Statistical Modelling of Print half-tone mottle in PET-G and PVC Shrink Films

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Abstract

PVC and PET-G (Glycol modified polyethylene terephthalate) have the highest consumption in the shrink sleeve market due to its high shrink abilities and cost effectiveness. The reproductions of fine tone details on these films are challenging as the occurrence of graininess and image-noise results in print defect such as print half-tone mottle. The presence of print half-tone mottle is visually disturbing leading to wastage of ink, substrate and time. The purpose of this study is to investigate the effect of gravure process parameters viz. ink viscosity, press speed, impression hardness and line screen and develop statistical model for print half-tone mottle in shrink films. The base line for print half-tone mottle was determined by conducting production runs on press with a defined set of process parameters and the target was set to minimize it from the baseline. The half-tone area was scanned and processed through SFDA algorithm to calculate print half-tone mottle. The design of experiments (DOE) was generated for above-mentioned process parameters and was analysed by analysis of variance (ANOVA) to find the significant factor affecting the print half-tone mottle. The analysis revealed line screen, viscosity and hardness as significant factors in minimizing print half-tone mottle. The results showed minimization of print half-tone mottle by 28% for both PVC and PET-G films. Furthermore, regression model was developed and validated for print half-tone mottle and a correlation coefficient (R^2) of 0.8696 and 0.879 was achieved for PET-G and PVC respectively. The proposed model is helpful in determining the impact of gravure process parameters and prediction of print half-tone mottle in shrink films.

KEYWORDS: Shrink films, Print half-tone mottle, DOE, ANOVA, Regression model.

1. Introduction

Shrink films are used to suffice the need of labelling a product, which shrinks to the contour of the product. PVC (Polyvinyl Chloride) and PET-G (Glycol modified Polyethylene Terephthalate) hold a major market share globally for shrink films. Shrink films are widely printed by gravure process due to its inimitable print quality and its capabilities for large volume runs. The key challenge for gravure printer is to reproduce fine details on prints and reduce rejections. The variation in ink density and tone reproduction leads to a defect called print half-tone mottle. Print half-tone mottle can be defined as unevenness in print density that causes inhomogeneity in the perceived reflectance.

The print defects such as print mottle, voids, and dot skips originate because of inconsistent and/or insufficient ink transfer from the gravure cylinder to the substrate. Since ink transfer has a direct impact on print density, it is important to understand the factors affecting ink transfer and subsequently mottle. Ink transfer is governed by process parameters such as press speed, printing pressure, ink viscosity and resin type. The transfer of ink on substrate increases at lower viscosity and lower speed. This is due to low absorptivity and porosity that restricts any further flow [1]. A high angled doctor blade results in a deposition of thinner ink layer on the substrate due to the lesser gap between the blade and the cylinder [2]. The density and ink transfer decreases at higher screen ruling and lower engraving needle tip angle. The higher cell angle leads to higher opening and results in more ink transfer [3]. The solid mottle in shrink films is reduced at higher viscosity, press speed, impression hardness and line screen while the print voids are minimized at lower ink viscosity, press speed, line screen and higher impression hardness [4,5]. The type of gravure cylinder-making (laser and electro-mechanical) and electrostatic assist (ESA) has an impact on dot gain and mottle on publication papers and packaging boards. Laser engraved cylinders exhibit higher dot gain and lower print mottle than electro-mechanical engraved cylinder due to higher cell volume [6,7]. The irregular dot fragments or missing dots result in mottled prints [8]. The occurrence of print half-tone mottle is due to non-uniformity of optical dot gain [9]. The surface roughness of the substrate has a major impact on print mottle. The surface characteristics of substrate have an impact on print mottle. The print mottle increases with decreasing surface roughness and optical density due to the non-uniformity of ink coverage [10].

Various instrumental methods have been established in identifying and quantifying the print mottle. These include Stochastic Frequency Distribution Analysis (SFDA), STFI and wavelet analysis. SFDA maps the average and variation in luminance values of pixels within a target area to calculate back-trap, solid and half-tone mottle index [11,12]. STFI employs band pass analysis from 1-8 mm to 8-16 mm, standard deviation and mean reflectance of selected target are evaluated to calculate the co-efficient of variation (CoV) [13]. The Discrete Wavelet Analysis discretizes the image into high and low frequencies. The two-dimensional discrete algorithm removes the noise from the image, which is regarded as mottle index [14]. Print mottle is essentially a visual phenomenon and any means of instrumental evaluation is expected to approximate the visual perception effectively.

Although much research has been focussed on methods to identify process parameters affecting print mottle, the development of statistical model for print halftone mottle on shrink films remains a lesser explored domain. Hence, there exists an imminent need for determination of optimum process parameters and development of model to minimize and predict the print halftone mottle so as to minimize the losses incurred.

