibrated against R_x , R_y , R_z using a calibration target with known reflectance spectra. Six printed signatures and one unprinted sheet of each sample were scanned. A 4% and a 100% tone, each 25 mm x 25 mm, were analysed. The white point was taken from a 9 cm x 13 cm area on an unprinted sheet.

Mean reflectance was obtained from the red image channel of 300 ppi scans, while physical dot size and internal reflectance were measured from 5000 ppi scans. Low-resolution scans were analysed using STFI Mottling Software (RISE) and high-resolution scans with DotStat (RISE). Imaging areas were 18-19 mm squares at 5000 ppi and 5.4 mm squares (printed) or 43.4 mm squares (unprinted) at 300 ppi.

2.3 Density and dot area calculations

Relative print density (D) was calculated from the mean reflectance of the printed area (R_{print}) and the unprinted paperboard (R_{board}):

$$D = \log_{10} R_{\text{board}} - \log_{10} R_{\text{print}} \quad [1]$$

The physical dot area was measured as the area fraction covered by ink in the high-resolution scans, using the software's automatically suggested histogram threshold located at the minimum between the ink and paper peaks. Dot area estimated as the apparent tone value given by the standard Murry-Davies equation (MD_{standard}) was calculated using the mean reflectance in the solid tone (R_{solid}), highlight tone (R_{tone}), and unprinted area (R_{board}):

$$MD_{\text{standard}} = \frac{R_{\text{board}} - R_{\text{tone}}}{R_{\text{board}} - R_{\text{solid}}} \times 100 \quad [2]$$

A modified dot area metric (MD_{modified}) was calculated to account for the internal reflectance (R_{internal}) within the dots, defined as the mean reflectance of pixels inside the physical dot area:

$$MD_{\text{modified}} = \frac{R_{\text{board}} - R_{\text{tone}}}{R_{\text{board}} - R_{\text{internal}}} \times 100 \quad [3]$$

Because small dots are optically lighter than the solid tone, the apparent tone value estimated by the standard equation deviates from that given by the modified one. This reflectance-related contribution to the apparent tone value (Δ_{internal}) is therefore defined as the difference between the modified (Equation 3) and standard (Equation 2) dot-area metrics:

$$\Delta a_{\text{internal}} = MD_{\text{modified}} - MD_{\text{standard}} \quad [4]$$

The contribution from optical dot gain ($\Delta a_{\text{optical}}$) was estimated as:

$$\Delta a_{\text{optical}} = MD_{\text{standard}} - \text{Dot Area (physical)} \quad [5]$$

The relative contribution of each mechanism is also expressed as its fraction of the modified Murray–Davies area, after subtracting the nominal tone value from both the physical area and the modified Murray–Davies area.

3. Results and discussion

Estimates of the contributions of mechanical and optical dot gain to print density in the highlight tones, while accounting for internal dot reflectance, were obtained from the full-scale printed paperboards. Scanner-based measurements show that the 4% tone is darker on paperboard with Base 2 than on Base 1, and with Base 1 it is darker on Top B than on Top A (Figure 1a). A darker tone can arise from larger dots (mechanical squeeze and lateral spreading through e.g. wetting), darker dots (ink layer thickness and internal dot reflectance), and a darker appearance between dots due to the unprinted paperboard and optical dot gain. As a first step, it can be observed that both the dots and solid are darker on Base 2 than on Base 1, while no corresponding difference is seen between the two top layers (Figure 1b). We attribute this to differences in ink transfer, likely caused by the way the baseboards alter the mechanical conditions in the printing nip.

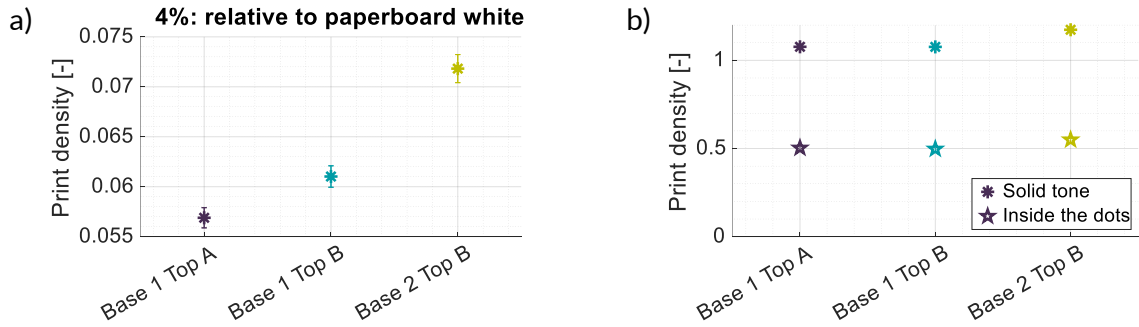


Figure 1: Relative print densities in a) the 4% tone, and b) the solid tone and the internal density of the dots in the 4% tone.

To investigate the underlying cause further, the dot area is calculated using the standard Murray–Davies equation (Equation 2). This method accounts for overall ink layer thickness as it appears in the solid tones and the white point (unprinted paperboard). The standard Murray–Davies dot area estimate follows the same trend as the measured highlight density (Figure 2a). However, this estimate reflects a combination of physical area and optical dot gain, and it underestimates the actual area when the halftone dots are brighter than the solid tone. These mechanisms should be separated to identify how to best improve and control the dot gain. To do so, both the physical dot area and the internal dot density must be quantified.

