The effect of process parameters on product quality of rotogravure printing

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Abstract: This paper describes an experimental investigation into the process parameter effects on product quality in rotogravure printing. A production printing press was instrumented for the measurement of parameters including strategic temperatures, speeds and web tension. Through-the-run analysis was used to evaluate the fluctuation of the press parameters and the product quality. The trials indicated the parameters where process control is important and allowed the elimination of several parameters, including ink drying, from the main experimental programme. The parameters selected for the main experiments were those most often used for control purposes, or those that were varied between print jobs. Orthogonal array experiments were used, as these allow the simultaneous variation of several parameters and the investigation of interactions between parameters. The experiments were performed using a typical commercial print run once the production of saleable copy had been completed. The analysis of the print quality was carried out in the image areas using spectrophotometry. The experiments highlighted the sensitivity of the process to changes in ink viscosity and the non-linearity of the response. Doctor blade setting was also found to be important, whereas blade load and impression pressure had negligible impact. No interactions were found between any of the parameters investigated. For viscosity change, analysis of the printed image confirmed the importance of hydrodynamic mechanisms, but it was not possible to isolate ink dilution. For doctor blade angular setting, hydrodynamic behaviour appears secondary to cell transport and release mechanisms. This latter mechanism requires further investigation in order to establish a clear understanding.

Keywords: rotogravure printing, orthogonal arrays, CIE$_{94}$, ink viscosity, doctor blade angle, doctor blade load, impression pressure

NOTATION

a^*	red–green scale in the CIE $L^*a^*b^*$ colour space
b^*	blue–yellow scale in the CIE $L^*a^*b^*$ colour space
CIE	Commission Internationale de l'Eclairage
k_C	parametric factor for chroma in the CIE$_{94}$ colour difference formula
k_H	parametric factor for hue angle in the CIE$_{94}$ colour difference formula
k_L	parametric factor for lightness in the CIE$_{94}$ colour difference formula
L^*	lightness value in the CIE $L^*a^*b^*$ colour space
S_C	weighting function for chroma in the CIE$_{94}$ colour difference formula
S_H	weighting function for hue angle in the CIE$_{94}$ colour difference formula
S_L	weighting function for lightness in the CIE$_{94}$ colour difference formula
ΔC^*_{ab}	chroma colour difference
ΔE^*_{94}	CIE$_{94}$ colour difference
$\Delta E_{a^*b^*}$	CIE colour difference
ΔH^*_{ab}	hue colour difference

1 INTRODUCTION

Knowledge of the effects of different process parameters on the image quality in rotogravure printing is limited. The purpose of this work was to address rotogravure printing as a manufacturing process and to establish

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the dominant factors to achieve a high-quality product. The paper describes an experimental programme on a rotogravure press where the influence of process parameters on the quality of the printed image was evaluated while printing on a flexible material. At present the process parameters for each print run are set by the operators, based primarily on experience. Whenever a new print job is run on the press, material and press time are wasted in obtaining the correct product quality. This quality then has to be maintained throughout the duration of the print run. The work was used to identify which parameters in the process have a large impact on the product quality during production and to put forward some suggestions as to why they have such an impact.

1.1 Rotogravure printing

The rotogravure process is used to print detailed colour images in many graphic and packaging applications. The aim of the process is to reproduce an original, be it photographic or computer generated, on to a substrate of either paper or flexible film. The rotogravure process is similar to other high-volume printing processes in that it is not possible to vary the ink film thickness directly. The changes in colour strength are achieved principally by using halftones. The halftone is a matrix area of dots of varying area coverage. The image to be printed is transformed into a series of dots varying between 0 and 100 per cent coverage, depending on the strength of colour required. These will give the impression of varying saturation when observed under normal viewing conditions. The variations in colour hues are achieved by the use of specific inks on multiple print units, in addition to the overprinting of inks from different printing units. The combination used will depend on the printing press configuration and the product being produced. Refinement of the final printed colour is achieved either by mechanical adjustment of the press settings or by making changes to the ink, notably its colour or viscosity.

The rotogravure printing process transfers ink from an engraved cylinder on to a substrate, and a schematic representation of a station of a printing press is shown in Fig. 1. A press can comprise up to 10 stations to apply inks and coatings to the substrate. Each unit is identical in mechanical design, comprising rollers to handle the web and an ink or coating transfer system. The ink transfer system comprises an ink duct in which the gravure roll rotates, thereby picking up ink in the cells that are engraved into its surface. The excess ink is scraped off the cylinder by means of a doctor blade arrangement. The blade is usually made of steel, although tapered polymeric systems are now finding application. In the case of a steel blade, this is supported by a strip placed directly against the back of the blade, or via a strip clamped independently from the doctor blade to form a Y configuration.

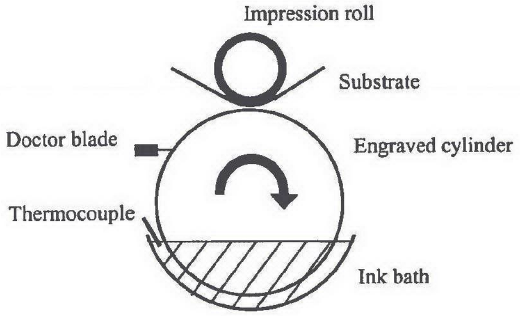

Fig. 1 Schematic representation of rotogravure printing

The surface of the gravure cylinder is engraved with cells representing the colour-separated image that is to be printed. This includes both solid and halftone areas. The substrate is brought into contact with the engraved cylinder under pressure from an impression roll, at which time the ink is transferred from the cells on to the substrate. Multiple units are placed in sequence to build up the final printed image and a drying system is normally placed between each printing unit. The drying of the ink prevents contamination between ink units and aids in the predictability of the final colour produced using overprints. Additional units may also be used to apply a coating to the non-printed side of the film for sealing or to prevent contamination, for example, in food products.

Many factors affect the quality of the final printed product (Fig. 2). These can be subdivided into five categories representing the pre-press, the cylinder, the substrate, the ink and the process. This shows the large and varied number of parameters that can affect the product quality. The majority of factors relating to the first four categories are not usually under the control of the printer and as such cannot be used for control purposes. The aim of the experimentation was to identify the process operational parameters having a major impact on the product quality. Those selected represent the variables most often altered by the press operators. The pressure and angle of the doctor blade may be altered according to many factors, including the image to be printed and the ink applied. The doctor blade was fully investigated in this study. It is known that the depth, size and shape of the cells in the cylinder influence the quantity of ink transferred **[1]**. However, in this work, the engraving type and control were fixed by the rolls used. The ink release from the cells can be altered by the ink properties, and the viscosity is the primary mechanism by which this is effected by the printers. This is carried out by the addition of solvent, but by altering the viscosity other properties such as surface tension may also be affected **[2]**.

