THE APPLICATION OF TAGUCHI METHODS TO THE STUDY OF INK TRANSFER IN HEAT SET WEB OFFSET PRINTING

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Abstract

As part of a programme aimed at improving the colour control in heat set web offset printing, the effects of process parameters on ink transfer using an eight unit press were investigated. The press was fully instrumented for the measurement of temperatures, roll speeds and web tension. After through the run monitoring exercises to establish the range of colour variations using a spectrophotometer and the optimum sample size for measurement. The effects of some of the press operating conditions were evaluated by a series of orthogonal array experiments designed using the Taguchi method. Orthogonal array experiments allow the simultaneous variation of several parameters, thus minimising the size of the experiment while still being able to analyse for the effect of each independently. The experiments were performed during normal production and analysis of the test strip was carried out using spectrophotometry with customised software. This allowed the effects of experiments to be assessed without a serious disruption of production. The experiments highlighted several key parameters whose control is vital to the stability of the ink transfer process. The font parameters varied showed no measurable effect.

Introduction

The aim of the experimental investigation was to more fully

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understand the control of colour on the printing press. This has been carried out as part of a joint DTI/EPSRC link project which was started in April 1991 and carried out in collaboration with Jarrold Printing of Norwich (with the support of Rockwell PMC of Peterborough). The overall aims of the project have been to introduce a fuller understanding of the web offset process in order to improve productivity and quality, reduce the waste and develop a series of generic process models.

This paper concentrates on the application of the orthogonal array (Taguchi) experimental technique to a web offset press. A detailed presentation and analysis of the results will be given in a later paper. The basis of the orthogonal array technique is presented. The means by which the operating conditions were altered during the programme is explained and their effects are assessed and analysed. This is followed by a presentation of the criteria which were used to select the parameters to be investigated in the programme. The means by which changes were made and monitored on the printing units are discussed along with the techniques used for the analysis. Comments are made relating to the through the run monitoring exercises to establish normal operating conditions. This is followed by a preliminary presentation of the results from the orthogonal array experiments. Some of the problems encountered while carrying out trials using a production press are also included.

Design of experiments

The orthogonal array technique may be used for experimental design as it reduces the number of experiments required to fully investigate a set of parameters and can be used to indicate interactions between the parameters investigated. It is especially important to minimise time and costs while performing experiments using a production press. The time window available is limited by production issues (including good copy needing to be achieved, job changes etc) which are outside the control of the experiment.

Traditionally industry has focused on the system design approach, i.e. the selection of components, materials, assemblies etc. which are brought together to form a product or a process. However, all of these components will have inherent variability which will affect the performance of the product or process. Little attention is given to the choice of design parameters to minimise the influence of this variation on overall performance. The converse problem of the selection of tolerances for components and processes by evaluating which parameters need to be closely controlled, or more importantly, those on which can the tolerances be relaxed has also tended to be ignored. However, more recently more emphasis has been placed on these last two aspects of design. This has lead to the concept of robust design, where the inherent variability of components has minimal effect on the overall performance of the process.

To optimise the design of an existing process then it is necessary to identify which factors have the greatest influence and which values produce the most consistent performance. All of this has to be achieved with the minimum of experiments. For example, if there are eight variables, seven with the possibility of setting them to 3 levels and 1 which can only be set to 2 levels. The traditional way to carry out scientific experiments is to change one variable while keeping the rest constant (a full factorial experiment). For the above scenario this it would require $3^7 * 2 = 4374$ experiments

An alternative is to adopt an elimination approach. The procedure is to hold every thing constant except one variable, this is then changed systematically to each value in its range. The value which gives the best result is selected and held constant for the rest of the experiments. Another variable is selected and treated similarly to establish its optimum value. Thus each variable is eliminated in turn. This is in effect a sub set of the full factorial experiment. However, this approach makes two sweeping assumptions which are not necessarily valid. Firstly it assumes that if two identical experiments are performed the results will be the same. In most cases the natural variability of the process will invariably prevent this occurring. In the best case and by coincidence the process is made near optimal. The validation of this optimum is not clear since the path to achieving it is not defined. All processes experience variability and this can be compensated for by repeating experiments and averaging the results. However, this still only allows the evaluation of the parameters for average conditions. It does not address the inherent problem of reducing process variability. The second and most dangerous assumption is that the variables do not interact (i.e. when one variable is changed the remainder are unaffected).