The high-resolution scans enabled direct measurement of the area fraction covered by ink, that is the physical dot area. The paperboard with Base 2 shows a larger physical dot area than Base 1, while Top A and B of Base 1 are similar (Figure 2b). This supports that the difference caused by the base board is primarily mechanical.

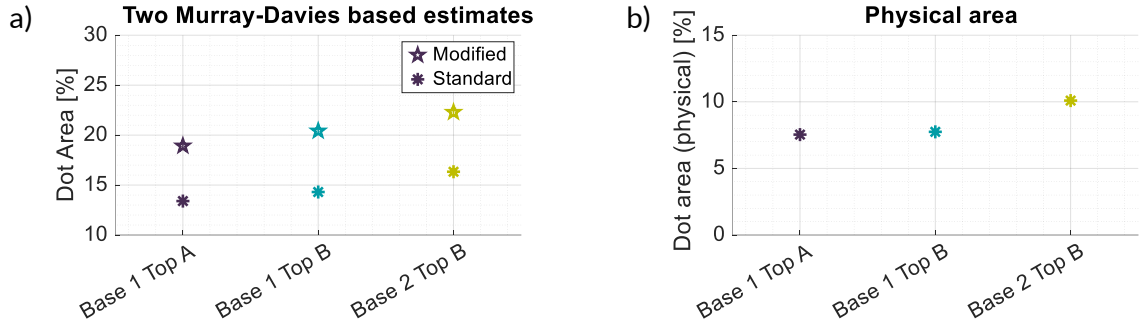


Figure 2a: Dot area estimates using a) the standard and modified Murray–Davies equations, and b) measurement of the physical area of the dots.

The solid tone density is significantly higher than the internal density of the dots (Figure 1b). Lateral light scattering will lower the internal dot density, more so in highlights than halftones. Further, the ink layer can be squeezed out thinner in raster dots compared to solid tones because of the smaller contact area and higher local pressure. Consequently, the standard Murray–Davies assumption that the dot reflectance equals solid tone reflectance does not hold.

The modified Murray–Davies estimate (Equation 3), which uses the measured internal dot reflectance, is higher than the standard estimate (Equation 2) (Figure 2a). This shows that when the dots are lighter than the solid, a higher apparent tone value is required to match the reflectance of the highlight tone. While the absolute solid and dot reflectance differs more between Base 1 and Base 2 (Figure 1b), the deviation between the internal dot reflectance and the solid-tone reflectance is larger for Top A than for Top B (Figure 3a). We suggest that this deviation relates to differences in optical scattering within the top layers.

Consistent with Ivanda et al. (2025), the present study shows that also the contribution from optical dot gain is substantial (Figure 3b). For the 4% tone, physical dot gain accounted for roughly 26%, optical dot gain for 39%, and internal dot reflectance for 35% of the total dot gain. Although the optical contribution is large and affects both optical dot gain and internal dot reflectance, the material changes in the present study had a larger impact on the physical dot gain. This is likely because differences in the baseboard construction influence the mechanical conditions in the printing nip, which in turn change the physical size of the dots and therefore the mean reflectance. In contrast, the top-layer formulation mainly affects optical scattering, and the resulting optical differences between the samples were relatively small.

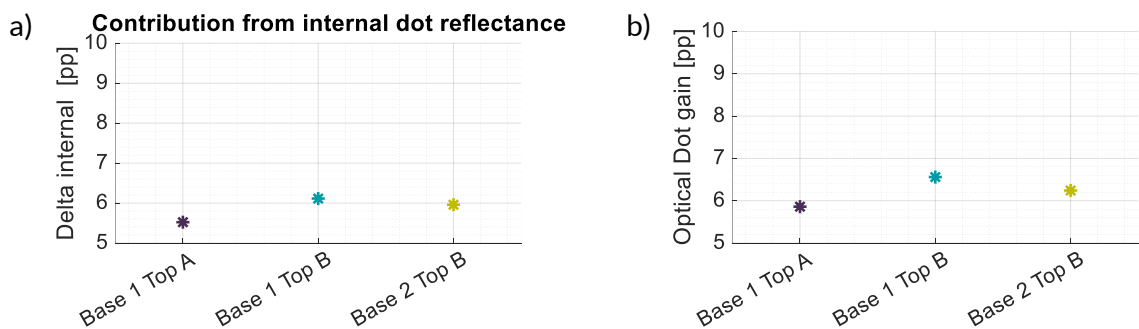


Figure 3: a) Reflectance-induced dot gain and b) optical dot gain.

4. Conclusions

This study set out to establish a practical method for separating physical and optical dot gain while accounting for the internal reflectance of dots, and to give a first indication of their relative

importance for the smallest reproducible flexographic dots. Based on full-scale printed 4% tones, we conclude:

1. Physical area, internal dot reflectance, and optical dot gain all influence the highlight tone, and none can be ignored when evaluating flexographic reproduction.
2. Optical dot gain had the largest overall impact on the apparent tone value, whereas differences between the paperboards were mainly driven by physical dot gain. The baseboard construction predominantly affected mechanical deformation, while the top layer primarily influenced optical scattering, which manifested as optical dot gain and lower reflectance inside the dots compared to the solid tone. This shows that each contribution is material-dependent and can be modified through substrate design.
3. The combination of high-resolution scanning, histogram based physical area and modified Murray–Davies calculations effectively separated the contributions, providing a practical way to identify the dominant mechanism for a given substrate and to guide optimisation of materials and printing.

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