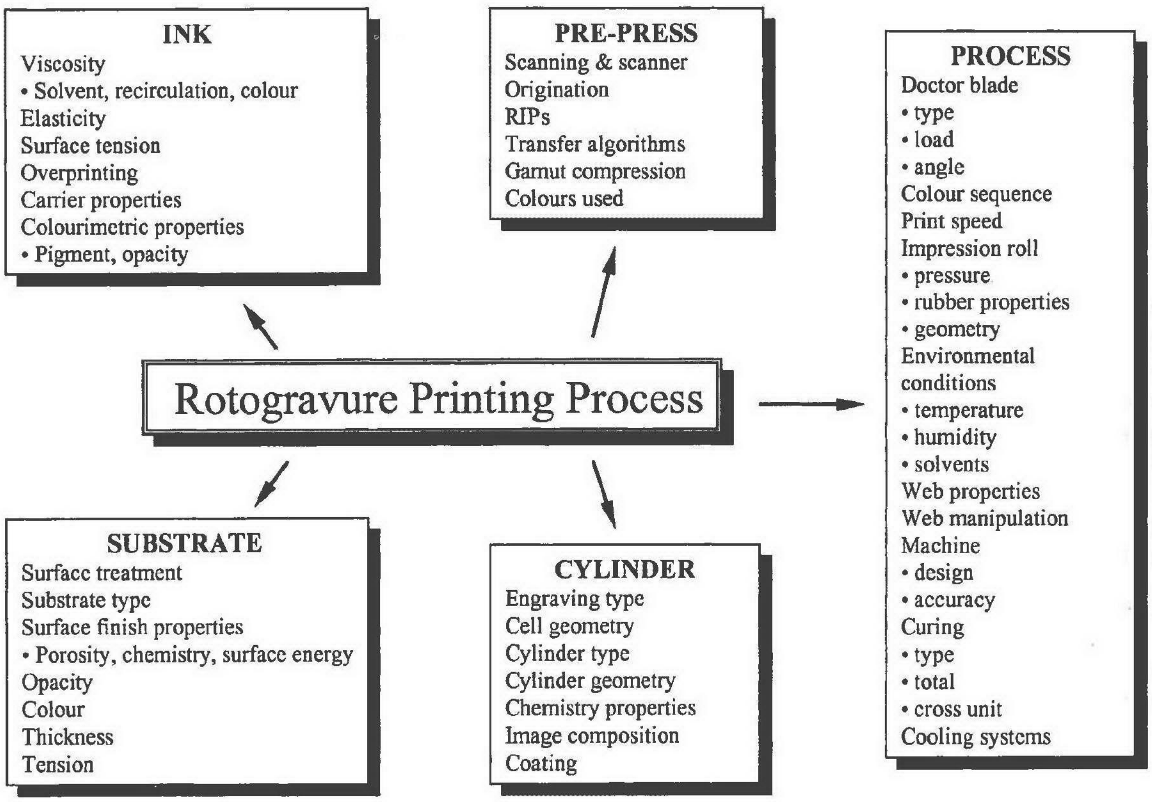

Fig. 2 Factors affecting print quality in rotogravure printing

2 EXPERIMENTAL INVESTIGATION

2.1 Strategic approach to the experimental programme

High-quality colour printing is a complex manufacturing process with a high operating cost and the experimental time for the investigation of parameter effects needs to be minimized while the results obtained are maximized. Orthogonal array techniques, which are subsets of a full factorial experiment, were utilized to achieve this [3, 4]. The subset is balanced, and each variable setting occurs the same number of times with no two experiments being repeated or mirror imaged. This allows multiple parameters to be investigated simultaneously, at multiple levels, and the effect of interactions to be quantified. The technique, by its statistical design, is advantageous in reducing the number of experiments while obtaining the maximum information from a limited set of trials. There are other designs of fractional factorial experiments, but in most cases these are less efficient or do not cover the full range of combinations of factors. In addition, with certain elements of the arrays it is possible to ignore the interactions, as their effects can be distributed equally across all the results. These points aid in minimizing the time and cost, which was of importance, as the trials were carried out using a commercial press.

A series of monitoring exercises were carried out to evaluate the process variability and the controls of the rotogravure press prior to the orthogonal array experimental programme. These were used to identify the important process parameters that would be investigated using the orthogonal array trials along with their normal operating ranges. These monitoring trials were performed during production with no loss of quality or product.

2.2 Assessment of product quality

The applicability and effectiveness of the monitoring and orthogonal array technique are dependent on the quality characteristic used to evaluate the effects of changes made on the press. The quality of the finished product has been traditionally assessed by observation by the operator. However, this is a subjective assessment and is not sufficiently accurate or repeatable for use with any experimental programme.

Various techniques are available to assess colour objectively, including colour atlases, densitometry and spectrophotometry. The colour atlases use a visual interpretation of the colour, with a colour match being made between the sample and atlas. The colour specified is dependent on the visual assessment, with the ability of the eye to discriminate and the conditions under which the match was made limiting the colour specification. Again, the errors introduced using the colour atlas are too great for detailed experimental evaluation.

Densitometers and spectrophotometers both illuminate the sample with a controlled light source and use the reflected light spectrum to calculate a numerical description for the colour. Densitometers use filter sets to investigate only a portion of the reflected light to calculate a density value. The instrument is designed for use with the four process colours of cyan, magenta, yellow and black. The filter sets are optimized so that, as the ink film thickness increases, the density value increases in an approximately linear manner. These instruments are limited to the measurement of the process colours.

Spectrophotometers use the whole of the spectrum to produce a set of tristimulus values to describe the colour. The instruments measure colour by illuminating the sample with a controlled light source. The reflected light is analysed across the visible spectrum, nominally 380–730 nm, to produce a reflectance curve. Using the reflectance curve, the illuminant and a set of standard colour matching functions, it is possible to calculate a set of CIE tristimulus colour space values [5, 6]. These can be used for unique numerical description of the colour of the sample being assessed. The uniformity of these systems to perceptible colour differences varies between the many different systems. The CIE $L^*a^*b^*$ colour space has been used for the analysis as this provides the most uniform colour space and is generally used in the graphic arts industry. This defines the colour with a lightness L^*, red–green scale a^* and blue–yellow scale b^*, shown schematically in Fig. 3. Spectrophotometers were used for the measurement of the colour as they could most accurately identify colour and measure the changes in the printed copy since they use the whole of the reflected light spectrum.

The colour difference between two samples, $\Delta E_{a^*b^*}$, is calculated as the distance between two points in the three-dimensional colour space and is defined as

$$\Delta E_{a^*b^*} = \sqrt{(\Delta L^*)^2 + (\Delta a^*)^2 + (\Delta b^*)^2} \qquad (1)$$

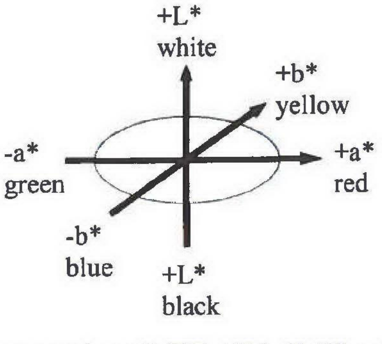

Fig. 3 Representation of CIE 1976 $L^*a^*b^*$ colour space system

Recent developments have led to the specification of a new colour difference equation, CIE_{94}, to compensate further for the non-uniformity within the CIE $L^*a^*b^*$ colour space [7]. This takes into account the location in the colour space and applies weighting functions to the calculation:

$$\Delta E^*_{94} = \sqrt{\left(\frac{\Delta L^*}{k_L S_L}\right)^2 + \left(\frac{\Delta C^*_{ab}}{k_C S_C}\right)^2 + \left(\frac{\Delta H^*_{ab}}{k_H S_H}\right)^2} \qquad (2)$$

The results were analysed and presented using the CIE_{94} colour difference equation. The weighting functions k_L, k_C and k_H were all set to unity.

Extensive analysis of printed images using spectrophotometry has indicated that the colour fluctuates between consecutive copies [8]. The colour variations between copies were analysed with Fourier and moving average analysis, using sample sizes of up to 130 copies. Fourier analysis of the samples indicated that the colour fluctuations were random, with no cyclic frequency occurring. Moving average techniques were used to optimize the number of consecutive measurements required for statistically repeatable measurements to be attained. The analysis indicated that 30 consecutive cylinder revolutions should be measured, with the CIE colour space values averaged. In performing these measurements on consecutive copies, the variance in ΔE was typically 0.09.