2. Method and material

2.1 Substrate

Polyvinylchloride (PVC) and Glycol modified Polyethylene terephthalate (PET-G) of 40-μm thicknesses was used for experimental trails. To determine the surface energy of Cast PVC and PET-G substrates, two standard tests viz. formamide and glycerol liquids with known contact angle, surface tension, polar and dispersive components were used. A Holmarc Contact Angle Meter was used to analyse the contact angle through the sessile drop using the test liquids on ten samples of PVC and PET-G. The substrate surface energy was evaluated by using geometric mean equation to determine the polar and dispersive components of the substrate. A summation of both the values was regarded as surface energy of the substrate, PVC and PET-G had surface energy of 36mN/m and 38mN/m.

2.2 Ink

A solvent based black ink with acrylic resin base was chosen and diluted with recommended solvent combination of ethyl acetate, toluene, iso-propyl alcohol (IPA) and butyl acetate in the ratio of 3:4:2:1 respectively. Kruss K 100 Ring Tensiometer was employed to determine the surface tension of the ink using Du Noüy ring technique. The surface tension of ink was observed to be 23.77mN/m. The viscosity of ink was gauged with #4 Ford cup for the entire experimental trials.

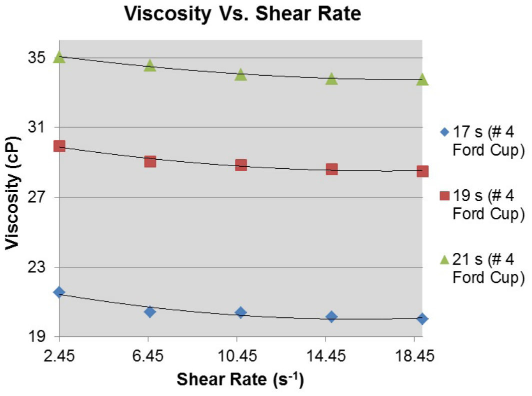
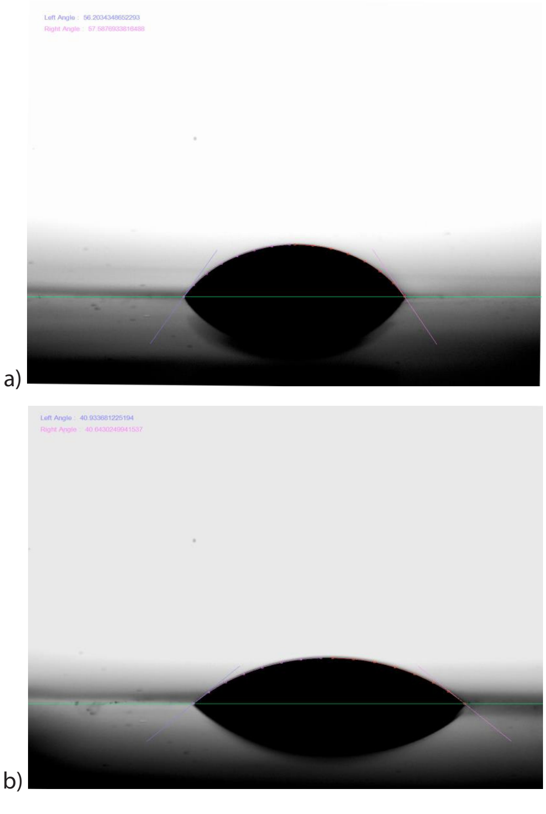


Fig. 1: Effect of Shear Rate on Viscosity

The figure 1 is a representative of the effect of shear rate on viscosity (cP) of ink at various viscosities (#4 Ford cup). A decrease in viscosity (cP) is observed with increase in shear rate, thereby exhibiting shear-thinning behaviour. Initially, the viscosity drops rapidly with increase in shear rate and then reduces at a lower rate after which even with increased shear rate the viscosity does not fall rapidly. A drop in viscosity (cP) with increased shear rate is higher at 21 s than 17 s (#4 Ford cup). This is due to the thixotropic tendency of ink which is dependent on solid to solvent ratio. A higher solvent content at 17 s shows lower thixotropy, thus negligible drop in viscosity. Low viscosity ink with lower yield value may result in print mottle during printing.

2.3 Ink-Substrate Interaction

The interaction between the ink and the substrate is critical to print quality. The behaviour of ink over the substrate after transfer from the image carrier exerts a direct impact on printability. The nature and extent of spreading of ink over the substrate can be correlated to various attributes of printability such as dot circularity, area, perimeter and print defects such as mottle. Higher spreading causes random distribution of pigment particles causing uneven reflectance from the print which finally contributes to higher mottling over non-absorbent substrates.



