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The application of orthogonal array analysis to the screen printing process.

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Summary

This paper outlines the development and results of a comprehensive experimental programme to investigate the effect of the primary screen printing parameters on the print quality. The selection of the parameters to be included in the experiments was based on both experience and discussions with industry. Three key areas were identified which were thought to have a substantial effect on the print quality; these were mesh characteristics, squeegee characteristics and ink rheology. Since the investigations found a number of parameters which may have an effect on the quality of the screen process a full factorial experiment was deemed impractical and thus it was decided to use orthogonal array analysis. By engineering design and astute choice of variables, an L_{18} orthogonal array for the print machine parameters consisting of mesh tension, mesh structure, mesh ruling, a squeegee pressure and edge hardness parameter, squeegee angle and ink characteristics was developed. A test form was designed which facilitated the measuring of image distortion and tonal reproduction Five copies were analyzed from each experiment using spectrophotometry. Control conditions were specified which ensured minimum variation between successive experiments by controlling the ink temperature, room temperature and screen ink film thickness. It was found that 7 of the 8 parameters chosen effect the quality of the printed image and that the experiment had been a success. Recommendations for further investigations are made.

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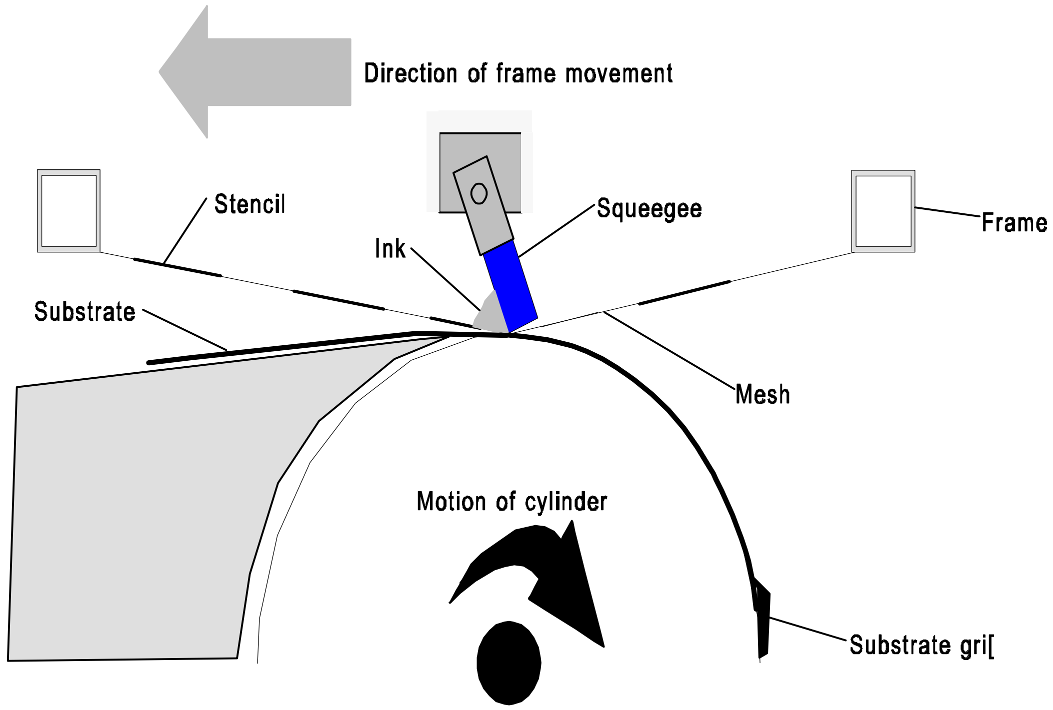
1. Introduction.

The screen printing process is a transfer process where a viscous medium is pushed through a permeable membrane which imparts an image on the substrate below. The principal behind the screen printing process is shown in *figure 1*, where the action of the squeegee forces the ink through a fine mesh. The image is dictated by a stencil which is mounted on the underside of the mesh, which is bonded on a rectangular frame. Its prime advantage over other printing processes is its flexibility, it may print almost any viscous medium on to almost any substrate. For this reason, it is widely used, not only in the reproduction of graphic arts, but in industry for a wide range of process applications such as printed circuit boards, vehicle decals, fabric printing,



ceramic transfers, instrument panels and compact disks.