2.3 Experimental instrumentation

The purpose of fitting instrumentation on to the press was to provide information relating to the major process parameters. This enabled a quantitative evaluation of the impact of various process changes. The printing press on which the experiments were performed consists of nine individual print units with the web running through each. The instrumentation was installed to provide general information from each of the individual units, which included the ink and burner temperatures. Additional instrumentation was then added to the units used in the orthogonal array programme to measure the doctor blade temperature and surface strain. The instrumentation incorporated into the press had to comply with strict electrical regulations owing to the quantities of solvent used in the process. Therefore, wherever possible, existing process instrumentation was used. The instrumentation installation is summarized in the following paragraphs.

The temperatures of the ink in the trays were measured on the gear and operator side of the press for each of the units, using sheathed K-type thermocouples of 0.8 mm diameter. These were used to detect temperature variations at different stations along the press and across the width of the web. Changes in ink temperature will have an effect on the properties of the ink, such as its viscosity

Table 1 Summary of parameter level settings

	Parameter											
	Blade load			Blade angle			Viscosity (Pa s)			Impression pressure		
Level	1	2	3	1	2	3	1	2	3	1	2	3
Setting	1.0b	1.4b	1.8b	Steep	Mid	Shallow	0.032	0.038	0.044	1.0b	1.3b	1.6b

and surface tension, and their change principally owing to solvent evaporation. This is likely to have an impact on the transfer characteristics in the process, both from the engraved cell and on to the substrate [2]. The temperatures in the four-burner systems and hood dryers above each of the units were monitored using existing press thermocouple instrumentation. The press line speed was monitored using the existing press instrumentation. Finally, web tension was measured using load cells at the unwind, in-feed, intermediate and out-feed of the press. The load cells were calibrated prior to the experimental programme. The data capture of these variables was effected using a data logger, allowing 40 channels of data to be recorded on a personal computer.

The viscosity readings were monitored continuously using a video facility, with the data being extracted later at set time intervals. The displays that are used as indicators for viscosity control were located above the main control console. The video gave additional indication of changes in the viscosity setting that were carried out by the print crew as part of their normal printing practice.

Two doctor blade designs were used in the orthogonal array experimental programme. Three K-type thermocouples were mounted on to each of the doctor blades, located at each end and the middle. To obtain an estimation of the blade surface strain, gauges were applied to the doctor blade/backing plate configuration. Three strain gauges were placed on both the doctor blade and backing plate for the straight doctor blade, with only three located on the backing plate for the Y-shaped configuration. All strain gauges were located in line with the thermocouples. The strain gauge data were collected using a high-speed data acquisition system, sampling at up to 100 000 data points per second, to investigate possible changes occurring around the circumference of the engraved cylinder.

2.4 Orthogonal array experimental design

The invasive experimental programme was designed using orthogonal arrays. This minimized the experimental time and allowed the evaluation of interactions between the parameters. L_9 orthogonal arrays were used for the experiments [9]. This allowed the linearity of the response to be evaluated with the parameters investigated being set at three levels. The analysis also provides information relating to any possible interactions between the parameters.

The effects of doctor blade angle and doctor blade load were assessed in experiment 1 and the ink viscosity and impression roll pressure in experiment 2. The parameters were paired according to where interactions were most likely. It was not possible to investigate all four parameters using one array owing to the possible significant interactions between all the parameters resulting in a much larger set of trials (64 tests for a full factorial experiment). The experiments were repeated on two units to assess the effect of different doctor blade configurations, with the straight blade used on unit 7 printing blue ink and the Y-shaped blade on unit 3 printing red ink.

The parameter levels were selected to represent conditions found during normal press operation and were obtained from the through-the-run analysis. These levels are shown in Table 1. The changes in blade load and impression pressure were effected by adjusting the pneumatic pressure to their loading systems. The blade angle was adjusted manually in its holder, and solvent was added to the ink to reduce its viscosity. Once the adjustments were completed on the press, a 5 min stabilization period was allowed and a marker was inserted into the reel to indicate the collection point. The reels were divided after the completion of the trials into those representing the individual runs within each experiment.

The print image for the orthogonal array experiments was selected on the basis of it containing large areas of single ink colours. This allowed accurate, repeatable and consistent measurements to be carried out on the film using spectrophotometry.

3 EXPERIMENTAL RESULTS

The results from the two experimental programmes are subdivided into those obtained from the assessment of the physical press parameters and those from the colour assessment of the print. The through-the-run results will be considered initially, followed by the orthogonal array investigations.

3.1 Through-the-run analysis

3.1.1 Physical parameters

The aim of the through-the-run analysis was to evaluate during production the natural parameter variations occurring in a rotogravure printing press and those in

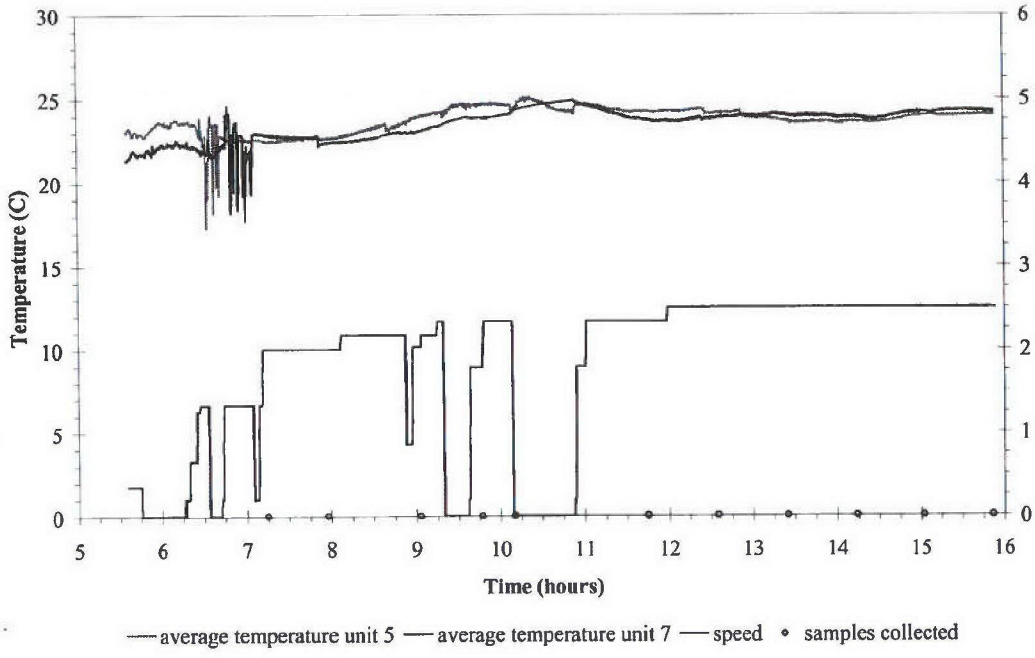

Fig. 4 Ink temperatures in the inking trays

the printed product. The data indicate the current control limits on the process parameters and provide ranges for the orthogonal array investigation. The disruptions caused by the monitoring had to be minimized, and therefore samples of printed film were collected at the end of each reel only. This approximated to 50 min intervals. The results presented are for one day in which a single, long-duration job was printed. The parameters investigated included the press temperatures, line speed, ink properties and web tension.

Temperatures in the burners and hood were examined initially. The temperature in the hoods and burners was very consistent with typical values of 120 ± 1 °C. The temperatures of the burners or hoods were not affected by process changes, including alterations in the press speed. Owing to the consistency of these temperatures, they were not used as a control parameter in the orthogonal array experimental programme. Their consistency is a requirement for in-register printing of flexible film owing to its increased extension at higher temperatures.