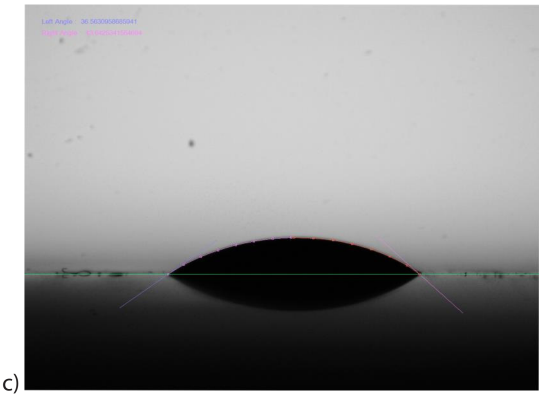


Fig. 2: Contact angle of Ink on substrate: (a) 21 s; (b) 19 s; (c) 17 s.

The contact angle was found to be lower at lower viscosity indicating higher ink spreading and consequently more mottle (Fig. 2). Moreover, lower ink spreading was observed in PVC than PETG. The higher surface energy of PET-G causes a higher spreading tendency and adhesive force against the cohesive force arising due to surface tension of ink.

2.4 Gravure Cylinder

Printability was evaluated on the basis of wedge, half-tone patch (30%), solid patch, skin tone, logo, surface and reverse text. The half-tone patch had size of 9.5cm x 11 cm to determine the ink laydown. The same design elements were replicated into two-ups across the layout. The gravure cylinder was electronically engraved, each design blocks was engraved with varying combination of 70 l/cm and 80-l/cm-line screen. The 70 l/cm had a cell opening of 178 μm while 80 l/cm 136 μm.

3. Experimental Process

The experimental trials were performed on rotogravure machine, which has pneumatic impression roller and automated web tension controller system. The maximum speed of machine for experimental runs was at 2 m/s. The web tension was set to 5 N/m. The impression pressure throughout the trail was constant and set to 3.5 N/cm. An ink-mixing roller was used to avoid foaming and pigment settling in ink pan. The base line for print half-tone mottle was determined by conducting production runs for 5 days with a defined set of process parameters. The data was collected from random 10 printed sheets being considered as sample size. The half-tone area was scanned and analysed with software to calculate print half-tone mottle. An experiment was designed for process parameters viz. ink viscosity, speed, impression hardness and line screen. The design of experiments was generated for process parameters and the data was analysed by analysis of variance (ANOVA) to find significant factors affecting the print half-tone mottle. A statistical model was developed and the results were interpreted with main and interaction plots to find optimal settings of the process parameters. The best setting results were further tested by conducting validation runs and were compared using a regression model to check its predictability.

3.1 Method of data gathering

The printed rolls were cut into sheets and were examined for print half-tone mottle. The printed half-tone area was scanned with Epson V700 scanner and was evaluated by Verity IA Print Target v3 software. The Verity IA software is employed with an SFDA algorithm technique to determine the print half-tone mottle. The prints were placed on the scanner bed and a white vinyl faced pad was placed on the printed sample to give a uniform pressure and to lie flat on scanner bed. The halt-tone patches were scanned in 1200ppi and were evaluated by print half-tone mottle measurement routine. The scanned images were analysed with an area of interest (AOI) of 70mm x 55mm. The SFDA algorithm interprets the recorded luminance value by dividing the area into smaller targets. Furthermore, the smaller targets are discriminated and analysed at sub-visible level.

3.2 Mottle Analysis Algorithm

Stochastic Frequency Distribution Analysis (SFDA)

SFDA firstly determines the properties of the texture contained in the image and then calculates the spatial distribution of this texture. When a digital image is fed to SFDA for analysis, it first samples the entire image in a regular pattern of contiguous target areas. These target areas are measured and the data obtained is stored simultaneously in two databases. One database stores the value of “s” while the other stores the mean value M_{TL} for each target area. “s” denotes the two dimensional standard deviation within the target area. Mean luminance value (M_{TL}) is the mean of luminance values of all the pixels present in a target area and describes the overall visual impact of the analyzed target area. The standard deviation “s” is calculated using the formula:

$$s = \sqrt{\frac{\sum (P_L - M_{TL})^2}{n}} \qquad \text{...Eq. 3.1}$$

Where,

P_L= individual pixel luminance
M_{TL} = Mean luminance for the pixels in the target and
n = Number of pixels in the target.