The third traditional approach is to use experience to optimise the process. Under this circumstance, assumptions are made with regard to the influence of some of the operating factors and the number of variables is reduced to enable the completion of a full factorial experiment on the variables. This approach presupposes that factors are unimportant and where the process detail is not well understood (as in printing), then this makes a dangerous approach. What is required is a means of exploring the whole field systematically and efficiently, leaving no area unexplored in order to maximise the range of the investigative process.

Genechi Taguchi initiated work to optimise complex production processes in the early 1950's, for details refer to Taguchi and Wu 1979. In his search through the published literature, he discovered investigations carried out by the agricultural research centre in Bedfordshire in the 1930's, by Sir Ronald Fisher. Their problem was to study the effect of different chemicals and growing conditions on species of plant. They could not carry out a full factorial experiment for practical as well as volume reasons and developed orthogonal arrays from the theory of combinatorial structures to reduce the experiment to manageable size. Orthogonal array theory was a design of experiment which allowed the independent assessment of each of the factors. The approach was opposed by some of the scientific community as the results were subject to inherent uncertainties. However, these uncertainties were in most industrial cases less than the experimental error and more importantly the orthogonal array approach allowed the ready investigation of interactions. The design of experiments remained the preserve of specialists who focused their attention on response surface methodology which still used the linear model theory of the factorial experiment. So, it was twenty years later that Taguchi started to develop the technique for using orthogonal arrays in process optimisation in manufacturing industry. The approach has become known colloquially as the "Taguchi" method, as one of Taguchi's major contributions was to present the arrays and the solution techniques in an user friendly format so that they can be used easily in the design of experiments.

The array is a subset of the full factorial experiment. It is balanced i.e. each variable setting occurs the same number of times. Also, no two experiments are the same (or even mirror images). The arrays are published in tables which are in effect a route map by which the experiment should be performed. The factors to be investigated are assigned to appropriate columns and the tables describe the settings which should be used for each experiment. If there is not an array to fit the problem then there are also ways by which they can be modified without destroying their orthogonality, i.e. the ability to analyze for each variable independently is not lost.

There are other designs of fractional factorial experiments, but in most case these are less efficient or do not cover the full range of combinations of factors. One of the main strengths of the orthogonal arrays are their ability to analyse for interactions between factors and with certain elements of the arrays to be able to ignore the interactions as their effects are smeared across all the results.

A standard L8 orthogonal array is shown below, Taguchi and Konishi (1987). This would be used to investigate the effect of four parameters in columns 1, 2, 4 and 7. The interactions investigated would be calculated from columns 3, 5 and 6. The quality characteristic (Q.C.) is the means of assessing the effect of changes in the process parameters, for example in printing, ink density or dot shape. These values would be entered for each of the run numbers in the experiment.

Column	1	2	3	4	5	6	7	Q.C.
Factor	A	B	-	C	-	-	D	
Run No.								
1	1	1	1	1	1	1	1	
2	1	1	1	2	2	2	2	
3	1	2	2	1	1	2	2	
4	1	2	2	2	2	1	1	
5	2	1	2	1	2	1	2	
6	2	1	2	2	1	2	1	
7	2	2	1	1	2	2	1	
8	2	2	1	2	1	1	2	
avg L1								
avg L2								
|L1-L2|								

Table 1 Taguchi L8 orthogonal array

This is a two level investigation for each of the four parameters. Multi level experiments can also be carried out. The samples would be analysed using a quality characteristic for each of the runs in the test. The results from each test at level one would be averaged, as would those at level two in each column. The difference between these values will, in each column, indicate the effect of the different parameters.

The interactions are calculated from columns 3, 5 and 6. A linear graph of these is shown in Figure 1. A knowledge of the process and possible interactions is of great use in the design of the experiments. This allows for the possible interactions to be detected and not eliminated as in the previous traditional experimental techniques.

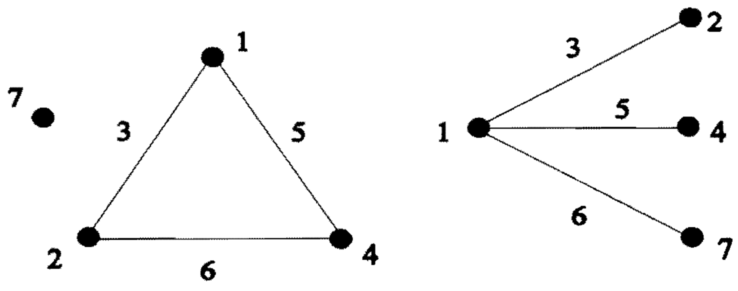

Figure 1 Linear graphs for L8 Taguchi array

To summarise, orthogonal arrays are used because:-

i They are an efficient sub factorial design for experiments.
ii They solve for interactions.
iii Some designs enable compounding of the interactions, i.e. to spread them across all columns so that all the columns can be used efficiently to study factors.

