Impact of Electrostatic Assist on Halftone Mottle in Shrink Films

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Abstract:

Gravure printing delivers intricate print quality and exhibit better feasibility for printing long run packaging jobs. PVC and PETG are widely used shrink films printed by gravure process. The variation in ink transfer from gravure cells on to the substrate results in print mottle. The variation is inevitable and requires close monitoring with tight control on process parameters to deliver good dot fidelity. The electrostatic assist in gravure improves the ink transfer efficiency but is greatly influenced by ESA parameters such as air gap (distance between charge bar and impression roller) and voltage. Moreover, it is imperative to study the combined effect of ESA and gravure process parameters such as line screen, viscosity and speed for the minimization of half-tone mottle in shrink films. A general full factorial design was performed for the above mentioned parameters to evaluate half-tone mottle. The significant levels of both the main and interactions were studied by ANOVA approach. The statistical analysis revealed the significance of all the process parameters with viscosity, line screen and voltage being the major contributors in minimization of half-tone mottle. The optimized setting showed reduction in half-tone mottle by 33% and 32% for PVC and PET-G respectively. The developed regression model was tested that showed more than 95% predictability. Furthermore, the uniformity of dot was measured by image to non-image area (ratio) distribution. The result showed reduction in half-tone mottle with uniform dot distribution.

Keywords:

Shrink films, Half-tone mottle, ANOVA, Regression model, Dot fidelity

1 Introduction

Gravure is a widely accepted printing process due to its versatility, flexibility and high print quality. The print mottle leads to print rejections and wastage of ink, substrate and time. The gravure print quality has further improved by endorsing electrostatic assist through elimination/minimization of dot skips. The electrostatic assist and gravure process parameters play vital role in delivering quality print jobs. However, there are some areas that need to be addressed to achieve
progressive and consistent print quality. The
printability is greatly dependent on ink, substrate
and process parameters (Fahlkrantz, 2005). The
variation in ink transfer is inevitable and can be
controlled by optimization of process parameters.
The variation in reproduction of half-tone dots
leads to poor print quality. The degree of variation
in ink transfer can be gauged by halftone print
mottle.

Print mottle can be defined as unevenness in
ink transfer which leads to uneven density distri-
bution which creates unpleasant visual appear-
ance for the human eye (Fahlcrantz, Johansson
and Aslund, 2003). The unevenness in print den-
sity can be evaluated by STFI, discrete wavelet
analysis and SFDA techniques (Teleman et al.,
2005). Stochastic Frequency Distribution Analy-
sis (SFDA) algorithm calculates mottle from the
two-dimensional scanned image where it analyses
the properties of texture through each pixel lumin-
ance values then calculates the spatial distribu-
tion of this texture. It interprets the data according
to algorithm designed and outputs an equivalent
mottle index value (Rosenberger, 2003). The non-
uniformity in optical dot gain also reflects mottle
in halftone area (Kawasaki, Ishisaki and Yoshi-
moto, 2009). The ink transfer from a gravure cell
on to the substrate depends on characteristics of
ESA semi conductor impression roller such as
uniformity of charge distribution, surface and
volume resistivity (Doppler, 2003 & Hyllberg,
1993). Higher surface and volume resistivity pose
high dissipation of charge and offers high surface
charge holding ability (Webster, 1998).