The degree of variation in “s” indicates the level of uniformity among the square targets while variance of M_{TL} is an indicator of uniformity in the luminance. The mottle value for the area of image inspected is then calculated using the formula:

$$\text{Mottle} = K * (\sigma_s * M_s * \sigma_m) \qquad \text{...Eq. 3.2}$$

Where K is the scaling factor,

σ_s= Standard deviation of s values
σ_m = Standard deviation of M_{TL} values
M_s = Mean of “s” values

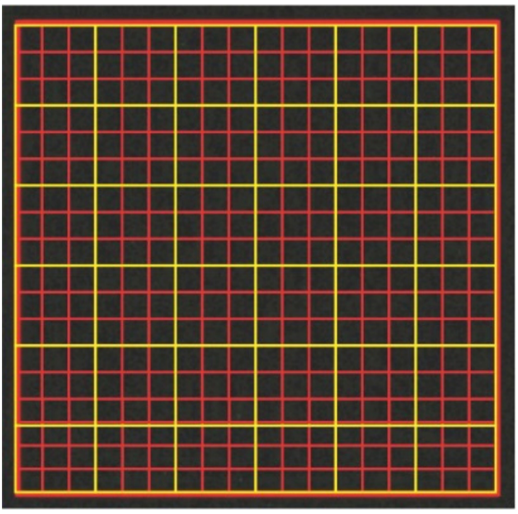
This equation yields a texture mottle number for the area of image inspected. When an area of interest within the image is selected, the “s” and M_{TL} values are extracted from their respective databases. An area having lower mottle will correspond to lower values of σ_s and M_s. This is not necessarily true for σ_m.

Texture can vary from area to area in an image. This variation also needs to be evaluated in order to present a precise account of mottle. So, next step involves analysis of spatial distribution of texture mottle. The image is divided uniformly into larger areas containing a group of smaller targets. Equation 3.2 is used as the base calculation for obtaining texture mottle number of each larger target area. These values are then employed for the computation of spatial mottle using the formula:

$$\text{Spatial Mottle} = K * (\sigma_O * M_O) \qquad \text{...Eq. 3.3}$$

where,
σ_O = Standard deviation of large target mottle number
M_O = Mean of large target mottle number

a)



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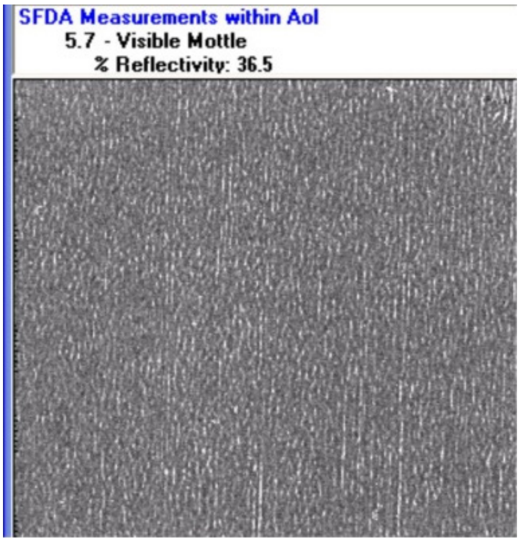


SFDA Measurements within AoI
5.7 - Visible Mottle
% Reflectivity: 36.5

Fig. 3: Area of Interest divided into target areas (a) analyzed output image (b) of Mottle

3.3 Experimental Design

The major factors, which affect the printability, was screened and chosen as input parameters. A general full factorial design of experiments (DOE) was generated to evaluate the print half-tone mottle. It comprised of two levels of line screen and three levels of viscosity, speed and impression hardness. Thus, the total trails in the design were 108 with 2 replicates (54 runs per replicate). The detailed experimental design along with input parameters and levels are represented in Table 1.

Table 1: Process Variables and Levels for Print half-tone mottle

S. No.	Variables	Unit	Levels		
			Low	Mid	High
1	Line Screen	l/cm	70	-	80
2	Viscosity	sec	17	19	21
3	Speed	m/s	1.33	1.67	2
4	Hardness	Shore A	60	70	80

4. Results and discussion

4.1 Dot Structure Analysis

The effect of process variables on dot fidelity for both PVC and PET-G were analyzed. To analyze the dot structure the 30% patch of the step wedge was captured using a Microscope at 200X. The captured images were processed through Dexel Imaging V 2.4.4 software to calculate critical aspects of the dot like area, circularity and perimeter (Fig. 4).

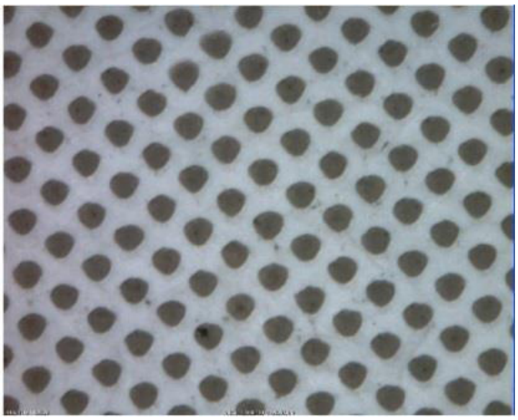
The dot circularity refers to the roundness of dot and represented as

$$\text{Circularity} = 4\pi A/p^2 \qquad \text{...Eq. 5.1}$$

Where A = area of dot
p = perimeter or the dot

The dot circularity is equal to 1 for a circle and less than 1 for gravure dot as the shape of dot is elliptical in structure. The closer to 1, better is the circularity and quality of the printed dot.