It has been shown by many workers, for example Saleh (1982), that there are a large number of parameters that will effect the printed image. These relate to the reprographic process, printing process, plate, paper, ink, water and the human effects. The use of the orthogonal array technique for the experimental program has allowed a larger number of these parameters to be investigated and facilitated the study the interactions between the parameters.

Quality Characteristic

In the context of printing, the usefulness and applicability of the orthogonal array experimental technique depends on the quality characteristic used to evaluate changes made on the press. The printed image consists of a series of halftones which when viewed appear to give a single tone dependent on the composition of the colours. The print is traditionally assessed by eye and changes made are based upon these observations. However, this is not sufficiently accurate for experimental analysis and is a subjective observation based on the individual observer. An evaluation of the possible measurement techniques was carried out by the use of densitometry, spectrophotometry and image processing.

Densitometers and spectrophotometers are the most commonly used instruments for colour measurement. These measure either the reflected or transmitted light using a controlled light source. The spectrophotometer measures the light collected at many points within the visible spectrum curve. The densitometer measures the light within certain wavelength bands corresponding to the characteristics of the process colours, these commonly being cyan, magenta, yellow and black. Hence, the densitometer will only give partial information relating to the colour being measured with the possibility of different colours having the same readings. It is only possible to accurately define the colour using the CIE colour space values. For measurement of changes of a process colour only it is possible to obtain most of the information using the densitometric readings.

The dot field analysis using image processing techniques provided useful information but due to the measurement and analysis times involved they proved prohibitive for full scale analysis of the orthogonal array results even with the smaller sample sizes as a result of the technique.

To maintain cost control and to ensure the applicability under normal printing conditions, it was decided that there would be no trial plates prepared specifically for the experiments and that they would be carried out within a normal production run. To enable measurement, features which were part of the plate composition were used to observe the effect of press operation which would influence the quality characteristic. A test strip (the Gretag CMS2 or latterly the CMS3) was included in every print job and provides information relating to all colours across the width of the web along with dot area, three colour grey and trap information for each of the production print jobs.

In the experimental work, an eight unit press was used and changes on the press were carried out primarily on one unit only. For this purpose the a magenta unit was chosen since changes made in this colour would be most apparent in the editorial matter. Although changes could be detected using the grey and trap patches it was decided to use the solid and halftone patches for measurement with a spectrophotometer capable of providing densitometry and CIE colour space values. Solid and halftone patches were selected as these were not affected by changes on the other print units.

As explained previously, the analysis of these measurement areas could be carried out in several ways, for example densitometry, colorimetry, spectrophotometry and image processing. In this work, a reflectance spectrophotometer (Gretag SPM50 with $0^0/45^0$ ring optics) was used for the measurements of the patches. As the operating conditions of only one unit was being adjusted it allowed the use of both density and CIE colour space values to be used in the analysis. The results presented in this paper will primarily be those obtained using the densitometric function.

Evaluation of the commercially available software initiated the design and writing of in house software to collect the data from the spectrophotometer. The software was written in a windows environment using Microsoft Visual Basic. The program is menu driven and can initiate the measurement by the instrument and then record all the data which is stored within the measurement instrument. This data can then be written directly to disc in ASCII format or exported into a Microsoft Excel spreadsheet for manipulation and analysis.

Selection of press parameters

The parameters to be investigated during the experiment were determined after initial brainstorming sessions which included all levels of personnel from the collaborators. A total of over 80 parameters were identified during these sessions.

A review of some of the parameters highlighted during these sessions, such as roller pressures and ink film thicknesses, indicated these were inappropriate and unpractical to investigate on a production press. This was due to many factors including instrumentation difficulties, method uncertainty, their possible failure causing mechanical damage to the press and the time required to set up the instruments. The investigation of these parameters was transferred to University laboratories for controlled experiments on a single press unit which has been set up and fully instrumented within the Department. Pressure sensors in the rollers, thermocouples embedded in the rollers, capacitance and inductive sensors (for ink film measurement) were used to investigate the contact and transfer properties in the roller nip.