The temperatures of the ink in the ink trays on units 5 and 7, the sample collection intervals and the press speed are shown in Fig. 4. The ink temperatures are not significantly affected by the changes in production speed. The results indicate a maximum ink temperature variation of 2 °C throughout the complete production run. The ink is stored in a tank below the unit and then circulated to the inking tray where it is resident for only a short time. The stability of the ink temperature is in contrast to other printing processes, such as web offset [10] where there is a gradual and much larger increase in the ink temperature during production. In addition, there is no cross-web variation in ink temperature, a feature also found in other printing processes. The consistent temperatures found during this analysis are the result of the limited shearing action occurring in the ink. This is due to the press not having a long roller train for ink transfer, the short ink dwell time on the cylinder and the low ink viscosity in comparison with that used in other printing processes.

While the temperature of the ink remains consistent, its viscosity varies considerably through the print run (Fig. 5). The variation in viscosity differed between the units as a function of the ink and the quantity used, with ink viscosity changes of up to 40 per cent occurring. The ink viscosity is controlled by the addition of solvent, which evaporates with time and thereby causes a gradual increase in the ink viscosity. The large sudden changes in the viscosity were a direct result of adjustments made by the press crew by the addition of ink to the tank reservoir or the introduction of solvent.

The web tension was nominally constant throughout the print run. At the in-feed, web tension was nominally 90 N and at the out-feed it was nominally 80 N. These levels ensure the successful flow of film through the press and a high-quality rewind of the film for further processing, such as slitting. Small variations through each reel of film were detected at the unwind nip, and these were consistent between reels. More extreme fluctuations were noted during reel changeover. During the monitoring stage, it was possible to collect samples only at the end of each reel and it was not possible to assess fully the effects of tension fluctuations. However, they are expected to be minimal since the unwind to

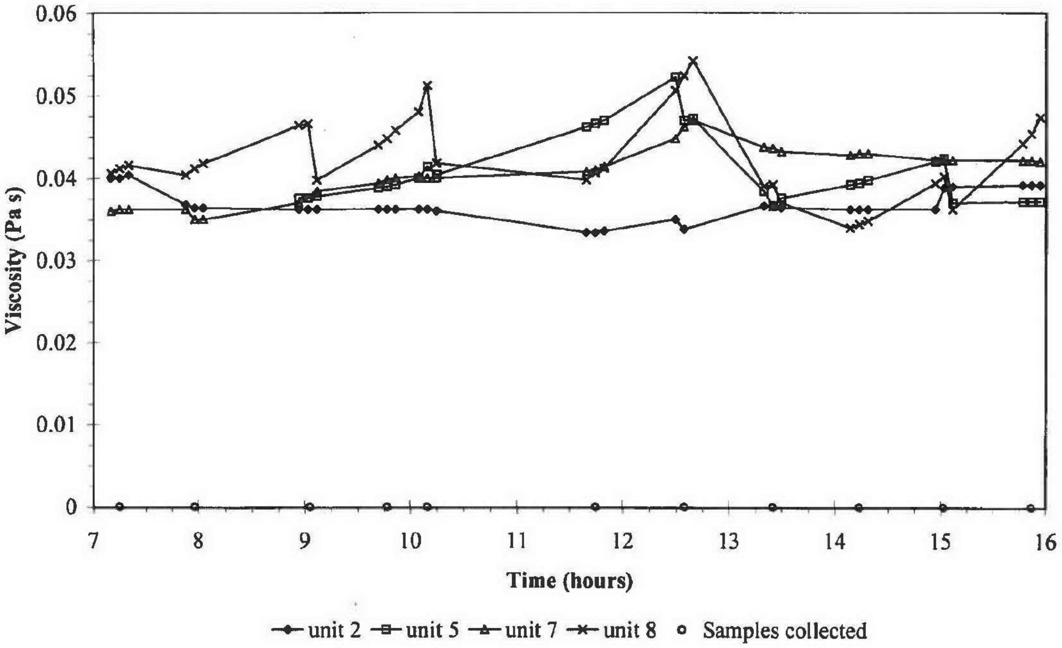

Fig. 5 Viscosity variations for the print units

out-feed stations are electronically geared and controlled to maintain a constant tension. These measurements confirmed that the tension control within the printing section of the press was precise.

3.1.2 Colour measurement

The printed image was a food wrapper that consisted of a series of solid and halftone areas repeated four times across the width of the web and four times around the circumference of the cylinder. A series of test patches were printed along the edge of the web, where, traditionally, any colour measurements would be taken. However, results obtained from these are prone to edge effects and therefore are not appropriate. Hence, the measurements were made on areas located within the repeated image. At these positions, only one ink colour was printed.

Measurements were carried out on yellow (print unit 2), green (print unit 5) and blue (print unit 7) in solid ink patches within the repeated image, for thirty consecutive cylinder revolutions. The CIE $L^*a^*b^*$ values showed a relatively large colour difference across the width of the web for nominally identical colour patches under the same print conditions. Analysis indicated an average ΔE^*_{94} of 0.7 for both the blue and yellow patches and a maximum of 1.8 for the blue and 1.65 for the yellow. In these measurements the variance was 0.36. The human eye can detect colour changes to an ΔE^*_{94} value of approximately 0.5 or greater, and therefore the changes noted above are just discernible. The measurement on the green patch was carried out to confirm the findings for the blue and yellow, and this will be discussed further below.

The reasons for these differences are not immediately apparent and there was no opportunity to investigate the gravure roll surface for image consistency. Indeed, topographical measurement equipment that is only now becoming available is not suited to performing measurement of gravure cell volume either on a cell or local area basis, and so a quantitative comparison is not possible at this time.

The variation in colour through the run between successive reels is shown in Fig. 6. The CIE ΔE^*_{94} values shown have been calculated with respect to the final sample and therefore the figure only displays change. The results are presented for each of the blue patches and an average of all the yellow patches. The results show a large variation in the blue patches through the run. However, the trends are similar on all patches, indicating the cause of the variation to be acting equally across the web width. The analysis of the yellow areas shows a much better consistency of colour with ΔE^*_{94} variations of $\leqslant 1.0$ from the second sample set onwards.

As shown in Fig. 6, the blue does not stabilize until well into the print run. In an attempt to establish a reason for this, colour and viscosity changes were investigated and correlation between the two carried out. Correlation coefficients of 0.8 were obtained, confirming that there is a reasonable correlation which indicates the dominant effect of ink viscosity on the press. To confirm this, additional measurements were carried out on the green patches, and these showed colour shifts where there were significant changes in ink viscosity.

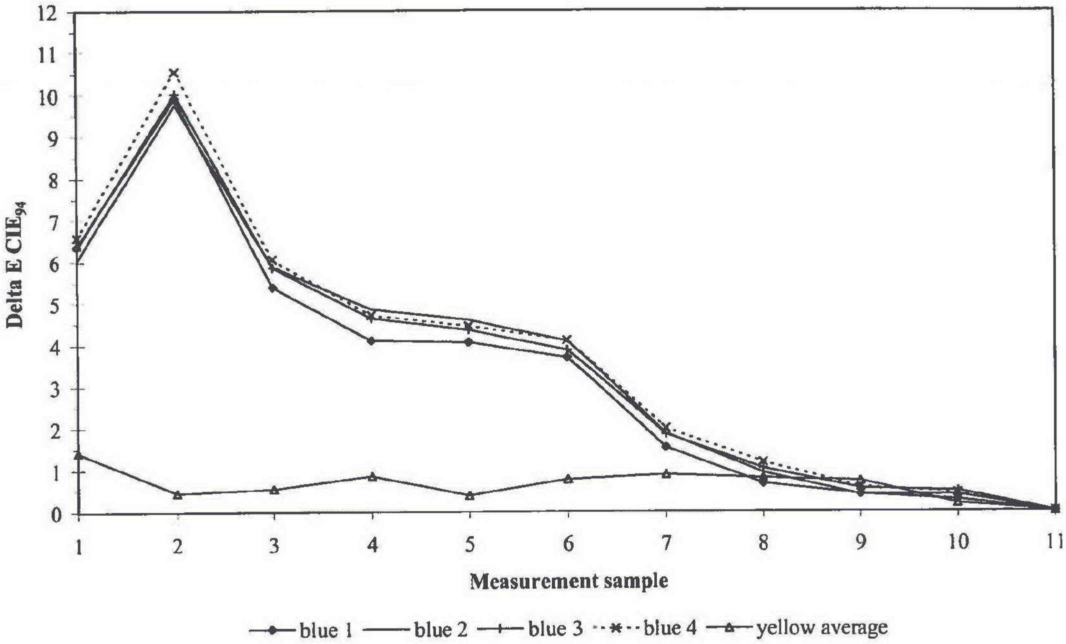

Fig. 6 Variation in ΔE^*_{94} through the duration of a run for blue and yellow colour patches

Because the findings from the analysis indicated the viscosity to be a significant factor in the ink transfer characteristic, the orthogonal array trials focused on the ink viscosity and the press component on which it has a direct impact. This includes the doctor blade configuration (load and angle) and impression roll pressure.

