Deformation of Flexographic Printing Plates

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Abstract

The flexographic printing plate undergoes deformation during the printing process that is dependent on the engagement, plate characteristics and the image. Previous work has shown that the individual dot, particularly in the highlight region experiences two forms of distortion that both result in tone gain. These are expansion of the surface of the dot and “barrelling”, where the compression of the dot by the pressure in the printing nip causes the shoulder to make contact with the printed surface. This paper examines the influence of geometry (dot size and shape) on tone gain behaviour.

A model of the dot structure was created using a finite element modelling system. The model allowed the study of the deformation of the dot with time as a load is applied simulating its passage through the printing nip junction. Numerical experiments were designed and used to establish the influence of the geometric characteristics with the minimum number of calculation runs. An L_{16} orthogonal array investigation was carried out where the dot geometry was derived from interferometer measurements on plates having different line rulings, dot depth and plate thickness. The simulations were run over a range of engagements and this also allowed the interaction of these parameters to be studied. The results highlight the importance of the dot structure on the plate and its likely impact on tone gain during printing.

Introduction and previous work

There are several key parameters that can affect the quality produced by flexographic printing. These include engagement, line ruling, dot geometry and plate thickness. Very little is currently understood as to how these parameters affect the printed tone gain, either as individual parameters, or by interactions

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with each other. The purpose of this investigation is to improve the understanding of the effects of the various plate parameters and to determine which parameter has the largest effect on plate deformation.

Using finite element models, an investigation was performed, using orthogonal array techniques, to determine the role each of the parameters has on the deformation of the printing plate. A generic model was developed, which consisted of a single flexographic dot with variable percentage coverage, line ruling, dot depth and plate thickness. In addition, the nip engagement, to which the dot was exposed, could also be adjusted.

A previous experimental investigation has been conducted by Bould et al. [1], which considered how different parameters on the printing plate affect image quality. Using a UV curing ink on an Oriented Polypropylene (OPP) film to eliminate any loss of ink to either the atmosphere or into the substrate, the investigation examined three different line rulings at four different engagements. White light interferometry was used to compare the physical growth of the dot relative to the original coverage on the plate. The results showed that engagement had a greater effect than line ruling. A volume conservation model showed that any tone gain due to plate deformation was only a small part of the overall gain observed during the printing trial, suggesting that ink spreading on the substrate is a significant mechanism of the total tone gain.

A subsequent numerical analysis [2] was performed to develop a model to quantify the proportion of tone gain due to the deformation of the plate and quantify the mechanisms by which the deformation occurs. A single flexographic dot was modelled and the percentage coverage, line ruling and engagement were varied. Data for the plate geometry, established in [1], was used so that the results from the models could be related to the experimental investigation. This enabled the tone gain due to plate deformation to be related to the total gain in flexographic printing. Results showed that deformation of the dot occurred by two distinct mechanisms. The first was lateral expansion of the dot surface as it is compressed, which is dependent on the Poisson's Ratio of the material. As Poisson's Ratio increases, the expansion of the dot surface also increases. The second mechanism concerned the shoulders of the dot barrelling and becoming part of the dot surface. The amount of barrelling is governed by the Young's Modulus of the material. For a stiff material, with a high Young's modulus, little or no barrelling will occur. A flexographic printing plate however, has a low Young's Modulus, allowing barrelling to occur. The two mechanisms of deformation are illustrated in Figure 1. Of the two mechanisms of plate deformation, barrelling was shown to be the dominant mechanism. Engagement and line ruling were both shown to have a large effect on gain due to plate deformation. Comparisons with [1] showed that ink spreading accounts for the majority of tone gain, except at low coverages, where the small dot area restricts the volume of ink on the dot surface, resulting in a higher proportion of gain due to plate deformation.