The parameters which remained within the experimental program at Jarrold Printing were then sub divided into categories, these being

- control parameters
- process stability parameters

The control parameters are those which can be adjusted to obtain a colour match between the copy and proof. These parameters have a large effect on the printed image and represent the controls that are normally available on a press (ink key setting, pan roll trim etc). Their behaviour has implications for the long term development of automatic (or closed loop) colour control and colour correction while the press is in operation.

The second set are concerned with process stability and represent those parameters which may vary naturally through the duration of a print run or from job to job. The control of these would enable a more consistent and predictable print. A few of these parameters may also be adjusted by the print crew in both obtaining good copy and in maintaining the good copy.

Taguchi orthogonal array experimental program

Prior to the commencement of the Taguchi trials an extensive set of monitoring exercises were carried out through the duration of several print runs with the measurement of both the press conditions and the printed image. These highlighted both long term drifts and short term fluctuations. These were analysed using moving average and Fourier analysis to determine optimum collection sample sizes and the presence of any underlying variations in print quality. Establishing which of the parameters were affecting the press stability was deemed essential to the long term success of the project.

The number of parameters being investigated resulted in it being possible to fully instrument only one of the press units. The unit chosen was magenta unit 7 since this caused most of the control problems in the image and the unit was close to the dryer, Figure 2. All the measurements were carried out on the magenta printed from this the upper side of this unit.

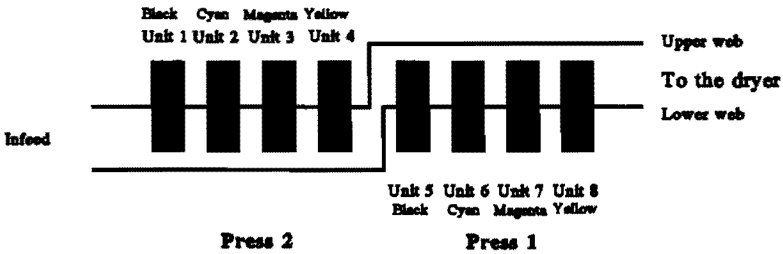

Figure 2 Schematic of a 8 unit press at Jarrold Printing

Several different experiments were carried out and these were primarily true orthogonal array experiments investigating control and process stability parameters. These were designated Taguchi sets 1 and 2 and these are summarised in Table 2. The third set was used to investigate uncontrollable factors, such as web breaks. The effect of ink trapping between different units was evaluated in Taguchi set 4.

Experiment number	Parameters investigated
Taguchi 1	Ink key setting Duct roll speed Pan roll speed
Taguchi 2A	Pan roll speed, CUIM roll speed Temperature of fount in pan Temperature of ink in duct
Taguchi 2B	Temperature of fount in pan Temperature of ink in duct On-line blanket wash Temperature of copper roll cooling water
Taguchi 2C	Temperature of fount in pan Temperature of ink in duct
Taguchi 2D	Temperature of fount in pan Temperature of ink in duct
Taguchi 2E	Temperature duct roll cooling water Temperature copper roll cooling water
Taguchi 3A	Web Breaks Temperature of fount in pan Temperature of ink in duct
Taguchi 3B	Ink key movement and hysteresis
Taguchi 4A, 4B	Trapping between units

Table 2 List of the main Taguchi experiments

The time period over which the experiments could take place proved to be one of the major problems which was encountered. The press needed to be stable before any experiment was carried out for any quantitative assessment of the process to be carried out. Monitoring the press showed that it takes up to two hours to stabilise thermally. Therefore, the experiment could not be started until this had been achieved. The problems were further increased by other stops on the press due to web breaks, dryer flame out, folder problems or other mechanical problems on the press. Also any experiment could not be started until the pass copy had been achieved (as determined by the colour passer and/or customer) and any specials required by the customer were removed. Furthermore, the changes made could not drastically affect the product quality so that production would not be