a)



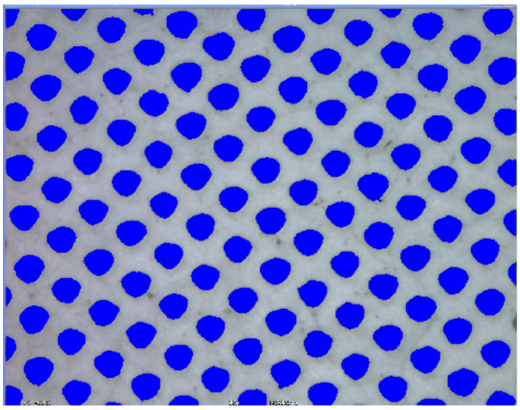

b)

Fig. 4: Dot structure: Original Captured Image (a), Image after processing (b)

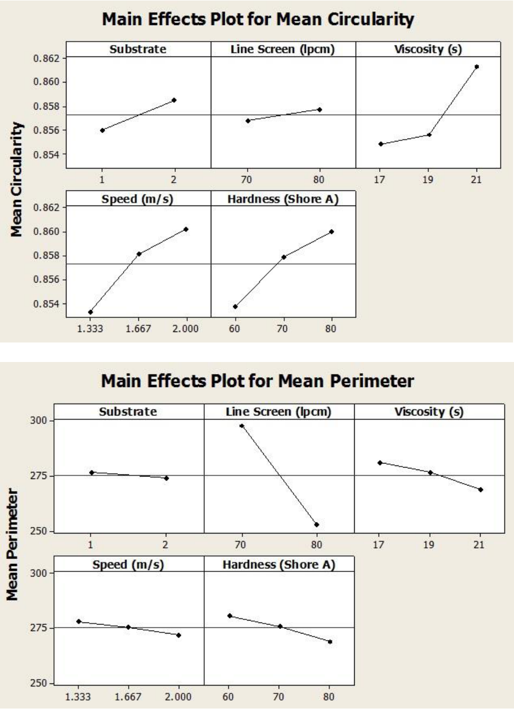


Fig. 5: Effect of Process Variables on Dot Circularity (a) and Perimeter (b)

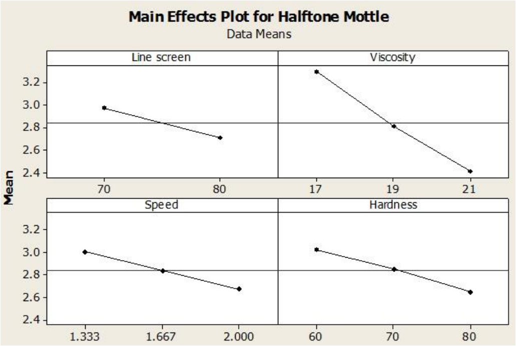
The main effects plot (Fig. 5) suggests higher dot circularity and lower dot perimeter at 80 lpcm line screen, 21 s viscosity, 2 m/s speed and 80 Shore A impression hardness for substrate 2. The substrate 1 refers to PETG while substrate 2 refers to PVC. Higher dot spreading leads to higher deviation of dot shape from ideal, negatively impacting the dot structure by showing lesser circularity and higher perimeter. A higher perimeter may also be attributed to irregular dot boundary which is more evident at lower viscosities due to irregular spreading. A higher line screen results in sharper ink transfer due to smaller cell opening. A higher viscosity ink spreads less hence showing good sharpness, higher circularity and lower perimeter. Higher printing speed allows lesser time for the ink to spread on the substrate, hence exhibiting lower dot perimeter and higher circularity. Lower hardness impression roller bulges comparatively more under the same pressure leading to a higher level of dot deformation. Furthermore, the higher surface energy of PET-G film promotes higher spreading and consequently higher dot perimeter and lower circularity. Thus, higher dot circularity and lower perimeter leads to reduced mottle.