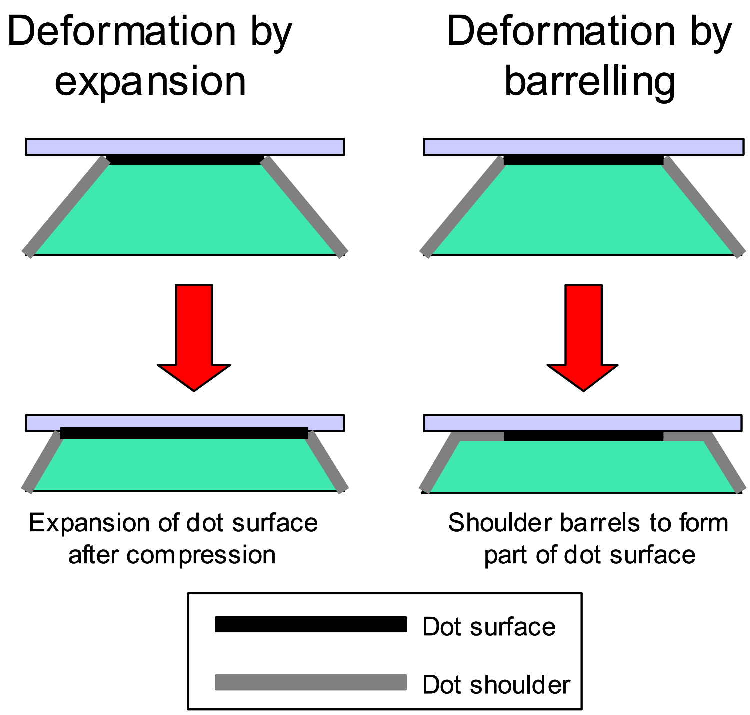


Figure 1 – Two mechanisms of dot deformation [2]

Mirle and Zettlemoyer [3] studied the viscoelastic properties of photopolymer plates. The purpose of their investigation was to develop a numerical model for the relaxation of the plate under operating conditions. Equations for the deformation of the plate across the nip, the pressure in the nip, and the pressure gradient across the plate were used to model the behaviour of the plate in the nip, with the printing plate assumed to be a plain roller. The theoretical model profiled the pressure and the ink thickness along the plate-substrate interface. Using estimates for the ink film thickness in the printing nip, the pressure profile was determined numerically. However, no mention was made of the material properties of the plates on which the models were based. The three plates were then tested experimentally, allowing the model to be corroborated. The nip pressures were adjusted so that all three plates transferred the same quantity of ink to the substrate. The theoretical model did not take into account the negative pressures experienced at the nip entrance or exit. However, the pressure distribution in the nip region was found to correlate well with the theoretical pressure distributions for the plates although the technique for measuring the pressure in the nip was not described. The results for the impression pressures appear very high, highlighting the importance of investigating the deformation of the printing plate and quantifying the tone gain due to the plate alone.

A description of orthogonal arrays and their use in experimental design and optimisation is presented by Phadke [4]. Orthogonal arrays are a subset of a full factorial experiment, which were developed to reduce the time required to study the effect of parameters by reducing the number of individual experiments required to complete the analysis without sacrificing accuracy. As well as reducing the number of experiments, it is possible to investigate any interactions, where the combined effect of any two parameters is different to the sum of the two parameters considered individually. In order to determine the importance of each parameter or interaction, statistical analysis, based on the normal distribution curve is used to produce half-normal plots [5]. Half-normal plots use the magnitude of the response of each column from the orthogonal array, ranked from lowest to highest. This is then plotted against a set of half-normal scores. The half-normal scores are determined from the positive portion of a normal distribution curve with a mean of zero. The positive portion of the normal distribution curve is used as it is the magnitude of the responses that is important and not the direction of the response. If no parameter had a significant effect on the process, a normal distribution would be produced and the plot of the responses against the half-normal scores would produce a linear relationship. Therefore, any parameters that have an effect on the process may be identified, as its point on the half-normal plot will be on the non linear part of the curve.