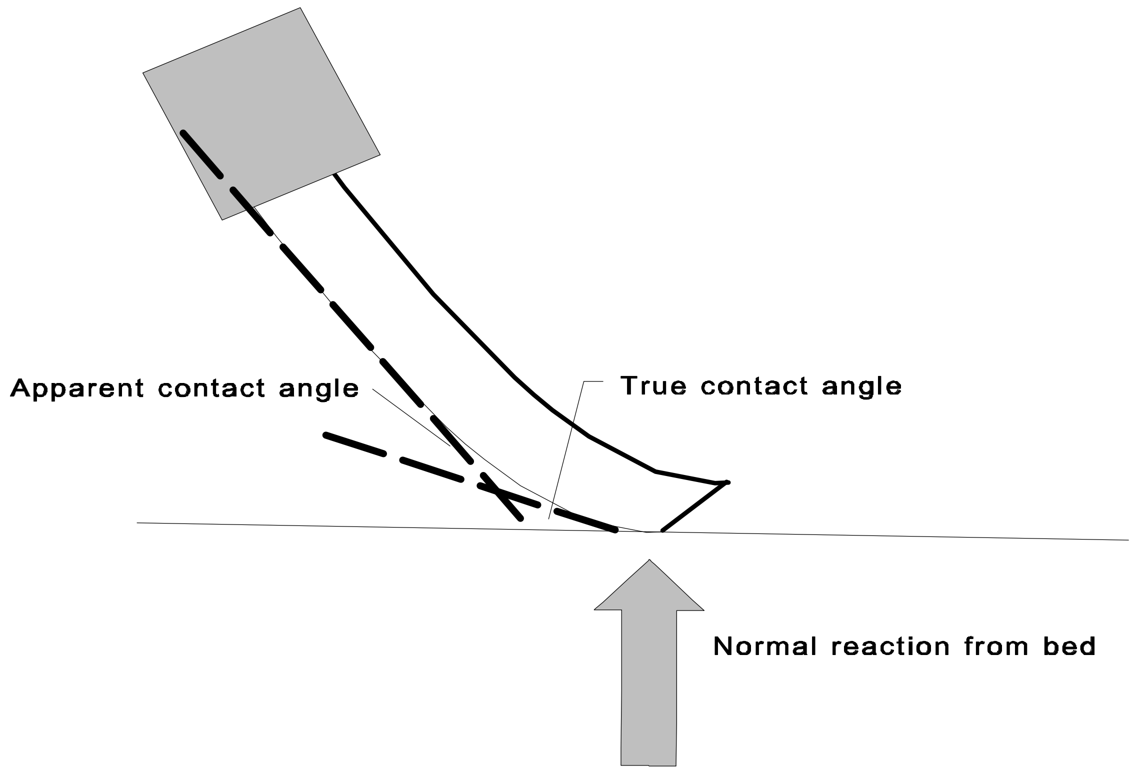
Many factors influence the quality of the screen printing process, and traditionally, as the process has been looked at as a craft, little is known about these factors' effect on the fundamental physics or on process quality. The aim of this preliminary study was to select parameters which were considered to be important and then to assess their effect on the printing characteristics. The tests were carried out on an automatic cylinder press at GLOSCAT. A discussion of the parameters considered important in the screen printing process is presented followed by a description of how a suitable experiment to evaluate the importance of these parameters has been designed. and the experimental procedure and control aimed at limiting errors is presented.

2. Derivation of the primary printing parameters

What ultimately affects the quality of the final print in screen printing is the forcing of the ink though the mesh / stencil and its subsequent adhesion to the substrate below. The discussions held during industrial visits highlighted a number of problems evident in the screen printing process. Three key areas were identified, these were mesh tension, the deformation of the squeegee during the print process and the rheology of the ink flow through the mesh to the substrate.