Monitored parameters	Taguchi experiments
Ambient around reel stands	Taguchi 1, 2A, 2B, 2C, 2D, 2E
Ambient behind unit 7	Taguchi 1, 2A, 2B, 2C, 2D, 2E
Ambient outdoors	Taguchi 2A, 2B, 2C, 2D, 2E
Chill water temperature	Taguchi 2A, 2B, 2C, 2D, 2E
Conductivity of fount in pan	Taguchi 2A, 2B, 2C, 2D
Cooling water temperature to copper rolls	Taguchi 1, 2A, 2B, 2C, 2D, 2E
Cooling water temperature from copper rolls	Taguchi 1, 2A, 2B, 2C, 2D, 2E
CUIM speed	Taguchi 1, 2A, 2B, 2C, 2D, 2E
Duct roll speed	Taguchi 1, 2A, 2B, 2C, 2D, 2E
Fount temperature in pan	Taguchi 1, 2A, 2B, 2C, 2D, 2E
Fount temperature in recirculation unit	Taguchi 2A, 2B, 2C, 2D
Frame temperature of unit 7	Taguchi 1, 2A, 2B, 2C, 2D, 2E
Humidity	Taguchi 2A, 2B, 2C, 2D, 2E
Ink temperature in duct	Taguchi 1, 2A, 2B, 2C, 2D, 2E
Ink temperature on duct roll	Taguchi 2A, 2B, 2C, 2D, 2E
Ink temperature on copper rolls	Taguchi 2A, 2B, 2C, 2D, 2E
Ink temperature on rubber rolls	Taguchi 2A, 2B, 2C, 2D, 2E
Pan roll speed	Taguchi 2A, 2B, 2C, 2D, 2E
Paper temperature	Taguchi 2B, 2C, 2D
Press speed	Taguchi 1, 2A, 2B, 2C, 2D, 2E
Roller speeds	Taguchi 1, 2A, 2B, 2C, 2D, 2E
Web tension	Taguchi 1

Table 3 Monitored parameters for Taguchi experiments 1, 2A, 2B,2C, 2D, and 2E

disrupted seriously.

The problems in carrying out the experiment emerged clearly during the first trial, Taguchi 1. This included the time for the press to stabilise and that the changes made required a longer period than originally anticipated. This determined the time window and which allowed at most the possibility of running a maximum of Taguchi L8 or L9 experiments.

The Taguchi trials which were undertaken are summarised in Table 2. The parameters investigated were the ink key settings, duct roll speed, pan roll speed, CUIM roll speed, the temperature of the fount in the pan, the temperature of the ink in the duct, the temperature of the copper roll cooling water and the effect of blanket washes. Additional parameters were also monitored during the experiment to evaluate their possible effects and eliminate (or establish) their influences on the findings from the Taguchi experiments. These are shown in Table 3.

In addition to these experiments, Taguchi 3A was used to investigate the effect of web breaks. Initially this was designated 2B but the occurrence of a web break part way through interrupted the collection of copies. Copies were again collected after the web break and this data was then used to evaluate the effect of the web break. Taguchi 3B was used to look at ink key movement and direction on the printed ink density. There have been several subsequent trials carried out in this area. Taguchi 4A and 4B were used to investigate the effect of pan roll trim on the trapping characteristics on and between three units.

The data from the majority of the controlled and monitored parameters were collected via two computer data acquisition systems. These recorded at ten second intervals the most important press roller speeds, strategic unit press temperatures, ambient and frame temperatures. Manual measurements were carried out for the humidity and conductivity readings. A hand held infra read thermometer (Heimann KT19.25) was used to measure the temperature of the ink in the inking train on the surface of the rolls where the filters used were matched to the spectrographic characteristics of the ink using a Fourier Transform Infrared Spectrometer. This was required so the ink film temperature was measured and not the bulk temperature of the roller on which the ink was flowing.

Results from the Taguchi orthogonal array experimental program

At the outset of the experimental program it was the intention to address both the gross changes in the image quality and the copy to copy variations (standard deviation etc) caused by process parameter changes. However, the normal fluctuations in the process made it impossible to investigate the effect of the process parameter changes on sequential copies.

The monitoring and evaluation of a single printing unit over a twenty day period showed there were significant temperature fluctuations. These occurred through the duration of a single print run and from day to day. Figure 3 shows the change in the ambient (above the unit), frame, cooling and chill water temperatures for unit 7 over an 18 hour period. The variation of duct ink, fount in the pan and duct roll coolant temperatures are shown in Figure 4. These show large fluctuations in the thermal equilibrium of the press. The temperatures of the frame and ink duct increase as the press is in operation. Once the press is stopped these will reduce to return to factory ambient conditions and tend to converge to a common base value.

