IMPACT OF INK/PAPER INTERACTIONS ON PRINTABILITY OF AQUEOUS PUBLICATION GRAVURE INKS

Part IV. Ink Transfer and Spreading on Paper

R. Sprycha and R. Krishnan

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ABSTRACT

Spreading of two inks of different surface tension on LWC paper was evaluated by a dynamic contact angle technique. Effect of paper roughness on ink spreading and the relevance of "free" spreading to the real "on press" situation were briefly discussed. It was found that no "free" spreading of the ink should take place on the press even at maximum ink transfer. Additional "free" spreading of the ink due to ink sagging when the web travels from the nip to the dryer is possible only in the direction opposite to the direction of printing. Based on the analysis of dot gain a mechanistic picture of ink transfer was proposed. Both, capillary flow of the ink in the grooves, formed between the paper and land area of the printing cylinder, and mechanical squeezing of the ink between the printing cylinder and impression roller are responsible for significant dot gain in gravure printing.

INTRODUCTION

Despite numerous studies being done to explain the mechanism of gravure ink transfer the mechanistic picture of the gravure printing process is still incomplete. In many cases the mechanisms proposed by different investigators contradict each other and most of the papers published deal with a determination of the amount of ink transferred from the gravure cylinder onto paper using different analytical techniques. Among the methods used were: atomic absorption (George and Welch, 1978), X-ray fluorescence (Birkett and Woodland, 1973), colorimetry (Joyce and Fuchs, 1966) and gravimetry (Pritchard and Finkle, 1964). Though the data presented in these papers is

Sun Chemical Corporation, 631 Central Avenue,
Carlstadt. New Jersey 07072

important in the understanding of the gravure printing process they do not offer a mechanistic description of the ink transfer. Among the papers dealing with the mechanistic picture of ink transfer (Kunz, 1975; Birkett and El Sayad, 1973; Bery, 1985) the papers by Bery (Bery, 1985) and Kunz (Kunz, 1975) offer the most complete description of this process.

The gravure printing process is a set of complex interdependent physico-chemical processes that take place under extremely dynamic conditions (e.g. dwelling time can be as low as ~ 1 millisecond). Because of this dynamic character the studies of the gravure printing process are very difficult and the processes which start from the moment of ink doctoring up to the moment when the ink enters the drying zone have a very important impact on print quality

The purpose of this paper was to study the mechanism of ink transfer and spreading on the paper surface using dot gain analysis. Prints, of two inks of different surface tension on light weight coated (LWC) paper, were made using a "Genik" press and the microphotographs of the cylinder cells and the respective dots in different tonal areas were taken. From an analysis of ink distribution on the paper within single dots, a mechanism of ink transfer is proposed and the effect of different factors on ink transfer is evaluated. In addition, the applicability of laboratory experiments on ink spreading to the real "on press" situation is discussed.

EXPERIMENTAL

Determination of Contact Angles

Spreading of inks on a paper surface was characterized by dynamic contact angle measurements using a Fibro 1100 Dynamic Absorption Tester with LWC paper and two inks of different dynamic surface tension (DST) being evaluated by the above method.

Dynamic Surface Tension

The DST of the inks was measured using a Sensadyne 6000 instrument and measurements were performed at a gas flow rate of 5 bubbles per second.

Dot Gain Evaluation

Photomicrographs (200x) of the gravure dots (Genik prints) and the respective gravure cylinder cells were taken and the dot and cell sizes were measured. Two types of engraving were analyzed in this way - elongated and normal cells. All the prints were pulled under the same pressure and speed conditions without Electrostatic Assist (ESA).