Development of orthogonal array and methodology

For the current investigation, a model of a round flexographic dot, developed in [2], was used, Figure 2. The model was constructed parametrically, allowing coverage, line ruling, engagement and dot depth to be easily adjusted. The dot was bounded by a square as shown in Figure 3. Engagement was applied by displacing a steel shell onto the dot surface. The shell was modelled as a flat plate, as the radius of the impression cylinder, which the shell simulated, is large compared with the size of the dot. Mounting tape was also included in the model as it is part of the overall system used in flexographic printing. The material properties for the plate and the mounting tape are shown in Table 1 [2].

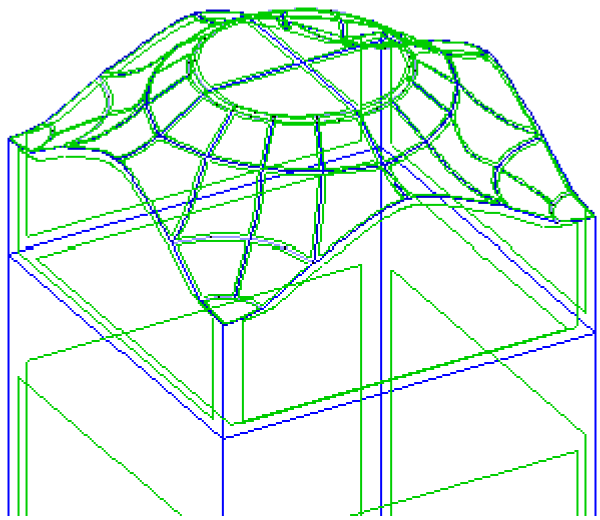


Figure 2 – Round dot model of flexographic dot [2]

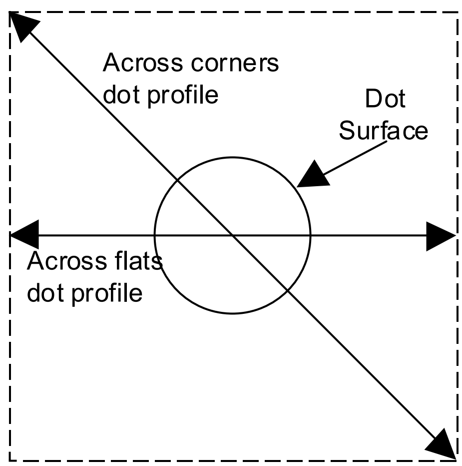


Figure 3 – Plan view of dot profiles on model [2]

	Young's Modulus (Nmm^{-2})	Poisson's Ratio	Shear Modulus (Nmm^{-2})	Density ($kgmm^{-3}$)
Flexographic Printing Plate	3.611	0.43	1.263	1.033E-6
Flexographic Mounting Tape	0.4611	0.45	0.1590	5.48E-7

Table 1 – Material properties used for numerical models [2]

A non-linear finite element solver was used for the models, as the dot geometry changed as the load was applied and the contact evolved, resulting in the use of an iterative solution. For the purposes of the numerical study, the models assumed dry contact with no ink, reducing the problem to a single phase analysis. In order to simulate any lubricating effects that the ink would provide, the coefficient of friction between the dot and the steel shell was set at 0.001, so any resistance to dot deformation was negligible and the dot could slide freely underneath the shell.

The orthogonal array was developed to consider key parameters that had an effect on the printing plate. These were plate coverage, line ruling, dot depth, nip engagement and plate thickness. It was decided to use a two level L_{16} orthogonal array shown in Table 2 to permit analysis of each parameter separately. This particular array was chosen as it enabled all plate parameters to be considered. In addition, all possible interactions between parameters could be investigated. The linear graph showing the interactions is displayed in Figure 4. The numbers on the graph refer to the column numbers in the orthogonal array. In the array, the plate parameters are assigned to columns 1, 2, 4, 8 and 15 (indicated by the nodes in Figure 4)and the interactions are investigated in the remaining columns (indicated by the connecting lines with the column numbers adjacent).