3.2 Orthogonal array experimental trials

3.2.1 Physical parameters

The programme was subdivided into two orthogonal array experiments, with the doctor blade angle and load investigated in the first and the ink viscosity and impression pressure in the second. The parameters were placed in these groupings as interactions were thought to be least likely between those from the different groups. The press operational parameters were captured using the data acquisition system and the results are presented for both experiments.

There was very little temperature variation across the width of the press either in the duct or across the doctor blade, as had been indicated during the through-the-run exercise. The average temperatures of the ink on the Y-shaped doctor blade and of the ink in the tray are shown in Fig. 7. Also indicated are the times at which samples were collected from the reels. During the first experiment (up to 13 h) when the ink viscosity was kept constant, the temperature shows little variation. However, during experiment 2, each time solvent was added to the ink to reduce its viscosity there was a small reduction in the ink temperature in the tray and on the doctor blade. This was due to the solvent being stored at a lower temperature than that on the press.

The results also showed that the doctor blade is at a consistently higher temperature than the ink in the tray. These higher temperatures are a result of the rubbing over the cylinder surface. However, these measurements indicate that the ink on the cylinder is close to the tray temperature and that the excursions measured are small and will not have a significant effect on the viscosity. These results are in sharp contrast to those from extensive studies [**10**] into web offset, where significant thermal excursions were detected over the duration of a print run.

Finally, the signals from the strain gauges were examined and found to be perfectly smooth, showing no variations in either the high- or low-frequency spectra. This confirms that the doctor blade system was operating in a mechanically stable state for a given set of operating conditions and that any circumferential changes in print quality were not associated with this machine element.

3.2.2 Colour measurement

The image in the orthogonal array trials was different from that used in the monitoring stage. In this phase, the image was repeated four times across the width of the gravure cylinder and five times around its circumference. Colour measurements were carried out on two areas within the print. The first was on a blue patch printed on unit 3 with the straight doctor blade and the

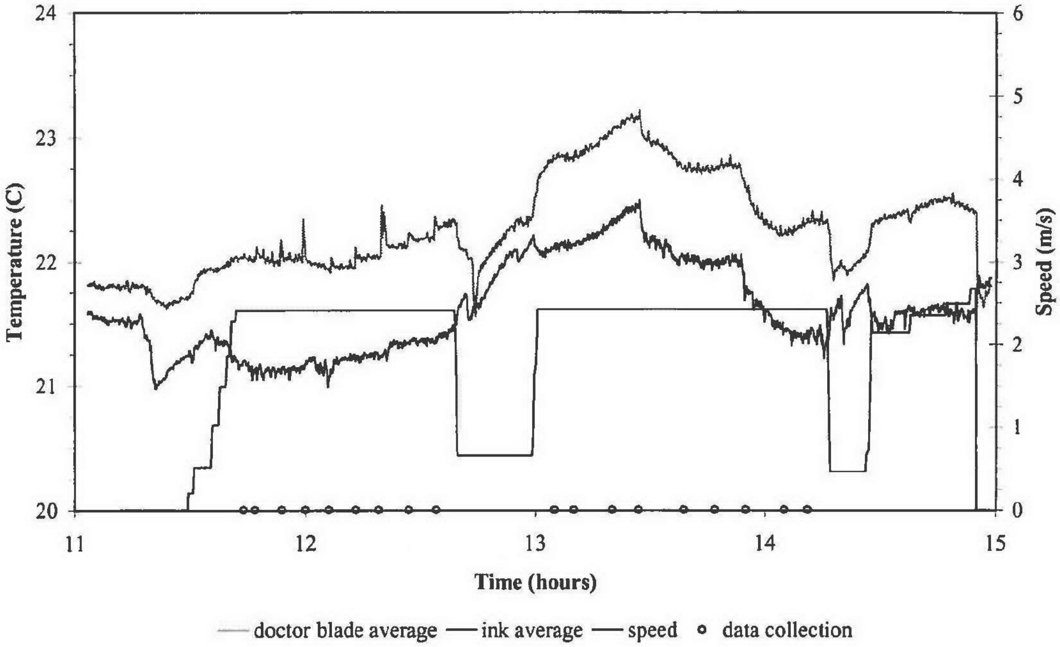

Fig. 7 Temperature of the ink on the doctor blade

second on a red patch printed on unit 7 with the Y-shaped doctor blade. Based on the findings from the through-the-run study, the image was measured across the full width and circumference of the cylinder, for thirty consecutive cylinder revolutions. The colour changes in the print were derived using the orthogonal array technique for analysis purposes. For each patch the averaged CIE $L^*a^*b^*$ values were calculated and these values were then combined for each level setting (1, 2 or 3) and the ΔL^*, Δa^* and Δb^* were calculated between each of the levels. These were then used to compute the CIE ΔE^*_{94} colour difference between levels. The results are presented in Figs 8 to 11. The pattern corresponds to the images across and around the cylinder. Thus, each complete histogram set represents 720 measurements.

Figure 8 shows that ink viscosity has the largest influence on the colour of the final printed copy, with $\Delta E^*_{94[1-3]}$ values of six detected. Subscript [1–3] refers to the physical settings in the experiment (Table 1). These figures show the $\Delta E^*_{94[1-3]}$ for the four patches across the cylinder and five around its circumference. These colour changes are significantly larger than those that can be detected visually and would be clear to an observer. For these gravure cylinders, the changes are relatively consistent in both axial and circumferential directions for the red ink, with some variation detected in the blue. It was noted that the coefficients of variation for both inks are low, confirming that the results are not a consequence of process variation or measurement accuracy. These results highlight the criticality of ink viscosity control.

When printing on to an impermeable film substrate, there are three possible reasons why ink viscosity change has a significant effect on the printed colour. The first possibility is that it may be attributed to simple dilution of the ink so that the colour strength of the ink itself is reduced as solvent is added. To investigate this effect fully requires the preparation of different ink formulations having different viscosity but identical colour strength via controlled pigment addition [11]. In reference [11] the research focused on flexographic printing using a UV curing ink, where it was demonstrated that, under all circumstances, print density decreased as ink viscosity increased. No physical reasons for this behaviour were proposed and these trends are contrary to those observed in the present study.

The second possibility for the trends observed within the present study can be reviewed by considering the hydrodynamic behaviour that is present within the printing machine elements of doctor blade and impression nip. It is well known that viscosity has a dominant effect on the film pressures that are generated within the printing nip and under the doctor blade edge. In each case, for a prescribed nip pressure or doctor blade load, a reduction in viscosity will lead to a reduction in film thickness and hence a reduction in the volume of ink that flows through the junction. Within the press, these elements are in series and therefore the ink flow will be affected at both stages. The consequent effect of viscosity on ink flow through these junctions is therefore large and will have a very noticeable effect on the final print density.