There is a significant temperature gradient across the width of the machine. The higher temperatures were measured on the operator side. This differential is due to the oil and mechanisms on the gear side acting as a heat sink and aiding the heat dissipation. The difference in the frame temperature is largest at approximately 5 degrees with the overall changes of 10 degrees in temperature. The ambient temperature around the press also increases, Figure 4.

Good control of the fount solution in the pan was achieved with no significant temperature rises throughout the duration of the print run, Figure 4. However, there is a cyclic oscillation in the temperature of approximately 2 degrees. This would suggest that the control system is too sensitive and is continually chasing the set temperature. Once the press is stopped the temperatures return to ambient values.

The ink in the duct also increases in temperature as the press is running. There is only a small cross machine temperature differential. The rise in temperature is due to the increased work being carried out in the duct in shearing the ink at the duct roll to ink key interface. Numerical modelling of this has been carried out and will be reported on in a later paper.

Temperature measurements were made across the width of the ink duct with thermocouples mounted at each side. The infra red thermometer was used to measure the ink temperature on both the rolls and in the ink duct. This allowed for comparison of the results between the two instruments to be cross checked since the rolls were not always covered with ink. The results from these tests are shown in Figure 5.

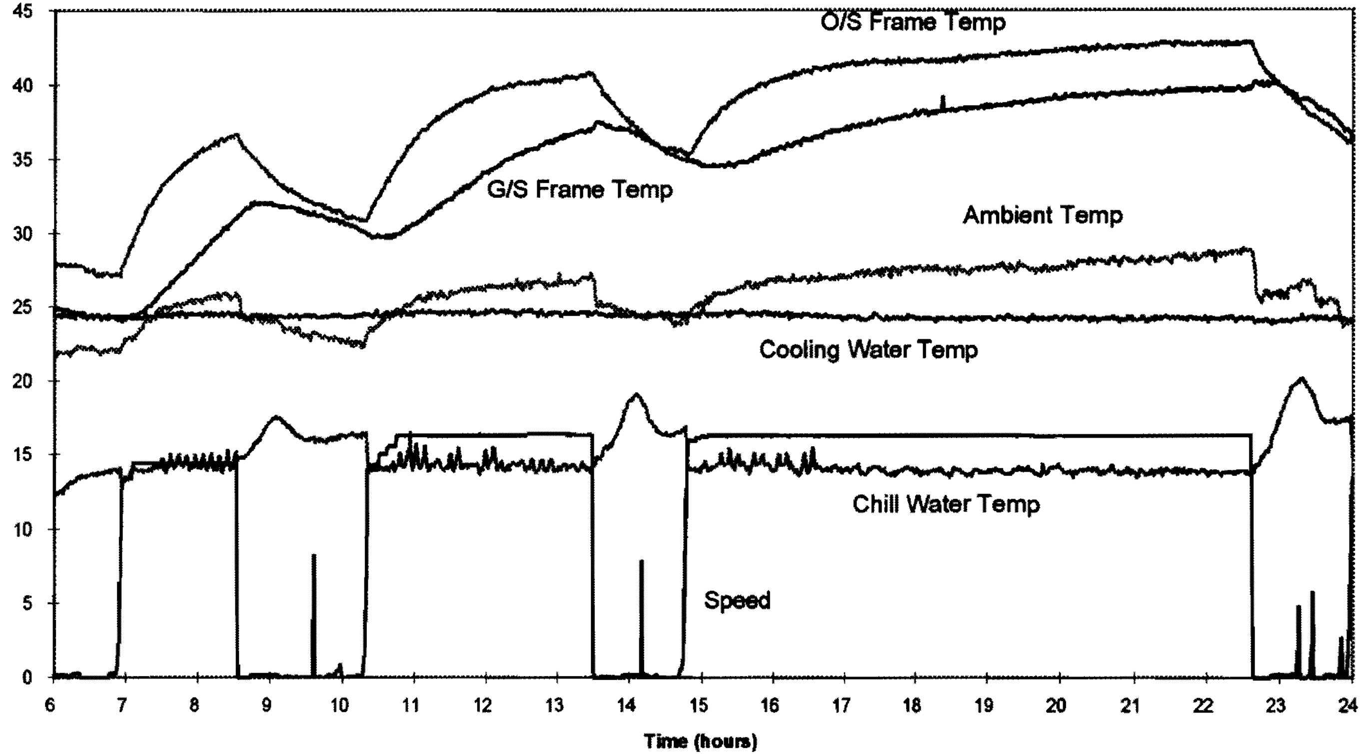

Figure 3 Temperature fluctuations of the frame, water and ambient temperatures

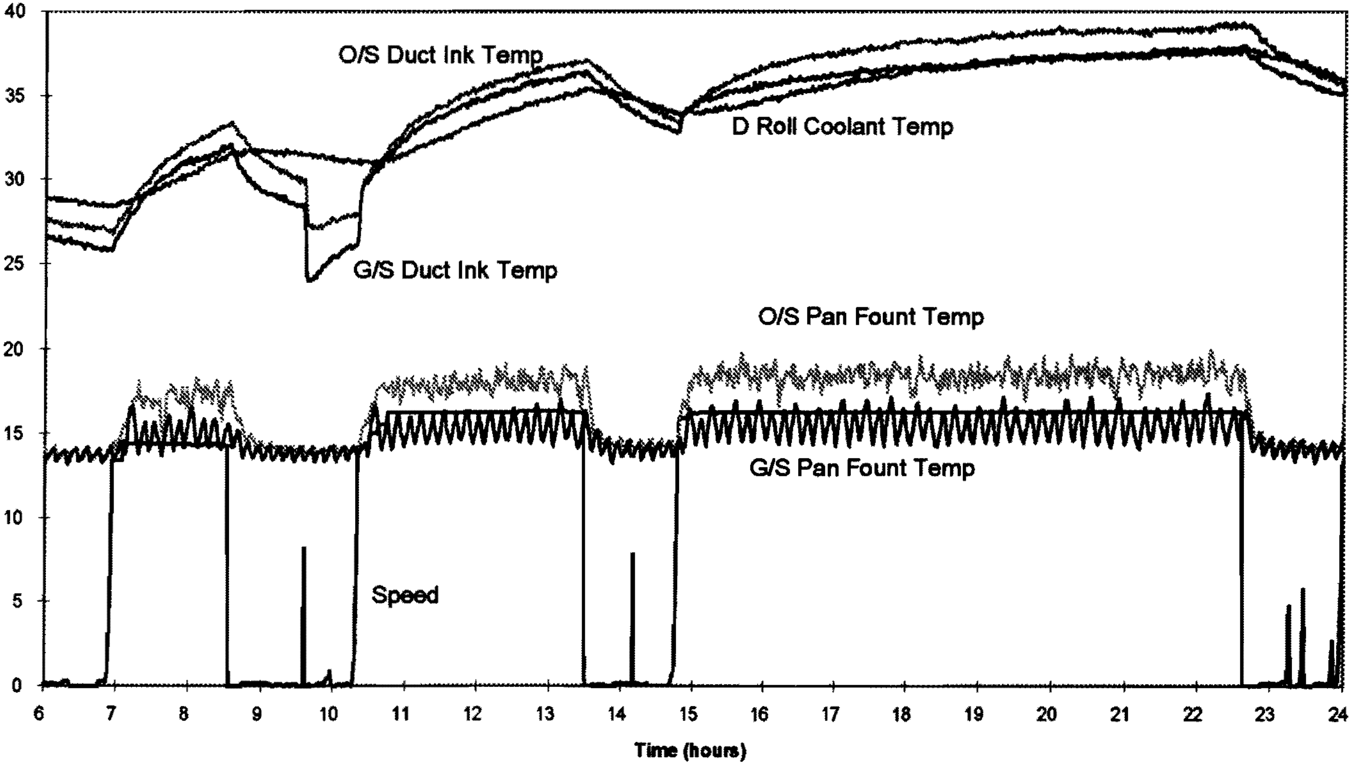

Figure 4 Temperature fluctuations of ink, fount solution and duct roll coolant

These show that there is good agreement between the two techniques and that there is only a small time lag between the temperature on the duct roll and in the ink duct. This allows the readings from the thermocouples in the ink duct to be used as an indicator of the duct roll temperatures.