The conductive substrate such as foil and inks
are not feasible for gravure printing with ESA,
due to poor charge holding capacity that gets
leaked immediately, resulting in an electric spark
(Zaretsky, Billow and Whitney, 2004). The sub-
strate properties such as topography, smoothness,
roughness, absorption and surface energy plays
an important role in determining print quality
(Velho and Santos., 2010). The topography and
roughness variation causes uneven ink spread-
ing and absorption which leads to differential
dot structure, density and gloss (Liu, Zhang and
Liang, 2013). Higher topography and roughness
leads to high print mottle (Olsson et al., 2007).
The electrical properties of the substrate show
great impact in determining the ESA parameters
(George & Oppenheimer, 1987). The introduction
of ESA had showed a significant improvement in
print quality by eliminating dot skips (Steingrae-
ber, 2012). The influence of electrostatic improves
the liquid spreading and wettability on the sur-
fase (Wright, 1993). The ink properties such as
viscosity and surface tension play a vital role in
print quality. Ink with higher surface tension has
high cohesion force which resist spreading on
the substrate surface resulting in inhomogeneous
wetting; thereby the print mottle (Durand, 2012).
The surface energy of the substrate determines the
spreading, adhesion and wettability of ink on the
surface. Lower surface energy leads to less affinity
to hold ink on the surface which results in poor
adhesion and wettability thereby results in print
mottle (Repeta, 2013). The application of ESA
current beyond the threshold limits also shows
adverse effect in print quality such as whiskering
(Gravure Association of America, 2003).

Print rejections can be minimized by optimi-
ization of process parameters and simultaneously
decline the non-value added operations and cost
incurred in it. Hence, there exists a need of re-
search work to be conducted on optimization of
ESA and gravure process parameters and its effect
on half-tone mottle.

2 Material

2.1 Substrate

PVC and PET-G shrink films (40 µm thick-
ness) were used for the experimental trials. The
surface energy of the substrate was determined by
testing with standard test liquids i.e. Formamide
and Glycerol. The test liquid contact angle on sub-
strate surface was evaluated using Holmarc con-
tact angle meter. Geometric mean equation was
employed to estimate the surface energy of the
substrate. The surface energy of PVC and PET-G
was found to be 35.62 mN/m and 37.51 mN/m re-
spectively. The PET-G substrate had
higher surface energy, surface and volume resistivity as compared to PVC.
2.2 Ink

A solvent based black ink with acrylic resin was used for the experiment. The ink viscosity was measured with #4 ford cup. The viscosity was adjusted using recommended solvent combination of ethyl acetate, toluene and iso-propyl alcohol (IPA) in the ratio of 4:4:2. The target density was set with a tolerance of 5% for the entire experimental trials. The ink surface tension was determined with Kruss K 100 Ring Tensiometer using Du Noüy ring technique. The surface tension of the acrylic ink was found to be 23.77 mN/m.

2.3 Layout Design

The layout comprises of image, logo, reverse text, normal text, step wedge, solid patches. The halftone patch (30%) size of 110mm x 95 mm was design to evaluate the ink transfer properties. The uniformity of image to non-image area was analysed at 50% step wedge. Electronic engraving technique was employed for gravure cylinder making.

3 Methods

3.1 Experimental Design

The line screen, air gap, viscosity, voltage and speed were the screened parameters for a general full factorial design of experiments (DOE). The DOE includes 216 runs with 2 replicates (108 runs per replicate) for each PVC and PET-G. Table 1 shows the levels of process parameters for the runs.

<table>
<thead>
<tr>
<th>S. No.</th>
<th>Variables</th>
<th>Unit</th>
<th>Levels</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Line Screen</td>
<td>lpcm</td>
<td>70 - 80</td>
</tr>
<tr>
<td>2</td>
<td>Air Gap</td>
<td>mm</td>
<td>3 - 5 - 7</td>
</tr>
<tr>
<td>3</td>
<td>Viscosity</td>
<td>s</td>
<td>19 - 21</td>
</tr>
<tr>
<td>4</td>
<td>Voltage</td>
<td>kV</td>
<td>8 - 10 - 12</td>
</tr>
<tr>
<td>5</td>
<td>Speed</td>
<td>m/s</td>
<td>1.33 - 1.67 - 2</td>
</tr>
</tbody>
</table>

The Table 2 shows equivalent current achieved for a given air gap distance and voltage for both PVC and PET-G films. The resistance was calculated by using Ohm’s law (1). The calculated resistance is summation of air gap, impression roller and substrate resistances. The ESA current magnitude generation depends on air gap distance, voltage applied and substrate electrical properties. The PET-G substrate offered high surface and volume resistance; thus, resulting in lower magnitude of current for set air gap and voltage as compared to PVC.
of interest (AOI) of 70mm x 55 mm. The algorithm divides the AOI in smaller targets and later each target is analyzed at sub-visible levels. The recorded pixel luminance value is interpreted by software and the mottle index is evaluated.