The third possible reason is associated with the rotation of the gravure roll from the ink tray to the doctor

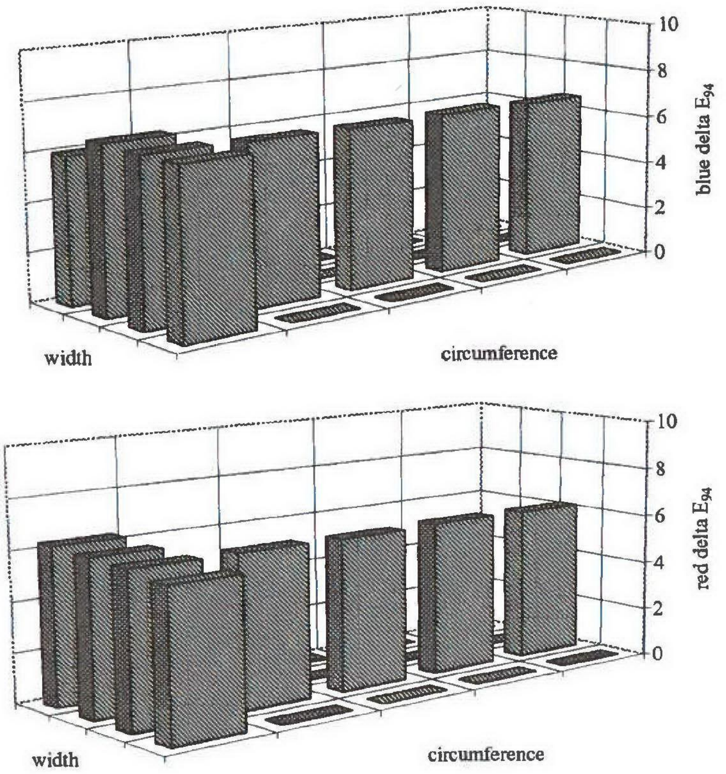

Fig. 8 Influence of ink viscosity on the $\Delta E^*_{94[1-3]}$ value

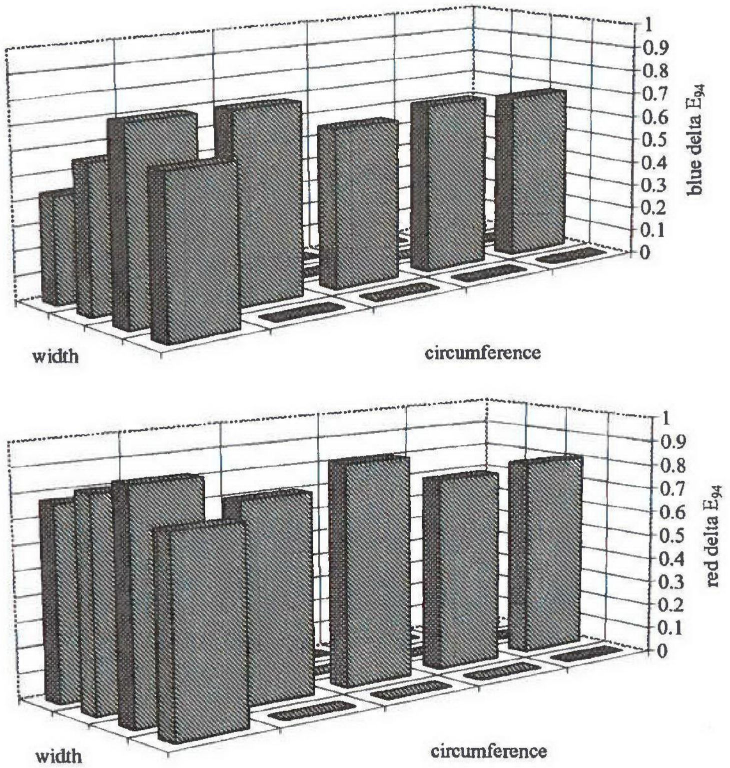

Fig. 9 Influence of blade angle on the $\Delta E^*_{94[1-3]}$ value

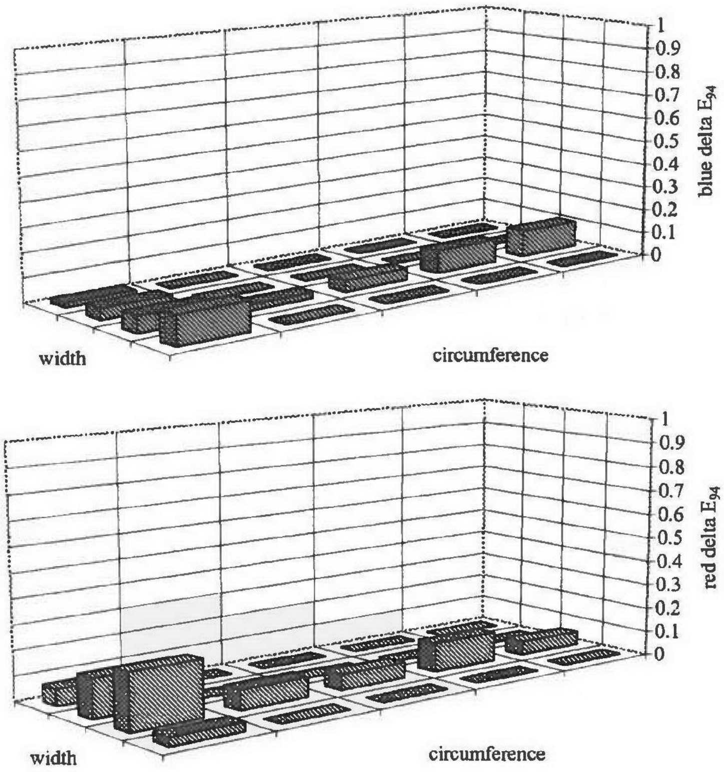

Fig. 10 Influence of blade load on the $\Delta E^{*}_{94[1-3]}$ value

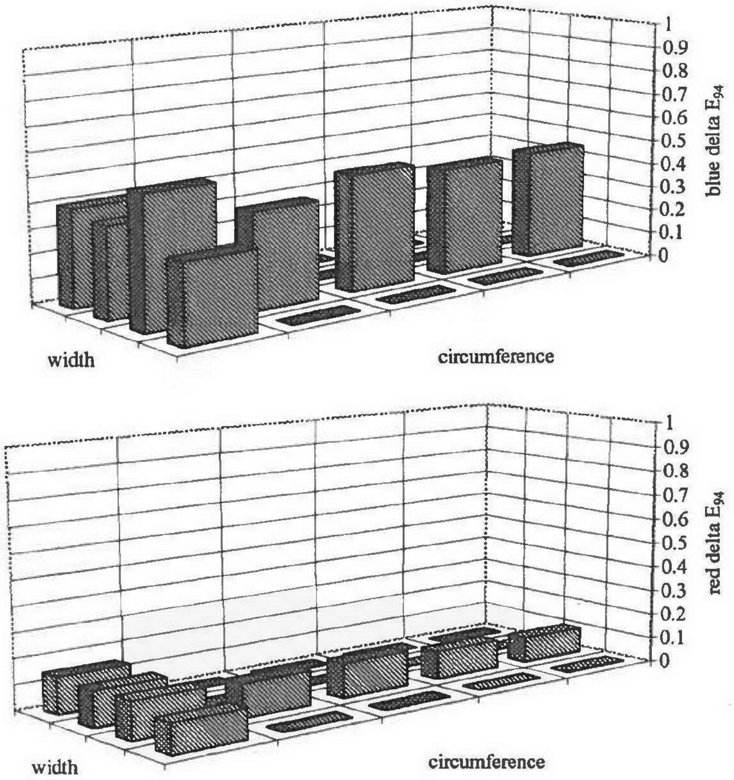

Fig. 11 Influence of impression pressure on the $\Delta E^{*}_{94[1-3]}$ value

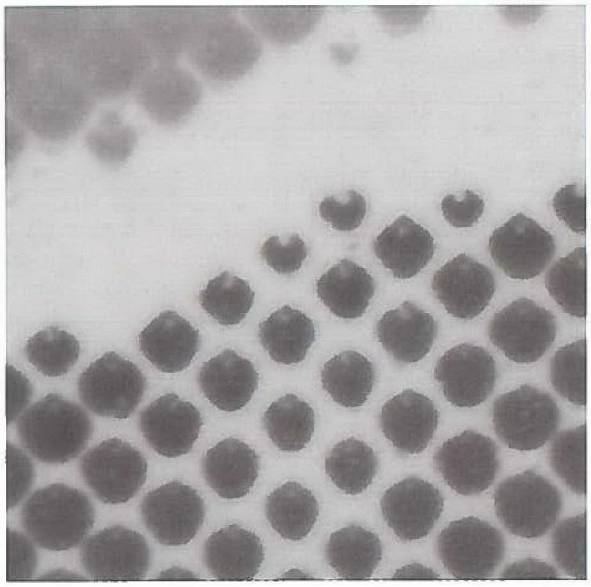

Fig. 12 Typical dot field

blade and from the doctor blade to the impression zone. During this rotation, some of the ink may flow out from the cells, and this is likely to be most noticeable with lower-viscosity ink [**12**]. To investigate this, typical halftone areas were investigated using image processing equipment. According to reference [**12**], ink outflow from the cell will be characterized by a reduction in ink film thickness within the dot region, and the images were viewed to establish whether this was the case. A typical image is shown in Fig. 12. The image was captured using a Leica Quantimet 500 and, for each viscosity level, the same 14 dots were analysed in five images, representing five cylinder rotations. None of the images displays emptying of the cells, which is characterized by an increased inner diameter in the doughnut-shaped dot where the colour density is lower. Therefore, this mechanism is not responsible for the colour changes shown in Fig. 8. The dot area was also measured for the different ink viscosities and the results are displayed in Fig. 13. As shown, the dot area increases as the ink viscosity decreases. This change in spread may be attributed to the squeezing action that is also present in the printing nip. The lower level of viscosity reduces the resistance to radial flow in the dot and therefore, for a given nip pressure, the lower viscosity will lead to a larger dot size.

This result points to a significant contribution by the hydrodynamic action over any emptying mechanism from the cells as they rotate from the ink duct to the impression nip. The mechanism of dilution may also contribute, but investigation of this requires the formulation of special inks as described in reference [**11**] and the tests run most conveniently on a laboratory-scale press.

The effect of blade angle on print quality is shown in Fig. 9 and the changes that are depicted in the figure are again significant. The $\Delta E^*_{94[1-3]}$ changes for the red ink are relatively even between the blade settings, while there is some unevenness in those detected using the blue ink. This result indicates the importance of the blade angle setting for the solid print areas. It was noted that, as the blade angle was reduced, so the image became darker with an increase in chroma, indicating that a thicker ink layer was being deposited.

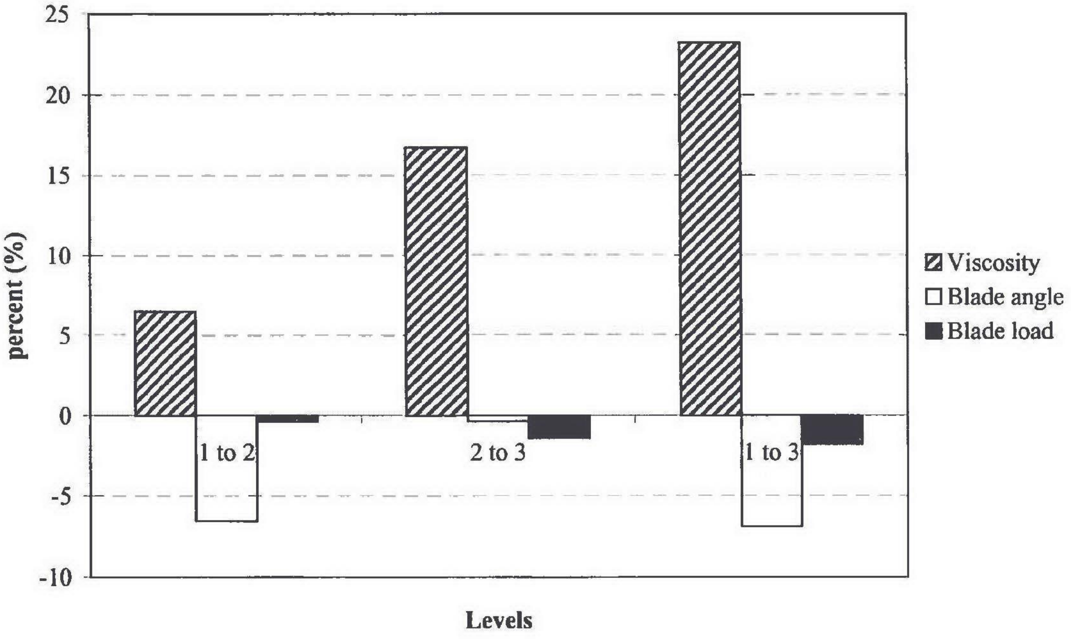

Fig. 13 Change in the dot area for different level settings