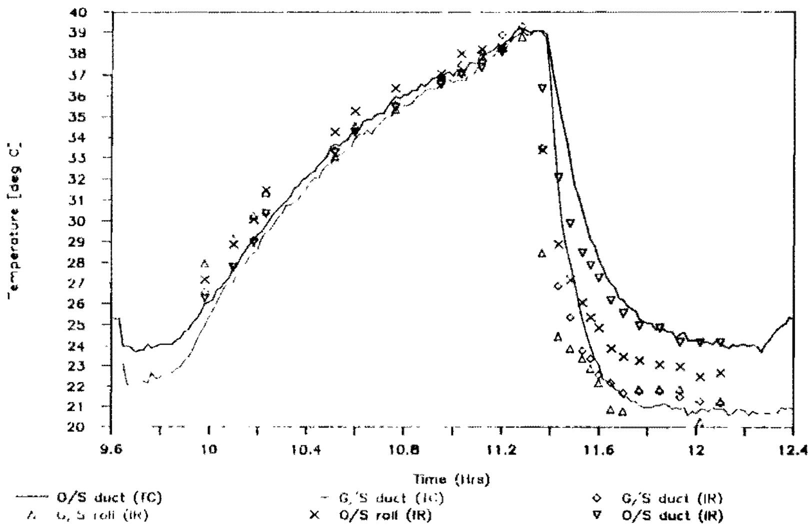

Figure 5 Temperature measurements in the ink duct under controlled conditions

The parameters addressed directly through the experimental program have been

- i CUIM roll speed (Taguchi 2A)
- ii Ink key setting (Taguchi 1)
- iii Duct roll speed (Taguchi 1)
- iv Duct roll temperature (Taguchi's 2A, 2B, 2C, 2D, 2E, 2G)
- v Fount temperature (Taguchi's 2A, 2B, 2C, 2D)
- vi Pan roll speed (Taguchi's 1, 2A)
- vii Copper roll cooling water temperature (Taguchi's 2B, 2E)

Changes in the CUIM roll speed, the ink key setting and the duct roll speed all affect the printed ink density. As the CUIM and duct roll speeds increase there is an increased ink density. The duct roll speed was altered using the trim and the 10% increase in speed resulted in an ink density increase of 0.097. A similar 10% increase in the CUIM speed resulted in a smaller average ink density increase of 0.070. These changes are significant and visible to the eye. The ink key movement significantly affects the ink density. As the gap between the duct roll and ink key is increased the ink density also increases. This relationship is complicated by hysteresis in the system and secondary effects in the ink flow. These effects will be reported upon and explained in much greater detail in a later paper.

The duct roll temperature also changes the printed ink density. It can be seen from the list of Taguchi trials that this parameter appeared several times in the programme. This was due to variable response in the first trial. The second experiment showed that for a change of duct temperature there were both magnitude and directional changes (i.e. the ink density decreased with the temperature change whereas in the previous trial Taguchi 1, it had increased). Originally in this experiment the coverage had been treated as "noise" in the analysis since no control was possible over this value. Following further analysis in this area it was found that there was a strong interaction with the print coverage and duct roll temperature. This has been confirmed by further trials where systems were fitted to the press to asses its significance. Understanding has also been derived from numerical models developed to represent the ink duct system.

No major effect on the ink density has been detected by changing either the fount temperature or the pan roll speed provided that they were maintained within control limits. However, it was found on press that deviations in the water levels outside the limits caused catastrophic and wholly unacceptable changes in the printed image. The changes made in the pan roll speed have been relatively small due to the requirement to produce saleable copy throughout the duration of the trials. Further image processing based evaluation of the test strip for some of these tests is being carried out to try to establish why the printer crews believe that they should control the water level closely and whether this is primarily to avoid the catastrophic change in the printed image.

Web breaks have a very large effect on the ink density and image since it effectively disturbs the equilibrium of the running press. Consequently a large number of parameters change when this occurs and this includes the thermal equilibrium of the system. Also it has been shown that an on line blanket wash will significantly affect the printed ink density, Taguchi 2B. The wash which is used while the press is stationary is believed to be much more effective and as such the changes in print quality are also greater. As such this needs to be further investigated and contrasted against on line systems which complete this on a running press if more efficient press operation is to be realised.

Closure

A series of orthogonal array experiments have been carried out on a web offset press with a minimal interruption to production. The monitoring exercise has shown the press to possess large thermal drifts during its operation. There is a secondary thermal gradient across the width of the machine. The orthogonal array experiments have increased awareness of print quality, identified parameters which are important for achieving print quality effectively and to improve system design which is important to control press stability. It has been shown that the CUIM, duct roll speed, duct roll temperature and the ink key settings all affect the final image. No discernable effect has been detected for changes in the fount solution.

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