3.3.2 Dot Uniformity Ratio

The analysis was performed at 50% patch of the step wedge and images were captured using a microscope at 200X. The captured images were processed through Dexcel Imaging V 2.4.4 software. The image and non-image area was evaluated and then ratio was determined.

3.4 Experimental Process

A baseline for halftone mottle was conducted by performing production run for a few days. The Design of Experiments (DOE) was generated for ESA and gravure process parameters. The halftone mottle data was analysed by analysis of variance (ANOVA) and main and interaction plots to spot out the optimal process parameters minimizing half-tone mottle. The developed regression model was tested for new observations to check the predictability of the model.

<table>
<thead>
<tr>
<th>Air Gap (mm)</th>
<th>Voltage (kV)</th>
<th>PET-G</th>
<th>PVC</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Current (mA)</td>
<td>Resistance (MΩ)</td>
</tr>
<tr>
<td>3</td>
<td>8</td>
<td>0.6</td>
<td>13.33</td>
</tr>
<tr>
<td>10</td>
<td>0.9</td>
<td>11.11</td>
<td>9.09</td>
</tr>
<tr>
<td>5</td>
<td>12</td>
<td>1.2</td>
<td>10.00</td>
</tr>
<tr>
<td></td>
<td>8</td>
<td>0.5</td>
<td>16.00</td>
</tr>
<tr>
<td>10</td>
<td>0.8</td>
<td>12.50</td>
<td>9.0</td>
</tr>
<tr>
<td>12</td>
<td>1.1</td>
<td>10.90</td>
<td>1.2</td>
</tr>
<tr>
<td>7</td>
<td>8</td>
<td>0.4</td>
<td>20.00</td>
</tr>
<tr>
<td></td>
<td>10</td>
<td>0.7</td>
<td>14.29</td>
</tr>
<tr>
<td></td>
<td>12</td>
<td>0.9</td>
<td>13.33</td>
</tr>
</tbody>
</table>

$$R = \frac{V}{I}$$

where,

\[ \begin{align*}
R &= \text{Resistance between charge bar and impression roller} \\
V &= \text{Voltage or Potential difference between charge bar and impression roller} \\
I &= \text{Current}
\end{align*} \]

3.2 Sampling and Printing

A sample size of 10 printed sheets per each run was considered for halftone mottle and dot uniformity. The experimental trials were conducted on a roto-gravure machine which was employed with pneumatic loaded impression roller, auto web tension control, top loading ESA charging bar system and ESA impression roller of 80 shore A hardness. The gravure machine had the maximum speed of 2 m/s. An ink mixing roller was dipped in ink pan to avoid foaming and pigment settling.

3.3 Measurement Technique

3.3.1 Halftone Print Mottle

The halftone patches were scanned at 1200 ppi with Epson V700 scanner. The halftone mottle was evaluated using Verity IA Print Target which employed Software Stochastic Frequency Distribution Analysis (SFDA) evaluation technique. The scanned images were analysed with an area.
4 Results and discussion

4.1 Production Run and Baseline

The baseline for halftone mottle was defined by conducting production runs at pre-determined settings for few days on PVC and PETG films. These runs were set at 70 lpcm line screen, 19 sec viscosity, 100 m/min speed, 80 shore hardness and 3.5 kg/cm² pressure with ESA OFF. The data collected from the production run showed mean halftone mottle as 2.838 and 2.938 for PVC and PETG, hence considered as a baseline. The aim was set to minimize the halftone mottle from the baseline.