	Coverage	Line Ruling	1+2	Dot Depth	1+4	2+4	8+15	Engagement	1+8	2+8	4+15	4+8	2+15	1+15	Plate thickness
	1	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**	**13**	**14**	**15**
1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
2	1	1	1	1	1	1	1	2	2	2	2	2	2	2	2
3	1	1	1	2	2	2	2	1	1	1	1	2	2	2	2
4	1	1	1	2	2	2	2	2	2	2	2	1	1	1	1
5	1	2	2	1	1	2	2	1	1	2	2	1	1	2	2
6	1	2	2	1	1	2	2	2	2	1	1	2	2	1	1
7	1	2	2	2	2	1	1	1	1	2	2	2	2	1	1
8	1	2	2	2	2	1	1	2	2	1	1	1	1	2	2
9	2	1	2	1	2	1	2	1	2	1	2	1	2	1	2
10	2	1	2	1	2	1	2	2	1	2	1	2	1	2	1
11	2	1	2	2	1	2	1	1	2	1	2	2	1	2	1
12	2	1	2	2	1	2	1	2	1	2	1	1	2	1	2
13	2	2	1	1	2	2	1	1	2	2	1	1	2	2	1
14	2	2	1	1	2	2	1	2	1	1	2	2	1	1	2
15	2	2	1	2	1	1	2	1	2	2	1	2	1	1	2
16	2	2	1	2	1	1	2	2	1	1	2	1	2	2	1

Table 2 – L_{16} Orthogonal Array

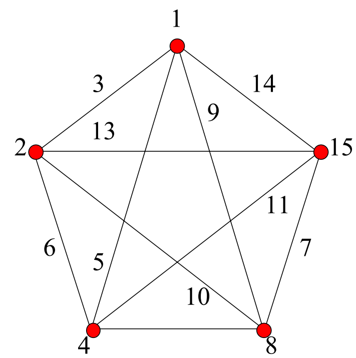


Figure 4 – Linear Graph of L_{16} Orthogonal Array

When selecting the values for the parameters in the orthogonal array, it was important that the effect of any one parameter was not too large, as this would distort the results from the investigation. The values for the coverage were 5% for level 1 and 30% for level 2. This ensured that the same dot structure was used for both coverage levels. The 5% dot was used instead of the 1% dot, as the difference in dot depth between the 5% and the 30% dots would not be as great as it would be for 1% and 30% dots. This would have resulted in exaggerated dot depths, distorting the balance of the variables in the orthogonal array. The difference in coverage was sufficiently large however, that any effect could be clearly observed. The two levels for the line ruling were set at the 39.4 lpcm line ruling for level 1 and 69.1 lpcm for level 2. For the coverages selected, the limits for the line ruling have been shown to cause a change in tone gain of less than 2% (Figure 5) [2]. To select the values for the dot depths, the four possible combinations for the dot depths from the two coverages and two line rulings were considered, as measured in [1]. For both the dot depth across the corners (major height) and the dot depth across the flats (minor height), the difference between the maximum and the minimum height was determined. The heights for level 1 of the orthogonal array were set by taking the smallest values for the major and minor dot depths and adding 25% of the difference between the smallest and largest values. The values for level 2 were obtained by subtracting 25% of the difference from the largest major and minor heights. This enabled models with dot profiles that clearly distinguished between the two levels, but were not so extreme as to have a dominant effect on the orthogonal array. The values for the two levels are shown in Table 3. The engagements selected were 25.4µm for level 1 and 50.8µm for level 2. These levels were chosen as they showed a clear difference in tone gain, Figure 6 [2], but the difference between the two levels was less than 2%. The two levels of the plate thickness were those used during the current investigation and were 1.14mm for level 1 and 1.70mm for level 2. The values of all parameters used in the orthogonal array are summarised in Table 4.