The mesh is tensioned to draw the mesh away from the substrate after the passage of the squeegee. As result the mesh lies a distance from the substrate, the off contact gap. Theoretically, in order to limit the distortion of the image caused by the deformation of the mesh the distance between the mesh and the substrate should be minimised. The smaller the off contact gap the greater the mesh tension required to overcome the viscous forces between the ink and the substrate and mesh. Higher mesh tensions however require stronger mesh and frame materials and mesh structures and may impart a greater drag force on the squeegee. It is not known whether higher mesh tensions may also incur penalties in terms of promoting image stretch and stencil degradation during a print run. Higher squeegee pressures may need to be applied which will apply greater loads on the mesh promoting mesh stretch. For this study, it was decided to evade the mesh tension - off contact gap relationship by keeping the off contact gap constant at 3 mm and concentrating on the mesh tension squeegee down force relationship. It is likely that the off contact gap - mesh tension relationship is less important in cylinder bed presses where there the rip off action of the grippers on the cylinder pull the substrate away form the mesh

The contact angle and pressure between the squeegee, which is made of a urethane compound, and the mesh are important parameters which influence the way the squeegee forces the ink through the mesh. The traditional primary squeegee parameters used by printers to control the squeegee action during the print process are squeegee angle, pressure and hardness. However, considerable interaction between these parameters is experienced. All three affect the contact angle and pressure at the squeegee edge / mesh interface where the printing process takes place, *figure 2*. The closer the squeegee angle to the vertical the smaller the deflection of the base of the squeegee due to the downward pressure force. Similarly a higher squeegee hardness or lower squeegee downward pressure also limit the deflection of the base of the squeegee. The deflection



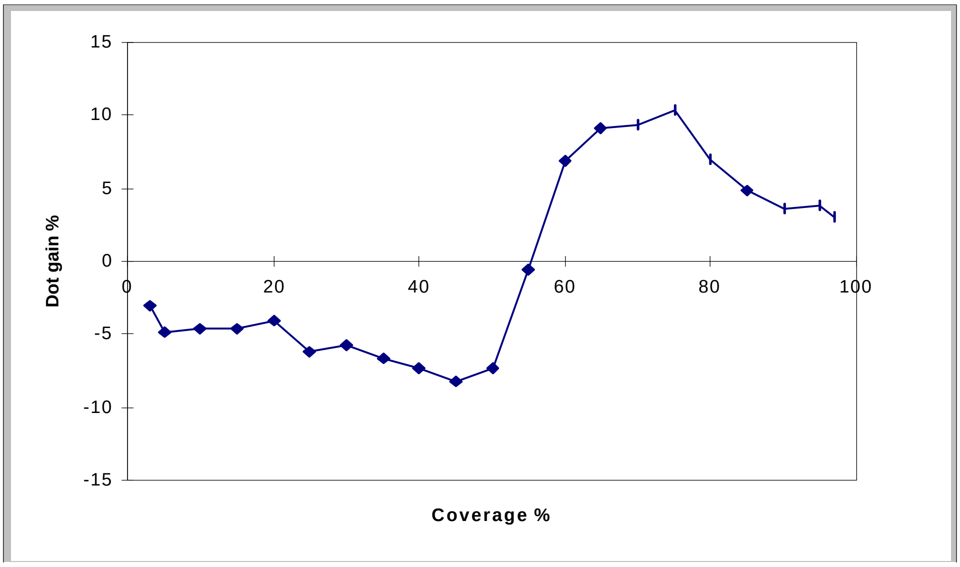
of the squeegee will directly control the mesh - squeegee interface angle.

The flow of the ink through the mesh is dependent on the mesh structure, ink viscosity and ink shear rate, the ink is normally highly non - Newtonian. For highlight areas the ink viscosity should be low to allow the ink to flow through the narrow openings in the stencil. In the shadow however the ink viscosity should be high to prevent the ink from spreading into the open regions around the dot.

3. The choice of quality characteristics and experimental implementation.

A crucial part of any experimental programme is the choice of the measurable quantity which will be used to analyze the results. Traditionally, the determination of print quality has been viewed from a subjective viewpoint with printers applying a good, adequate and bad description for the quality. For the close control of colour and ink deposit, a more scientific approach must be used with tonal reproduction as measurable quality characteristic.

Most multi colour prints produce a wide colour spectrum by printing only 4 colours (Cyan, Magenta, Yellow & Black, CMYK). They achieve this by a process called halftoning where each colour is printed as a discrete set of variable size fine dots, which when observed from a distance may give the impression of many hues. The size and density of each individual dot dictates its contribution to the observed colour. If there is a small deviation in the dot size and density then this may be confounded for each colour and produce a substantial change in the observed colour. A tonal reproduction curve is a way of measuring this deviation from ideal behaviour by comparison of the printed average dot size to the ideal dot size across a range of dot



sizes. An example of a tonal, or dot, reproduction curve is shown in *figure 3*.