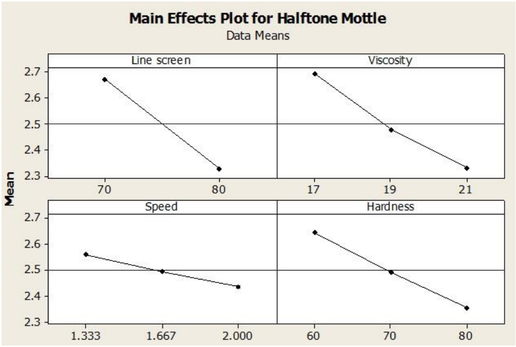
4.2 Baseline for Print half-tone mottle

The production runs were conducted on PET-G and Cast PVC films of 40-μm thicknesses for 5 days on rotogravure press with pre-determined settings of press parameters. Each day 10 sheets of samples were examined to create a baseline for print half-tone mottle. The mean print half-tone mottle from the test samples for PET-G and PVC was found to be 2.97 and 2.89 respectively. The aim of the experiment was set to reduce the print half-tone mottle from baseline values.

4.3 Print half-tone mottle

4.3.1 Main Effects, Interaction and ANOVA

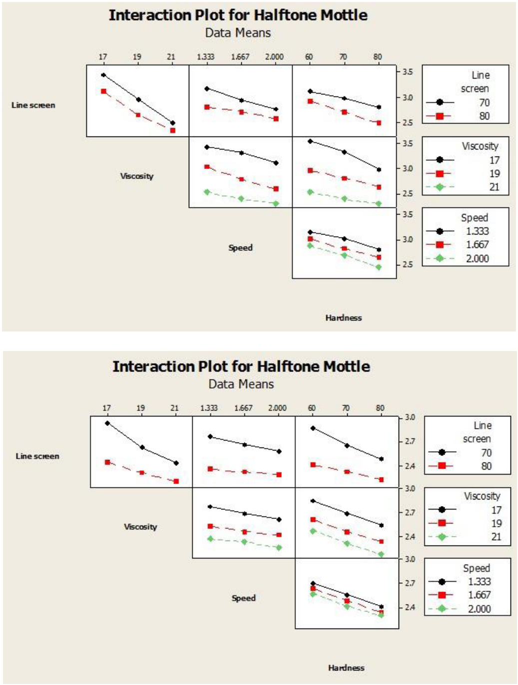




b)

Fig. 6: Main Effects for print half-tone mottle (a) PET-G; (b) PVC

The main effect plot (Fig. 6) suggests that viscosity is the key parameter affecting mottle in half tones. A slight shift in viscosity may affect the ink evacuation and ink transfer significantly in halftones (30% dot) because of comparatively smaller cell opening than solid patch (100% dot). The presence of higher solvent content in lower viscosity ink results in higher liquid transfer from the cells at a given press speed. This wet ink film on the substrate is more susceptible to deformation under impression pressure. At 21s viscosity the dots are more circular due to higher contact angle of ink on the substrate thereby resulting in less ink spreading (Fig. 2). Higher dot circularity is an indicator of stable ink transfer and deposition onto the substrate, which in turn reduces mottle. Moreover, ink viscosity higher than a threshold limit may lead to uneven ink transfer due to cell clogging thereby resulting in higher halftone mottle. Cylinder screen ruling, printing speed and impression roller hardness do affect print half-tone mottle, but comparatively to a lower extent. The print half-tone mottle reduces at higher levels of line screen (80 lpcm), printing speed (2 m/s) and impression roller hardness (80 shore A). The smaller cell opening at 80 lpcm yields to lower dot gain as compared to 70 lpcm, thus resulting in lower halftone mottle. Higher speed ensures effective transfer of ink from cells due to higher centrifugal force. At lower speed, the centrifugal force is less with additional dwell time in the nip. This results in inadequate ink evacuation from the cell and distorted dot reproduction thus leading to higher halftone mottle. Moreover, as observed in Fig.1, the ink is exhibiting shear thinning behaviour with increase in shear rate. This indicates better flow with increase in printing speed. It also generates more shear stress in the ink, which has a stabilising effect on ink after transfer as it resists spreading more effectively. Also, a lower hardness impression roller tends to bulge more under the same pressure as compared to a higher hardness roller, leading to greater substrate deformation in the nip. This in turn leads to inconsistent dot deformation and consequently contributes to mottle.



a)

b)

Fig. 7: Interaction Plot for Print half-tone mottle (a) PET-G; (b) PVC

The interaction plot (Fig. 7) indicates that the lowest print half-tone mottle is obtained at an interaction of 80 l/cm, 21 s, 2 m/s and 80 Shore-A hardness. A significant interaction exists between viscosity and hardness. Due to the lower cell opening in 30 % halftone patch, the parameter interacts comprehensively with other parameters to define ink transfer and mottle. Higher speed helps higher viscosity ink to transfer better from cylinder onto the substrate held against harder impression roller. Higher viscosity and higher hardness perform the task of limiting random spreading and pigment distribution, maintaining stable dot shape and hence resulting in lower mottle. Higher cell depth will give higher ink transfer, provided the ink is not too viscous to cause cell clogging.