A possible reason for the higher deposit can be explained with reference to the hydrodynamic behaviour under the blade. Within the zone occupied by the cylinder and the blade tip, there will exist a convergent gap at which there is either hydrodynamic or boundary lubrication. For a given load, the film thickness will increase as the blade angle decreases **[13]**. This may apply to both engraved and non-engraved regions of the roll. However, the non-engraved area is subjected to boundary lubrication since the surface is clean with no ink passing under the blade. For the engraved cells, the change in angle may be reflected in a different level of fill, and the printed image was again analysed using the image processing techniques and sample measurements described above in an attempt to establish this. Figure 13 shows the percentage change in dot area as a function of the doctor blade angle and load. Clearly, the initial change from a steep to normal setting is the most significant where there is a reduction in the printed dot size. This behaviour is not attributed to the threshold setting on the image processing system since this was altered to compensate for any variations in illumination. Extensive calibration trials have been carried out to ensure the accuracy and repeatability of area measurement. This trend is contrary to that expected from the hydrodynamic behaviour that appears to fit the observation in association with Fig. 9. This result now suggests that the ink containment within the gravure cell and its subsequent release may be a more dominant mechanism. Furthermore, there was no evidence of haze on the printed copy, which would represent ink pick-up from over the complete gravure cylinder surface. The development of such a film in the non-engraved areas is controlled by hydrodynamic mechanisms.

The results in Fig. 10 show that the $\Delta E^*_{94[1-3]}$ colour difference with respect to changes in the blade load are small. The colour changes calculated for the inks are not much larger than the ΔE repeatability accuracy for the spectrophotometer. Changing the blade load has no overall or perceptible influence on the colour. The increasing load does not affect the ink in the cell since the blade load is reacted to principally by the non-engraved surface of the roll. This is also confirmed by the results from image analysis that are also shown in Fig. 13. Increasing blade load merely increases cylinder wear in the long term, with a consequential drift in colour as the cell volume is decreased, and the blade tip shape conforms to the roll surface profile.

Figure 11 displays the effect of impression roll pressure on ink transfer. This shows that impression pressure has a small effect on the colour and that it was only noticeable for the blue ink. The hydrodynamic behaviour in the nip zone is complex. For an impermeable film, the pressure generated in the nip needs to include the deformation of the rubber-coated impression roller **[14]**. The levels of these pressures are dependent on a number of factors including the viscosity (as discussed previously), speed and nip load which Fig. 11 shows to have little impact on ink transfer. This is an expected result, since an analysis of the parameters that influence ink flow through a nip junction confirm that nip load has only a small effect in comparison with viscosity which is the most dominant **[15]**.