Areas of high coverage refer to the shadow regions where a greater proportion of the substrate is covered by ink while low coverage areas are those in the highlight. While it may be favourable to produce a tonal reproduction which gives a zero dot gain across the tonal range, it is a consistent dot reproduction curve which is crucial since the recent use of computers to generate the film positive has allowed allow the film production to compensate for any dot reproduction characteristics. The aim of the this study was to investigate the effect of the chosen printing parameters on the tonal reproduction characteristics.

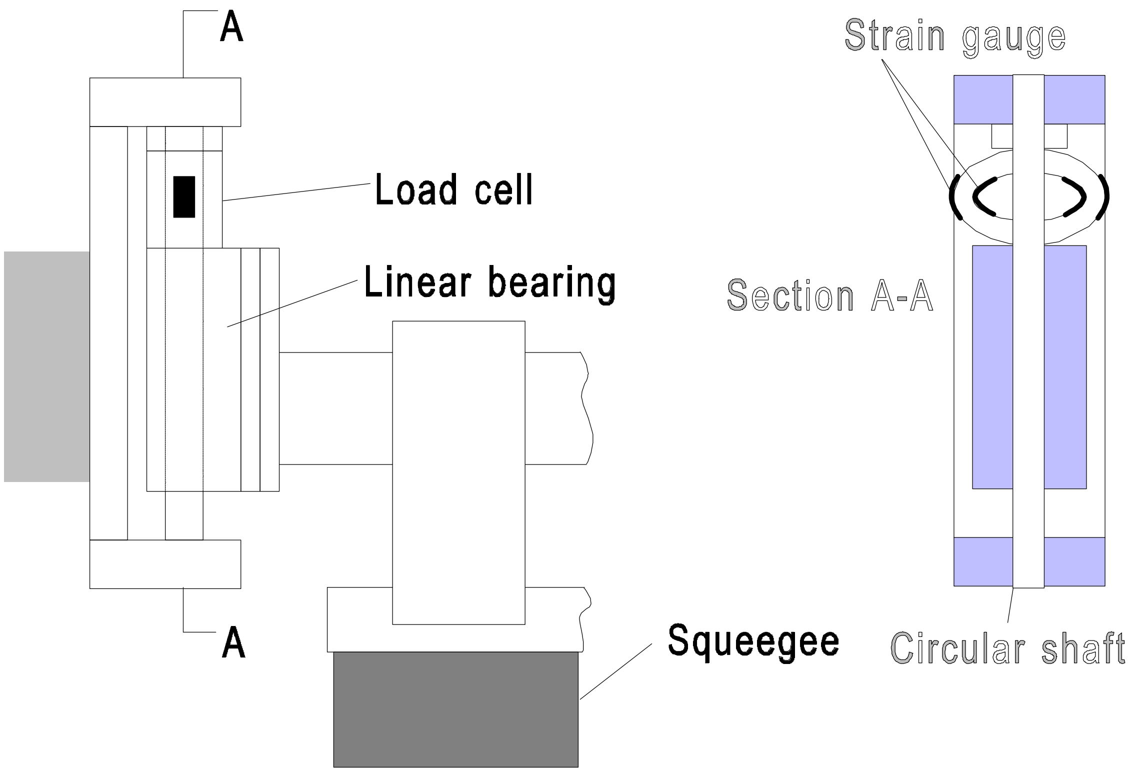
The test image printed is shown schematically in *figure 4*, while a local detailled view is shown in *figure 5*. This image was chosen since it facilitates the measurement of all the quality parameters. Tonal reproduction may be measured using the gradation scales situated unsymmetrically around the image. The gradation scales contain 5% steps in the coverage form 5% to 95%, together with 3% and 97 %, and for elliptical and square dot shapes at dot rulings of 65, 100 and 150 dots per inch.