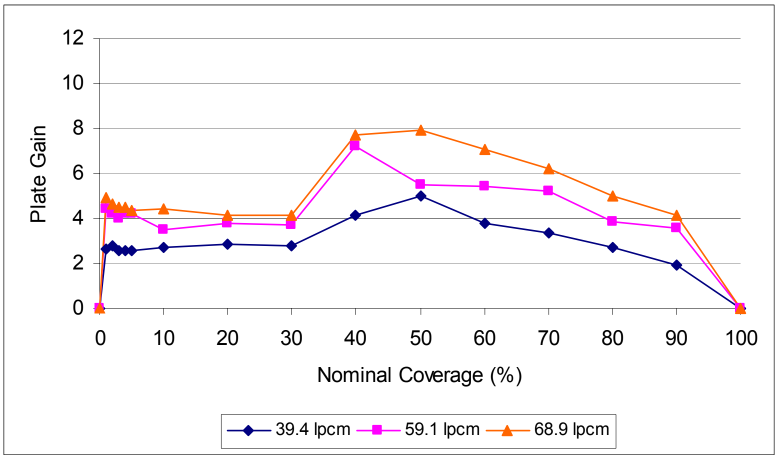


Figure 5 – Effect of line ruling on plate gain [2]

	Coverage Level 1		Coverage Level 2		Dot depth Level 1	Dot depth Level 2
	Line Ruling Level 1	Line Ruling Level 2	Line Ruling Level 1	Line Ruling Level 2		
Minor Height	87μm	53μm	29μm	17μm	35μm	70μm
Major Height	131μm	77μm	78μm	44μm	66μm	109μm

Table 3 – Determination of Levels for Dot Depth

	Coverage (%)	Line Ruling (lpcm)	Dot Depth (μm)	Engagement (μm)	Plate Thickness (mm)
Level 1	5	39.4	35 & 66	25.4	1.14
Level 2	30	68.9	70 & 109	50.8	1.70

Table 4 – Summary of values for parameters in Orthogonal Array

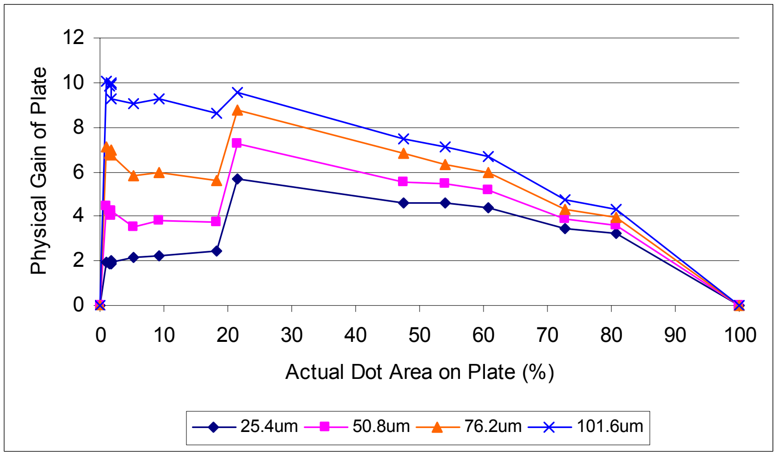


Figure 6 – Effect of engagement on dot gain [2]

Interactions between two parameters were assessed by plotting graphs of their combined effect on the process, Figure 7. Parameter 1 is plotted along the x-axis of the graph, between levels 1 and 2. Two curves are produced, one showing the effect of parameter 2 at level 1, as the first parameter increases from level 1 to level 2. The second curve shows the effect of parameter 2 set at level 2, as the first parameter increases from level 1 to level 2. If no interaction exists, the two curves will be parallel. However, if an interaction does exist, the gradients of the two lines will be different. A larger gradient for the second line than for the first indicates a positive interaction, and a smaller gradient for the second curve indicates a negative interaction. A positive interaction shows that the effect of the two parameters together will be larger than the sum of the parameters individually, and the combined effect of the two parameters will be less than the two parameters on their own for a negative interaction.