With regard to the mechanism of ink transfer, subambient pressures are generated in the nip exit zone. It is possible that this is a key issue with regard to ink transfer from the gravure cell to the substrate where there will be an interaction between pressure, surface tension and cohesion forces **[16]**. The level of pressure force is affected by the press settings and operation, whereas the surface tension and cohesive forces are a property of the ink. To investigate this fully requires the formulation of inks having controlled properties of surface tension and cohesion. Within the nip, a further mechanism that may affect the printed colour is one where the very thin film substrate is pressed locally into the engraved surface. Under this circumstance, it is impressed into contact with the surface of the ink within the cells.

In comparing the results from this study, it is interesting to note that they are at variance with those reported in earlier investigations. This earlier work used a simulator **[17]**, a press printing coated board **[18]** and a study using a paper substrate **[12]**. In each of these previous studies, absorbent substrates were used and changes in the impression pressure increased the ink flow into the substrate. In the case of the film substrate used in this investigation, flow into the substrate does not take place.

Analysis showed there to be no interactions between the blade angle and load or the ink viscosity and impression pressure. The average ΔE^*_{94} calculated was approximately 0.1 which is well below any significance level. This allows the system to be optimized by adjusting each of the parameters independently to achieve acceptable and consistent print quality.

3.2.3 Response

The linearity of process parameters on ink transfer can be determined from the changes in averaged colour between each level, and these are displayed in Fig. 14. These highlight the fact that viscosity is the dominant factor by an order of magnitude and that it is non-linear, with $\Delta E^*_{94[1-2]}$ being much greater than $\Delta E^*_{94[2-3]}$. This indicates that the process is increasingly sensitive to changes in the ink viscosity as the viscosity level is reduced. This finding was observed on all units.

The remaining parameters have a significantly smaller effect and they are presented in rank order. The response of the system to changes in the blade angle is nearly linear, with the rate of colour change increasing as the angle is reduced. Also, the changes are not as pronounced with the straight doctor blade. However, this is due to the mounting arrangement of the blades. Both

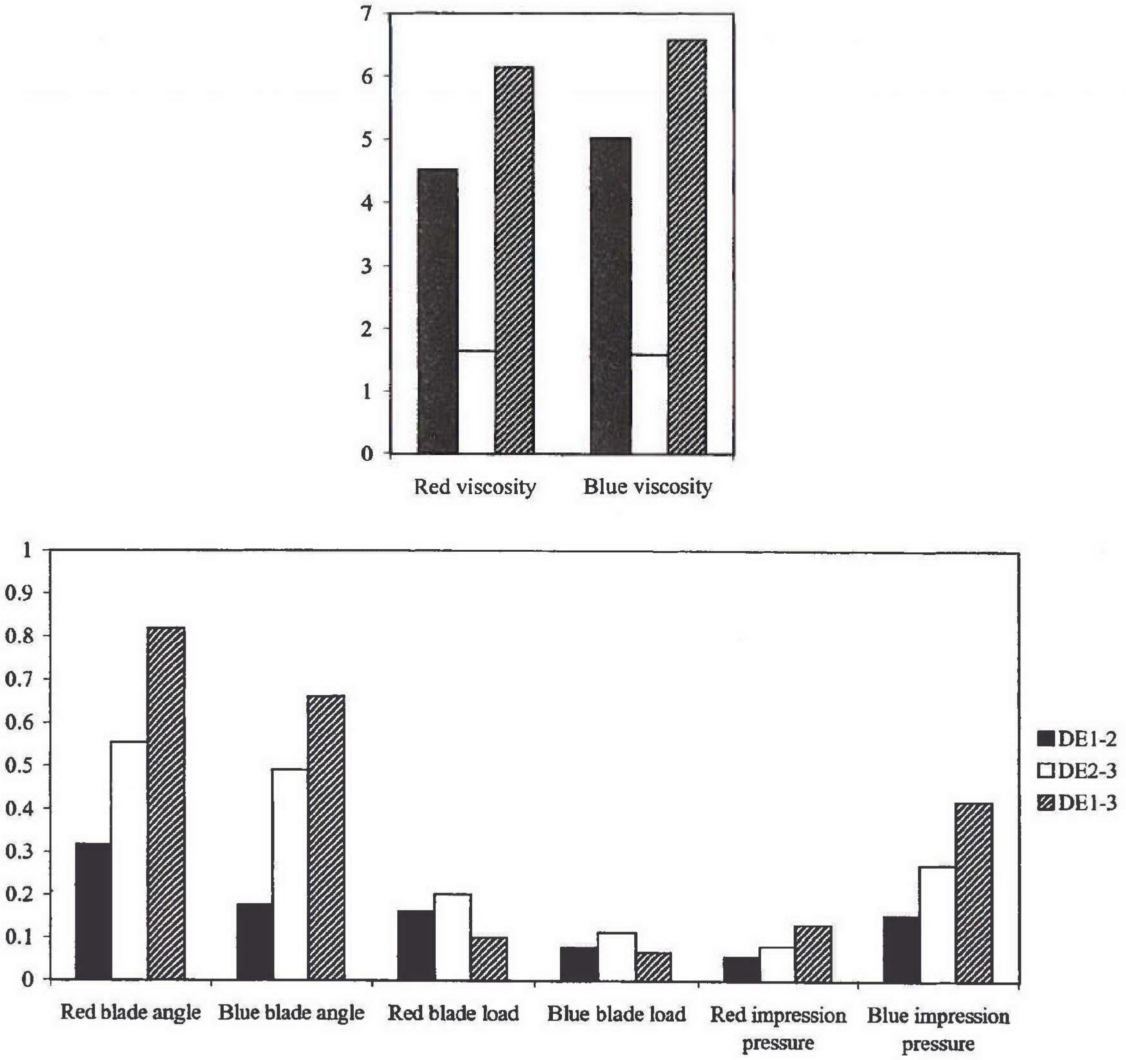

Fig. 14 Average colour change between each level

are mounted into a holder with the two blades having marginally different angles at the fixing point. The angle of the blade is set using the holder, and therefore the Y-shaped blade is at a less acute angle with respect to the roller surface than the straight blade. Thus, the angular difference between levels two and three is the same, but at a less acute angle, and hence a larger colour difference is measured for the Y-shaped configuration.

4 CONCLUSIONS

A number of conclusions may be drawn from this investigation. Examples of typical process variation through a gravure print run have been presented. The study has also shown the practical considerations that are necessary in order to conduct experiments on a printing press. It has also shown how orthogonal array experimental procedures may be used while having little impact on the routine running of the press. With regard to press operating practice, the ink viscosity has been seen to be the dominant factor affecting print quality as measured by the solid inking areas. The interaction between ink viscosity and colour difference was shown to be non-linear. Thus, to provide a stable and consistent quality throughout the duration of a print run, control and quality methods need first to be applied to the ink viscosity. An analysis of the colour changes and the image details suggests that, for viscosity changes, the mechanism of cell emptying between the font and impression nip is secondary to hydrodynamic mechanisms and possibly dilution. The latter requires an experiment that uses specially formulated inks of equal strength but different viscosity in order to isolate this. The influence of doctor blade angle was also found to be significant, but now it appears that hydrodynamic influences are secondary to cell transport and emptying mechanisms. The details of this physical interaction are not clear from this type of study and this requires further separate attention. Doctor blade load changes were insignificant and therefore this should be set as low as possible in order to minimize wear on the cylinder and blade itself. Finally, it was noted that impression pressure had little impact on print quality since film thickness within the nip is not particularly sensitive to load, particularly where the films are initially very thin.

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