4.3.2 Verification and Consistency

The best settings (80 l/cm line screen, 21 s viscosity, 2 m/s speed and 80 Shore A hardness) as obtained from the interaction plots from Fig.5 were confirmed by conducting a verification press run and then checked for its consistency by re-running for few days.

Table 2: Production, Verification and Consistency Run for Print Halftone Mottle

Trials	PET-G		PVC	
	Halftone Mottle	Std. Dev.	Halftone Mottle	Std. Dev.
Production Runs	2.97	0.2147	2.89	0.1989
Verification Run	2.2	0.1247	2.1	0.1141
Consistency Runs	2.15	0.1154	2.07	0.1020

The Table 2 shows an evidence of significant improvement from Production run to consistency run in print half-tone mottle for both PVC and PET-G films. The print half-tone mottle is minimized by 28% for PET-G and PVC respectively.

4.3.3 Development of Models for Print half-tone mottle

The next objective was to develop regression model for halftone mottle and validate to check the predictability for PET-G and PVC shrink films.

Table 3: Summary of Model for Print half-tone mottle - PET-G

S	R-Sq	R-Sq (adjusted)	Press	R-Sq (predicted)
0.126152	93.00 %	92.51 %	1.83608	91.92 %

Table 4: ANOVA Table for Regression Print Halftone Mottle - PET-G

Source	DF	Seq SS	Adj SS	Adj MS	F	P
Regression	7	21.130	21.130	3.019	189.680	0.000
Line Screen	1	1.928	0.390	0.390	24.490	0.000
Viscosity	1	14.098	0.690	0.690	43.378	0.000
Speed	1	1.911	0.225	0.225	14.132	0.000
Hardness	1	2.580	0.488	0.488	30.649	0.000
Line Screen* Viscosity	1	0.149	0.149	0.149	9.389	0.003
Line Screen*-Speed	1	0.147	0.147	0.147	9.223	0.003
Viscosity* Hardness	1	0.317	0.317	0.317	19.910	0.000
Error	100	1.591	1.591	0.016		
Lack of Fit	46	0.856	0.856	0.019	1.355	0.135
Pure Error	54	0.735	0.735	0.014		
Total	107	22.722				

Regression Equation for Print half-tone mottle - PET-G

$$\begin{aligned} \mathit{HT\ Mottle} = {} & 26.47 - 0{,}16\ \mathit{Line\ Screen} - 0.85\ \mathit{Viscosity} \\ & - 2.52\ \mathit{Speed} - 0.1\ \mathit{Hardness} \\ & + 0.005\ \mathit{Line\ Screen} \times \mathit{Viscosity} \\ & + 0.03\ \mathit{Line\ Screen} \times \mathit{Speed} \\ & + 0.004\ \mathit{Viscosity} \times \mathit{Hardness} \qquad \ldots\text{Eq.4.1} \end{aligned}$$

Table 5: Summary of Model for Print Halftone Mottle - PVC

S	R-Sq	R-Sq (adjusted)	Press	R-Sq (predicted)
0.0464092	97.34 %	97.16 %	0.251824	96.94 %

Table 6: ANOVA Table for Regression Print Halftone Mottle - PVC

Source	DF	Seq SS	Adj SS	Adj MS	F	P
Regression	7	7.895	7.895	1.128	523.650	0.000
Line Screen	1	3.162	0.727	0.727	337.447	0.000
Viscosity	1	2.380	0.431	0.431	200.086	0.000
Speed	1	0.285	0.069	0.069	31.986	0.000
Hardness	1	1.514	0.272	0.272	126.333	0.000
Line Screen* Viscosity	1	0.308	0.308	0.308	143.054	0.000
Line Screen*-Speed	1	0.058	0.052	0.052	24.023	0.000
Line Screen* Hardness	1	0.194	0.194	0.194	90.199	0.000
Error	100	0.215	0.215	0.002		
Lack of Fit	46	0.124	0.124	0.003	1.580	0.053
Pure Error	54	0.918	0.092	0.002		
Total	107	8.110				

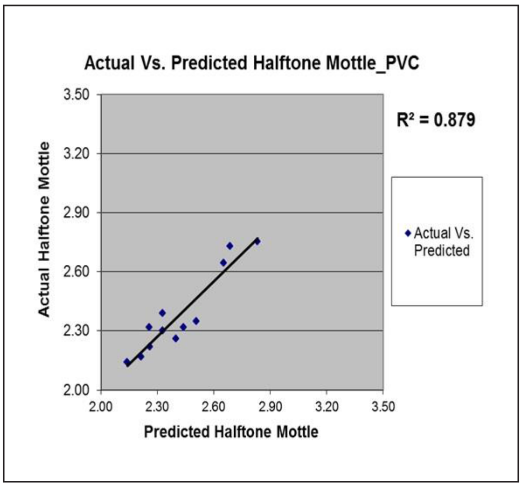
Regression Equation for Print half-tone mottle - PVC

$$\begin{aligned} \mathit{HT\ Mottle} = {} & 25 - 0{,}26\ \mathit{Line\ Screen} - 0.6\ \mathit{Viscosity} \\ & - 1{,}4\ \mathit{Speed} - 0.1\ \mathit{Hardness} \\ & + 0.006\ \mathit{Line\ Screen} \times \mathit{Viscosity} \\ & + 0.02\ \mathit{Line\ Screen} \times \mathit{Speed} \\ & + 0.001\ \mathit{Viscosity} \times \mathit{Hardness} \qquad \ldots\text{Eq. 4.2} \end{aligned}$$