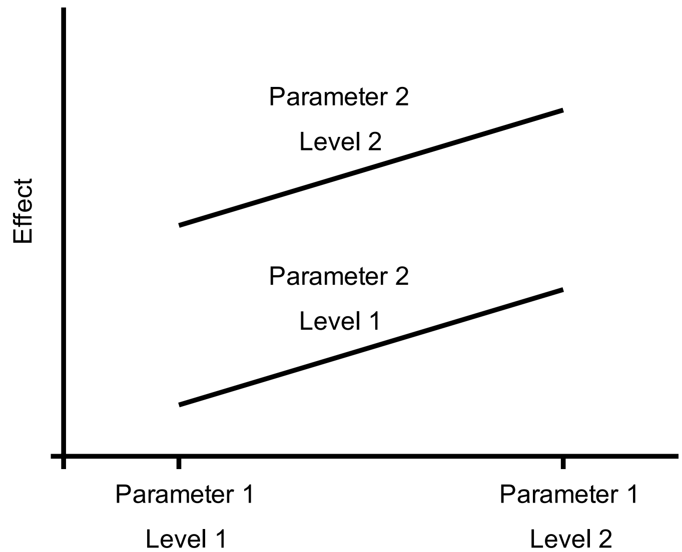


Figure 7 – The effect of interactions on two parameters

Results

The results from the orthogonal array study are shown in Table 5. The tone gain at the two levels of each column was summed and the difference tabulated as the response. This was then ranked from 1 to 15, according to its magnitude and a half-normal plot of the distribution was graphed. The parameters ranked 10 to 15 lie on the linear portion of the half-normal plot (Figure 8) and therefore have no significant effect on the tone gain for the flexographic printing process. Coverage was shown to be the least significant parameter, having the lowest ranking of all the parameters and interactions. This was observed in [2], where there was very little variation in tone gain for the nominal coverages due to the opposite effects of dot expansion and dot barrelling. The results also show the difficulty in producing a 1% dot, as deformation of plate alone causes 3.7% gain for all coverages of the round dot structure. Highlight dots in flexography are therefore difficult to control.

	Coverage	Line Ruling	1 + 2	Dot Depth	1 + 4	2 + 4	8 +15	Engagement	1 + 8	2 + 8	4 + 15	4 + 8	2 + 15	1 + 15	Plate Thickness
	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
Tone Gain															
Level 1	3.734	3.167	4.092	4.037	4.204	3.816	3.741	2.720	3.427	3.781	3.658	3.562	3.409	3.754	4.013
Level 2	3.737	4.304	3.378	3.433	3.266	3.655	3.729	4.750	4.043	3.689	3.813	3.908	4.061	3.717	3.457
Response	0.003	1.137	0.714	0.604	0.938	0.161	0.012	2.030	0.616	0.092	0.155	0.346	0.652	0.037	0.556
Rank	15	2	4	7	3	10	14	1	6	12	11	9	5	13	8

Table 5 – Table of results from orthogonal array study

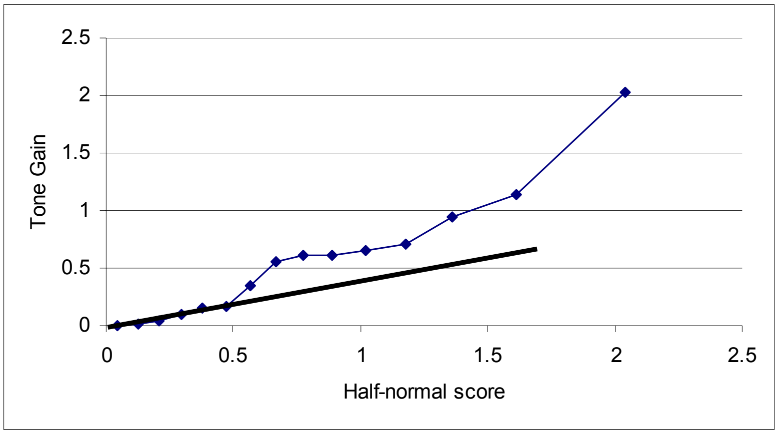


Figure 8 – Half-normal plot

The most significant parameter on the tone gain was engagement, which showed a 2.03% increase in tone gain. This is in agreement with the results displayed in Figure 6 [2], which showed an increase of approximately 2% as engagement increased from 25.4μm to 50.8μm. As dot expansion and barrelling are both affected by changes in engagement, they are both significant mechanisms of dot deformation and therefore both have an effect on overall tone gain.