4.2 Print mottle

4.2.1 Statistical Analysis

The main effect plots (Fig. 2) suggest the significance of all the parameters on halftone print mottle for PVC and PET-G films. The overall lower halftone mottle was obtained at higher level of line screen, viscosity, voltage, and speed with lower air gap. The lower line screen cell has larger cell opening and corresponding ink volume carrying capacity. This leads to high ink transfer rate under the high net force of impression roller. This causes deterioration of dots resulting in less circularity thereby, high print mottle. The higher line screen cells have low ink volume carrying capacity. The ink distribution was uniform on the substrate under the influence of ESA at higher line screen resulting in sharper dots with good circularity; thereby lower mottle. The halftone cells are very sensitive and highly reactive to change in ESA process parameters.

The ink contains polar molecules which are randomly orientated when no electrostatic force is applied. An applied electrostatic force polarizes the molecules by orienting them in a defined direction due to dipole moments. It helps the ink elevation from the cells and reaches to the substrate surface against the force of gravity. However, the ink evacuation efficiency changes with respect to viscosity and ESA current magnitude.

![Fig. 2: Effects of Process Parameters on Halftone mottle on (a) PVC; (b) PETG](image)

![Fig. 3: Interaction Plots of Halftone Mottle for (a) PVC; (b) PETG](image)
The lower viscosity with ESA shows high ink drift velocity due to low mass content and corresponding low viscous drag force. Thus, ink transfer is high in lower viscosity. The higher ink transferred possesses a higher tendency to spread and thereby causing local variations in reflectance and density leading to print mottle. The higher viscosity of ink has high viscous drag force and ink mass content. Therefore it needs high ESA current to break the inherent resistance and to create dipole movement. Moreover, the high ESA current can be achieved only with lower air gap. The combined influence of higher viscosity which poses less spreading of ink, high voltage with lower air gap resulted in lower halftone mottle. The larger centrifugal force at higher printing speed shows effective ink evacuation from cells.

The interaction plots (Fig. 3) consist of non-parallel lines representing interaction of line screen, air gap, viscosity, voltage and speed. The interaction at 3 mm air gap and 12 kV voltage showed increase in halftone mottle for PVC. It can be postulated to the breakdown of dielectric liquid (ink) beyond 10 kV voltage. The applied voltage is increased beyond the critical voltage of the liquid which results in higher degree of dipole repulsion.

The high energy induced in the ink set turbulent or impulsive motion of molecules leading to reproduction of higher distortional dots resulting in whiskering. This slight discrepancy between the desired and actual applied electrostatic force leads to a significant change in dot reproduction which resulted in higher halftone mottle. Moreover, the spacing between cell is relatively high thus dot has more liberty for distortion which leads to higher halftone mottle. The difference in voltage required for PVC and PET-G has varied due to difference in electrical properties of substrate. The substrate surface and volume resistivity has played a significant role in determining the ESA current. The current generated at 3 mm air gap with 12 kV was 1.2 mA and 1.4 mA for PET-G and PVC respectively. The higher ESA current of 1.4 mA for PVC led to dot deformation; thereby resulting in higher mottle in halftone areas. The optimum ESA current magnitude of 1.2 mA with 12 kV voltage for PETG and 1.1 mA with 10 kV for PVC showed improved dot reproduction. The interaction plots indicate reduction in halftone mottle at an interaction of 80 lpcm line screen, 3 mm air gap, 21 s viscosity, 2 m/s printing speed with 10 kV voltage for PVC while 12 kV voltage for PETG; hence considered as best settings.