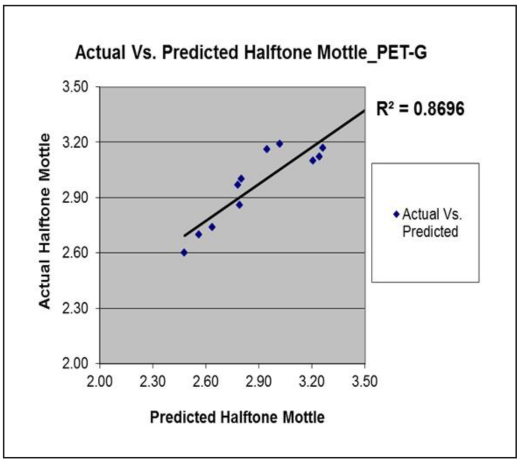
From Table 3 and Table 5, the intercept of print half-tone mottle is 26.47 and 25 for PET-G and PVC respectively. This indicates that if all the regressors (line screen, viscosity, speed and hardness) are zero, then the response value (print half-tone mottle) is equal to the intercept. The higher percentage of coefficient of determination (R-Sq.) indicates that the model could explain 93% and 97.34% of the variability for PET-G and PVC at 95% confidence level. The adjusted R-Sq of 92.57% and 97.16% indicates a significant improvement of the model by using four factors. The minor difference between R-Sq. and adjusted R-Sq. indicates significant regression of the model by using four factors for both the substrates. The highest R-Sq. (predicted) of 91.92% and 96.94% indicates that the model predicts new observations nearly as well as it fits the existing data. The lack of fit with α > 0.05 indicates that the data fits well in the model. The lack of fit value of 0.135 and 0.053 represents the adequacy of the model for both PET-G and PVC. The ANOVA table 4 and table 6 for print half-tone mottle on PET-G and PVC indicate that all the main factors are significant as the p-values are below α value of 0.05. The larger F-statistics with $P<0.05$ from the ANOVA tables for PET-G and PVC confirms the significance of all the main factors with line screen, viscosity and hardness having paramount influence on minimising the print half-tone mottle. The interaction of line screen with viscosity, speed and hardness; viscosity with hardness were significant in minimizing the solid mottle at 95% confidence level.

4.3.4 Validation of Models

By comparing the experimentally obtained values of print half-tone mottle with the values predicted from regression equation (Eq. 4.1 and 4.2) the models were validated.



a)



b)

Fig. 8: Actual vs. Predicted Print halftone Mottle (a) PET-G (b) PVC

The plots of actual observations versus predicted values for print half-tone mottle showed correlation coefficients of 0.879 and 0.8696 for PVC and PET-G respectively (Fig. 8).

5. Conclusion

The experimental study was focused on identification of key process parameters affecting half-tone print mottle and development of models for PET-G and PVC shrink films. The interaction plot showed the best combination of gravure process parameters for print half-tone mottle reduction at 80 l/cm line screens, 21 s viscosity, 2 m/s printing speed with 80 Shore-A impression roller hardness. The regression analysis revealed the significance of all the process parameters in minimizing the print half-tone mottle defect for both the substrates. The analysis indicated line screen, viscosity and hardness as the highest strength of impact on print half-tone mottle.

The phenomenon of print mottle is directly associated with ink spreading on the surface of the substrate. The print half-tone mottle was reduced by 28% for both PET-G and PVC shrink films. However, higher mottle index was observed in production and consistency runs for PETG than PVC. This is due to the higher difference between surface energy of PET-G (38 mN/m) and surface tension of ink (23.77 mN/m) than that of PVC (36 mN/m). This higher difference, also called as the wetting difference, results in lower contact angle and higher spreading; thereby leading to higher print half-tone mottle in PET-G (Mottle Index: 2.15) than PVC (Mottle Index: 2.07). The regression models showed good predictive ability for print half-tone mottle in shrink films.

The outcomes of this study shall help the printers to optimize the gravure process parameters for minimization of halftone mottle, thus reducing the print rejections. Further studies may be performed on the effect of Electrostatic Assist (ESA) on print defects.

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