A full factorial experiment of the process variables is uneconomical and as such orthogonal array analysis was employed as an experimental method to analyze the results. An L_{18} orthogonal array was decided upon since the relationship between the parameters and the measured quality is unknown requiring a three level experiment to be carried out. The L_{18} array also allows an interaction to be studied in columns 1 and 2, all other interactions are confounded across the other columns, and allows the effect of 8 process variables to be studied. The L18 was designed so as to minimise the number of time consuming changes that must be carried out during the experimental programme, *table 1*, and deals with process variables over which the printer has control, such as initial frame tension, choice of squeegee, ink, mesh and the press speed.

The most time consuming and costly aspect of the varying the parameters chosen, is the stretching of the mesh and the exposure of the image on the stencil. In order to limit this expense to 6 meshes, the mesh tension was inserted in column 1 at two levels of 17 and 21 N cm^{-1} with three levels of mesh ruling of 90 T, 120 T and 150 T threads per cm (where the T represents a thin mesh diameter), with the appropriate stencils of 15, 20 and 25 micron width respectively. This combination of mesh and stencils was chosen by experience gained through ISO colour standard research.

Initially it was hoped that the squeegee parameters of angle, downward force and edge hardness could be investigated separately. To ensure that the interactions between the squeegee parameters of angle, downward force and hardness were eliminated adaptions were made to the squeegee. The new squeegee was supplemented by a stiff steel back so that its deflection would be insignificant allowing the mesh - squeegee interface angle to be measured directly as the squeegee angle. Initial trials found that the squeegee down force and squeegee edge hardness interacted so strongly that some combinations could not print at all. Subsequently, a new parameter was designed which maintained the squeegee down force to hardness ratio at a constant value, i.e If x newtons were applied to a squeegee of y hardness then 2x newtons would be applied to a squeegee of 2y hardness.

Conventionally, the setting of the squeegee load by the printer is done by "feel". Threaded screws on the squeegee are tightened until a satisfactory print is obtained. This is often adjusted during the initial stages of the print run and as such a variation in quality, and increased product waste, is often encountered. To enable a pressure to be set as a control level in the array, the squeegee arm was mounted on linear bearings beneath load cells, *figure 6*. The imbalance voltage of the load cell gives a direct measure of the load applied at the squeegee tip. The 3 load levels were defined as the static, dry load in the centre of the mesh. Since the squeegee has been designed to remove the interactions between the downforce - hardness parameter, they may be placed anywhere in the array. The squeegee down force was set using load cells mounted at either end of the squeegee arm which allowed fine control and measurement of the squeegee down



force.

Experience has shown that ink characteristics can have a substantial effect on the image quality. Currently the majority of the ink used is solvent based (cyclohexane) but impending legislation will force printers to turn to waster based inks. To establish what difference the ink has on the reproduction characteristics, a traditional solvent based, water based air dried and water based u.v cured inks were inserted in column 7. Column 8 also contains an ink characteristic, in line (optimised for printing solids and fine lines) or chromatic (optimised for halftone printing). For the ink colour used, black, the rheological characteristics of the inks are similar. Inclusion of this parameter as two levels in column 8 allowed the validity of the experimental design to be assessed as their respective tonal reproduction should be comparable.

The most time consuming aspect of the experiment trials was the press set up and analysis, therefore two parameters were included as a full factorial in the experiment but then inserted in the L_{18} array to be analyzed, speed in column 2 and paper type in column 5. The inclusion of these parameters into the trials allowed some full factorial validation trials to be completed but only increased the experiment time by around 10%. A list of the parameters that were set as standard to the experiments are shown in *table 2.*

To ensure that there was a minimal effect from the initial variation of the mesh tension one hundred copies were run from each mesh prior to testing. Each print run consisted of ten prints giving a print total of 180 prints for the orthogonal array analysis within a total of 1620 prints. During the course of the experiments a number of parameters which were beyond the scope of normal controlled operating conditions, but which may have an effect on the process were controlled. The ink used was from one production batch and its temperature, which has a considerable effect of the ink rheology, was controlled using a thermostatic water bath. The 100 copies printed prior to measurement ensured the squeegee maintained thermal equilibrium with the ink prior to printing.

5. Results.

The results of the analysis of the experiment, for one of the gradation scales, are shown in *figures 7 to 14* which proceed in the column order. It was found that 7 of the 8 parameters had an effect on the dot reproduction. An overall summary of the findings is given in *table 3.* The results are presented in terms of the process parameters. Generally similar results were obtained for all the gradation scales.