Table 3: Summary of Model for Halftone Mottle - PVC

<table>
<thead>
<tr>
<th>Source</th>
<th>DF</th>
<th>Seq SS</th>
<th>Adj SS</th>
<th>Adj MS</th>
<th>F</th>
<th>P</th>
</tr>
</thead>
<tbody>
<tr>
<td>Regression</td>
<td>9</td>
<td>6.6228</td>
<td>6.6228</td>
<td>0.7358</td>
<td>600.851</td>
<td>0.000</td>
</tr>
<tr>
<td>Line screen</td>
<td>1</td>
<td>1.4696</td>
<td>0.3677</td>
<td>0.3677</td>
<td>255.399</td>
<td>0.000</td>
</tr>
<tr>
<td>Viscosity</td>
<td>1</td>
<td>3.0442</td>
<td>0.3127</td>
<td>0.3127</td>
<td>300.282</td>
<td>0.000</td>
</tr>
<tr>
<td>Voltage</td>
<td>1</td>
<td>0.4881</td>
<td>0.0074</td>
<td>0.0074</td>
<td>6.082</td>
<td>0.014</td>
</tr>
<tr>
<td>Speed</td>
<td>1</td>
<td>0.1600</td>
<td>0.1600</td>
<td>0.1600</td>
<td>130.697</td>
<td>0.000</td>
</tr>
<tr>
<td>Line screen*Viscosity</td>
<td>1</td>
<td>0.2987</td>
<td>0.2987</td>
<td>0.2987</td>
<td>243.929</td>
<td>0.000</td>
</tr>
<tr>
<td>Air gap*Viscosity</td>
<td>1</td>
<td>0.0068</td>
<td>0.0068</td>
<td>0.0068</td>
<td>5.602</td>
<td>0.018</td>
</tr>
<tr>
<td>Air gap*Voltage</td>
<td>1</td>
<td>0.1011</td>
<td>0.1011</td>
<td>0.1011</td>
<td>82.582</td>
<td>0.000</td>
</tr>
<tr>
<td>Viscosity*Voltage</td>
<td>1</td>
<td>0.0054</td>
<td>0.0054</td>
<td>0.0054</td>
<td>4.431</td>
<td>0.036</td>
</tr>
<tr>
<td>Error</td>
<td>206</td>
<td>0.2522</td>
<td>0.2522</td>
<td>0.0012</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Lack of Fit</td>
<td>98</td>
<td>0.1258</td>
<td>0.1258</td>
<td>0.0012</td>
<td>1.097</td>
<td>0.318</td>
</tr>
<tr>
<td>Pure Error</td>
<td>108</td>
<td>0.1264</td>
<td>0.1264</td>
<td>0.0011</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Total</td>
<td>215</td>
<td>6.8751</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Regression Equation:

Halftone Mottle for PVC = 15.978 - 0.165 Line Screen (lpcm) + 0.193 Air Gap - 0.629 Viscosity + 0.073 Voltage - 0.100 Speed + 0.007 Line Screen*Viscosity - 0.004 Air Gap*Viscosity - 0.008 Air Gap*Voltage - 0.003 Viscosity*Voltage.                    (2)

The ANOVA (Table 4 and Table 6) indicate that all the main factors are significant as the p-values are below α value of 0.05. The higher F-statistics value for viscosity of 300.282 and 2066.35 for PVC and PETG indicates the most significant factor which influences the halftone print mottle. The interaction of voltage with air gap, line screen and speed; viscosity with air gap, voltage and line screen and air gap with line screen were significant in minimizing half-tone mottle at 95% confidence level for both PVC and PETG films. The Table 3 and Table 5 shows a higher percentage of coefficient of determination (R-Sq.) indicating that 96.33% and 99.44% of the variability could be explained by the model for PVC and PETG at 95% confidence level. The adjusted R-Sq of 96.17% and 99.41% indicates significant improvement of the model by using five parameters. The highest R-Sq. (predicted) of 95.95% and 99.37% indicates that the model predicts new observations nearly as well as it fits the existing data.

Regression Equation:

Halftone Mottle for PETG = 23.796 - 0.206 Line Screen + 0.051 Air Gap - 0.967 Viscosity - 0.216 Voltage - 0.372 Speed + 0.00033611 Line Screen*Air Gap + 0.00907481 Line Screen*Viscosity + 0.00050556 Line Screen*Voltage - 0.00314479 Air Gap*Voltage + 0.00785972 Viscosity*Voltage + 0.0131402 Viscosity*Speed.                          (3)
4.2.2 Verification and Consistency

The best settings (80 lpcm line screen, 3 mm air gap, 21 s viscosity and 2 m/s speed with 10 kV for PVC and 12 kV for PETG) as obtained from the interaction plot was confirmed by conducting a press run and then checked for its consistency by re-running for few days.