Line ruling was the second highest ranked parameter from the orthogonal array. It has previously been shown [2], that greater tone gain at higher line rulings is due to the greater dot barrelling than for lower line rulings. Thus, the behaviour of the plate through the nip needs to be fully understood in order to achieve low tone gain at high line rulings.

The dot depth was also shown to influence the tone gain, but to a lesser extent, being the seventh highest ranked parameter. However, varying coverage, line ruling and dot depth simultaneously created a range of different shoulder angles, which affected the shoulder barrelling of the dot. As a decrease in dot depth for a constant coverage and line ruling (Table 5) corresponds to a increase in the shoulder angle, it was concluded that tone gain increased as the shoulder angle increased. This is in agreement with the findings of Warfford [6]. To assess the effects of dot depth and shoulder angle in greater detail, it is necessary to perform further numerical analysis using shoulder angle as a parameter, instead of dot depth.

The plate thickness was ranked eighth highest, and its effect was therefore only slightly significant. As the plate thickness increased from 1.14mm to 1.70mm, there was a decrease of 0.6% in tone gain. This was attributed to a lower engagement relative to the thickness of the plate.

Interactions

Significant interactions exist for coverage/line ruling, coverage/dot depth, coverage/ engagement, dot depth/engagement and line ruling/plate thickness. The coverage/dot depth interaction (Figure 9a) had the third largest effect on tone gain in flexography. This is to be expected as the interaction of the different dot depths, coverages and line rulings in the orthogonal array will create different shoulder angles. Thus if can be inferred that the shoulder angle is a critical element in plate deformation, although it cannot be quantified in this investigation.

The coverage/line ruling interaction was the fourth highest ranked factor from the orthogonal array investigation. The interaction is shown in the response graph, Figure 9b. For coverage at level 1 (5% dot), the dot was unstable. For line ruling of 39.4 lpcm (level 1), the dot barrelling is less significant than for higher line rulings [2]. As coverage increased to 30% (level 2) the dot stability increased due to the larger dots, but as line ruling was still at level 1, dot barrelling remains less significant than for higher line rulings and the net effect was that tone gain decreased. For the 5% coverage (level 1) and line ruling of 68.9 lpcm (level 2), the dot was unstable due to the low coverage and smaller dot area. The dot barrelling increased due to the higher line ruling, resulting in a higher tone gain than for a line ruling of 39.4 lpcm. As coverage increased, the dot stability remained low, due to the high line ruling, and this, combined with the increased significance of the dot barrelling resulted in an increase in tone gain.

The line ruling/plate thickness interaction (Figure 9c) was the fifth highest ranked parameter from the orthogonal array investigation. For the plate thickness set at level 1, increasing the line ruling from 39.4 lpcm (level 1) to 68.9 lpcm (level 2), decreased the dot stability, and due to the higher relative engagement for thinner plates, the resultant tone gain increased. However, for the plate thickness at level 2, there was more plate material to deform and the relative engagement was smaller. As the line ruling increased the effect of the decreased dot stability due to the higher line ruling at 68.9 lpcm (level 2) was very small and there was very little difference in the tone gain.

The sixth highest ranked parameter was the coverage/engagement interaction (Figure 9d). For low coverages, the dot is unstable and increasing the engagement had a large effect on tone gain. For the 30% coverage (level 2) and lowest engagement, there is a slight increase in the tone gain. For higher engagements, the effect of increasing the coverage resulted in a decrease in the tone gain. As engagement increased, the reaction force of the plate on the impression cylinder also increased, which coupled with greater dot stability for higher coverages, resulted in less tone gain. The tone gain for both coverages was still greater when the engagement was highest, which is consistent with earlier findings that showed engagement to have the greatest effect on tone gain.

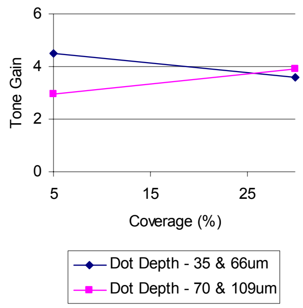
The dot depth/engagement was the smallest significant interaction. The two lines of the response graph are almost parallel (Figure 9e) indicating that the effect of this interaction is very small. However, this result may be masked by changes in shoulder angle due to the combinations used in this orthogonal array.