Higher mesh tensions decreased the amount of dot loss; It is believed that this phenomena is linked to the higher drag forces increasing the shearing of the ink, lowering its viscosity and therefore allowing it to pass through the mesh more easily. The dot gain characteristics of the gradation scales was not directly related to the printing speed which suggests that both time between successive printing strokes and shear rate of the ink are important factors. The 90 and 120 threads/cm mesh rulings gave similar results while the 150 mesh ruling produced greater dot loss throughout the mid tones. On 3 occasions the 150 mesh produced very poor quality prints which may over emphasise this parameter and have a contributory effect on the high values of highlight and mid tone throughout the analysis. Increasing the angle between the squeegee and the vertical reduced the dot loss, i.e less ink was laid as the squeegee neared the vertical. The satin and gloss papers produced similar results while higher dot gain in the shadow was experienced on the matt paper. The hardness - downward squeegee pressure showed that a higher down force on a harder squeegee produces the same dot gain characteristics. The three ink types used showed different characteristics while the choice of chromatic or line ink produces little difference in the dot gain characteristics, producing some validation of the experimental design.

6. Closure

The primary process parameters which have an effect on the final quality of the print have been derived from engineering observations and discussions with industrial partners. These have been broadly classed in to mesh, squeegee and ink parameters. An experimental programme has been designed using orthogonal array analysis which economically allowed the effect of mesh tension, ruling and structure, squeegee force, hardness and angle and ink base and type on the print quality. Overall, the experimental procedure has been successful yielding results which not only agreed with theoretical predictions but showed that close control of a number of parameters is needed to ensure consistent process quality.

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Table 1: L_{18} Orthogonal array used for analysis purposes.

Expt.	**Column**							
	Mesh tension (N)	**Speed copies / hour**	**Mesh ruling thread s/cm**	**Squeegee angle degrees**	**Paper**	**Squeegee hardness - pressure**	**Ink**	**Ink type**
1	17	1000	90	70	matt	60-65	solvent	chrom
2	17	1000	120	75	satin	75-80	water	chrom
3	17	1000	150	80	gloss	90-95	water (UV)	line
4	17	2000	90	70	satin	75-80	water (UV)	line
5	17	2000	120	75	gloss	90-95	solvent	chrom
6	17	2000	150	80	matt	60-65	water	chrom
7	17	2500	90	75	matt	90-95	water	line
8	17	2500	120	80	satin	60-65	water (UV)	chrom
9	17	2500	150	70	gloss	75-80	solvent	chrom
10	25	1000	90	80	gloss	75-80	water	chrom
11	25	1000	120	70	matt	90-95	water (UV)	chrom
12	25	1000	150	75	satin	60-65	solvent	line
13	25	2000	90	75	gloss	60-65	water (UV)	chrom
14	25	2000	120	80	matt	75-80	solvent	line
15	25	2000	150	70	satin	90-95	water	chrom
16	25	2500	90	80	satin	90-95	solvent	chrom
17	25	2500	120	70	gloss	60-65	water	line
18	25	2500	150	75	matt	75-80	water (UV)	chrom

Table 2: Standard conditions.

Parameter	Value
Mesh / stencil types	Coloured polyester 90T XR 15, 120 T XR20, 150T XR15
Press type	Sakurai, Automatic Cylinder.
Dot shape	Elliptical, round and square.
Snap off gap	3 mm.
Mesh angle	90^{o}

Table 3 : Summary of overall effect of the parameters on dot gain.

Parameter	**Overall effect on dot gain.**
Mesh Tension	Higher mesh tension gives less dot loss.
Speed	Inconclusive results, an interaction between shear rate and rest time may be occurring.
Mesh ruling	90 and 120 meshes produced similar results, 150 mesh increased dot loss.
Squeegee angle	Angles closer to the vertical produce more dot loss.
Paper type	Matt gives more dot gain in the shadow when compared to satin and gloss.
Squeegee hardness - pressure	A soft squeegee at a low pressure produces the same dot gain characteristics as a hard squeegee at a high pressure.
Ink base	Ink base has an effect.
Ink type	Chromatic and line ink produce like results.