From Table 7, a significant improvement is evident from Production run to consistency run in halftone mottle for both PVC and PET-G films. The halftone mottle is minimized by 33% for PVC and 32% PETG.

<table>
<thead>
<tr>
<th>Trials</th>
<th>PET-G</th>
<th>PVC</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>HT Mottle</td>
<td>Std. Dev.</td>
</tr>
<tr>
<td>Production Run</td>
<td>2.938</td>
<td>0.109</td>
</tr>
<tr>
<td>Verification Run</td>
<td>2.002</td>
<td>0.077</td>
</tr>
<tr>
<td>Consistency Run</td>
<td>1.98</td>
<td>0.075</td>
</tr>
</tbody>
</table>

4.2.3 Validation of Model

The model developed through regression analysis was validated by comparing the halftone mottle values as obtained from actual experimental data with the values predicted from regression equation (Eq. 4.1, 4.2).

The plot of actual observations versus predicted values (Fig. 4) shows a correlation coefficient of 0.8922 and 0.8754 for PVC and PET-G respectively. This justifies the prediction ability of the model.

4.3 Dot Uniformity: Image to Non-image Area Ratio

The 50% dots from the step wedge were captured by microscope at 200 x magnification. The ratio of image area to non-image was calculated for uniformity of dot distribution (Fig. 5). The ratio of 1 indicates maximum uniform distribution of image to non-image area.
The main effect plot indicates that higher dot uniformity was achieved at lower air gap with higher levels of line screen, viscosity, voltage and speed for PVC and PET-G. i.e. 80 lpcm line screen, 3mm air gap, 21 s viscosity, 12 kV voltage and 2 m/s speed. Comparatively PVC showed better uniformity ratio than PET-G. It can be manifested to the higher surface energy of PET-G substrate which led to higher spreading. The dot spreading is high at lower line screen due to transfer of high ink volume which affects the dot distribution uniformity. Lower air gap with higher voltage can achieve high electrostatic force magnitude where the ink evacuation from cells is more effective which results in more uniform dot distribution. Also, very less residuals ink is present in the cells. The lower viscosity ink has high tendency to spread which leads to more area coverage and results in uneven distribution of ink. The higher
viscosity ink has less solvent content, thus spreading of ink is limited inherently which results in sharper and more uniform ink distribution. Higher speed has larger degree of centrifugal force acting on cylinder. The uniform ink evacuation from cells results in uniform dot distribution.

5 Conclusion

The study aimed to identify the significant factors which affect the halftone print mottle and the goal was to minimize the defect. The design of experiments (DOE) was generated for gravure and ESA process parameters to identify the impact of each parameter on halftone mottle. All the factors were significant in minimizing the half-tone mottle. The interaction of voltage with air gap, line screen and speed; viscosity with air gap, voltage and line screen and air gap with line screen were significant in minimizing half-tone mottle at 95% confidence level for both PVC and PETG films. The halftone mottle was minimized at 80 lpcm line screen, 3 mm air gap, 21 s viscosity, 2 m/s speed and 10 kV voltage for PVC while 12 kV voltage for PETG. The optimal process parameters showed reduction in halftone mottle by 32% and 33% for PET-G and PVC respectively. Furthermore, the developed regression model was tested for new observation which showed more than 95% predictability. In addition, the uniformity of image to non-image area distribution was measured. The halftone area with higher dot uniformity showed reduced halftone mottle.

Poor or uneven ink lay down results in half-tone mottle which causes variation in reflectance resulting in differential ink gloss, density and color on the printed graphics. The half-tone mottle can be minimized and governed by the gravure process parameters. Thus, this research aims to understand the impact of ESA on half-tone mottle for shrink films. The findings of this study shall furnish the gravure printer to utilize the optimal settings to deliver quality print jobs with reduced print waste. The reduction in print waste contributes towards sustainability and helps to reduce possible environmental damage.

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7 References