Analysing the results in terms of their overall effect on print quality, the two most important parameters that need to be controlled are the plate/substrate engagement and the line ruling on the plate. These produced the strongest responses for analysis with respect to tone gain. It is therefore very important to ensure that the line ruling is controlled during production of printing plates, as any variation will affect the printed image. Although coverage has been shown to have little effect on tone gain, it is important to control the dot size, as this will still affect the quality of the final print.

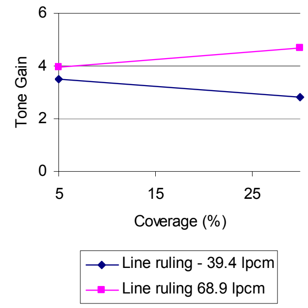
Conclusions

The effect of plate parameters on tone gain due to the deformation of the printing plate have been systematically evaluated using an orthogonal array experimental design. From this investigation, the following conclusions have been drawn:

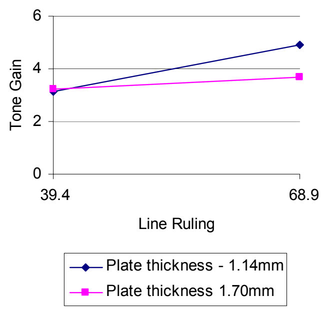
- The most significant parameter related to the printing plate is the engagement between the printing cylinder and the impression cylinder. Both dot expansion and barrelling were shown to increase as engagement increased from level 1 to level 2 and therefore both have an influence on image quality
- Line ruling was shown to be a significant parameter, with tone gain increasing as line ruling increased from level 1 to level 2. This has an effect on image quality, as higher line rulings give a better image definition, but quality may be lost due to greater tone gain, if not correctly compensated for, during prepress.
- Coverage has no effect on tone gain as an individual parameter, due to the opposing effects of dot expansion and dot barrelling, but was shown to have interactions with dot depth, line ruling and engagement to increase the size of the dot on the plate after deformation.



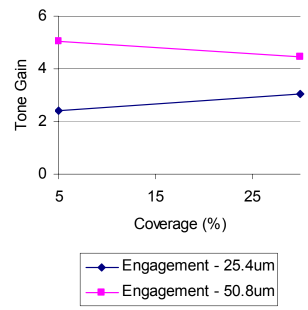
(a) Coverage/Dot Depth



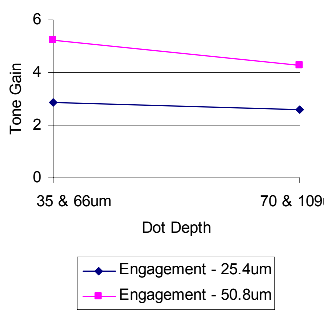
(b) Coverage/Line Ruling



(c) Line Ruling/Plate Thickness



(d) Coverage/Engagement



(e) Dot Depth/Engagement

Figure 9 – Interaction Graphs

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References

[1] Bould, D.C., Claypole, T.C. and Bohan, M.F.J. "An experimental investigation into flexographic printing plates" accepted for publication, Journal of Graphic Technology, TAGA, 2003
[2] Bould, D.C. "An Investigation into Quality Improvements in Flexographic Printing" PhD Thesis, University of Wales Swansea, 2001
[3] Mirle, S.K. and Zettlemoyer, A.C. "Viscoelasticity of photopolymer plates and ink hydrodynamics in modelling flexographic printing" Mathematical Computer Modelling Vol. 11 1988 pp1162-1165
[4] Phadke M.S. "Quality Engineering using robust design"
[5] Grove D.M. & Davis T.P. "Engineering quality and experimental design" Longman, 1992
[6] M. Warfford "Shoulder Angle Determination With Flexographic Photopolymer Plate Material" TAGA Proceedings 1997 pp906-929