RESULTS AND DISCUSSION

Measurement of the contact angle of a given ink on paper is a commonly used technique to characterize ink spreading. It is well known that spreading is affected by the surface tension of the liquid (Rosen, 1978) and substrate surface roughness (Huh and Mason, 1977; Oliver et.al., 1977). Interpretation of contact angle (θ) measurements on rough and heterogeneous surfaces is, however, very controversial. Generally, the random roughness of a surface promotes spreading when $\theta < 90°$ and inhibits spreading when $\theta > 90°$. In many cases surface roughness creates mechanical barriers for the spreading liquid with such barriers and edges being responsible for different values of macro and micro contact angles (Oliver et.al., 1977; Oliver and Mason, 1977). The effect of surface roughness on the contact angle is a rather complex issue and under certain conditions can be responsible for super-spreading (complete wetting) or super repellency (complete non-wetting) - (Onda et.al., 1996). Paper, especially uncoated paper, is a good example of a rough surface with a large number of edges and mechanical barriers.

Another factor having a strong effect on liquid spreading is surface tension. Generally, the lower the surface tension of the ink the lower its contact angle on the substrate i.e. better spreading. Printers and ink makers very often use the term "leveling" to describe ink spreading on the paper surface. This is incorrect because "spreading" and "leveling" are two totally different processes. Examples of spreading and leveling are illustrated in Fig. 1.

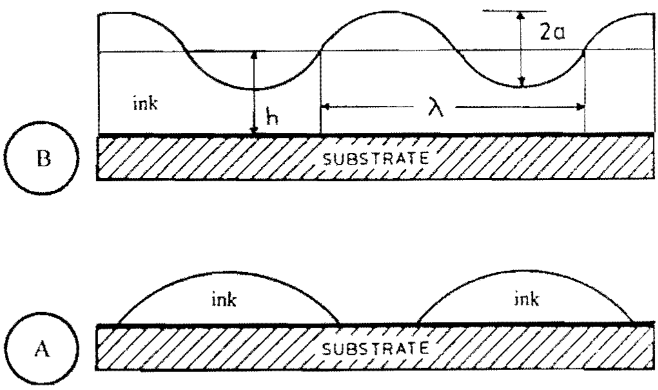

Fig. 1. Spreading (A) and leveling (B) of ink on paper

For spreading the indispensable condition is existence of tri-phase contact (e.g. paper-air-ink). "Leveling" refers to the process of elimination of surface irregularities of the liquid continuous phase under the influence of its surface tension. The process of spreading (Rosen, 1978) can be described by Equation [1]

$$S = \gamma_{sa} - (\gamma_{sl} + \gamma_{la}) \qquad [1]$$

where: S - spreading coefficient (if positive spreading can occur spontaneously)

γ_{sa} - solid/air interfacial tension

γ_{sl} - solid/liquid interfacial tension

γ_{la} - liquid/air interfacial tension

and the leveling process (Chan and Venkatraman, 1991) by Equation [2]:

$$l_s = \frac{16\,\pi^4 h^3 \gamma_{la} \ln (a_t/a_0)}{3\,\lambda^3\,\eta} \qquad [2]$$

where: l_s - leveling speed

h - averaged thickness of the film

a_t - final amplitude

a_o - initial amplitude

λ - wavelength

η - viscosity of a liquid

Equation [2] refers to a thin film of a liquid with an idealized sinusoidal surface. As seen from Eqs. [1] and [2] the surface tension of the liquid plays a very important role in both processes but its effect on spreading is opposite to its effect on leveling. For good spreading the surface tension of the ink should be as low as possible while for good leveling the surface tension should be as high as possible. In practice a compromise has to be reached regarding the value of γ_{la} to ensure optimum spreading and leveling. Two examples of spreading of water based ink of different surface tension on LWC paper are presented in Fig. 2. As expected a lower contact angle (better spreading) was observed for the ink of lower surface tension. The problem of "free" spreading in the real systems on the gravure press will be discussed later.

A quantitative description of gravure ink transfer is a very difficult task due to many factors involved and the complexity of the physico-chemical phenomena. Different approaches have been used by different investigators but to our knowledge nobody has offered the mechanism of ink transfer based on the analysis of the gravure dot gain. For the purpose of this work we analyzed the

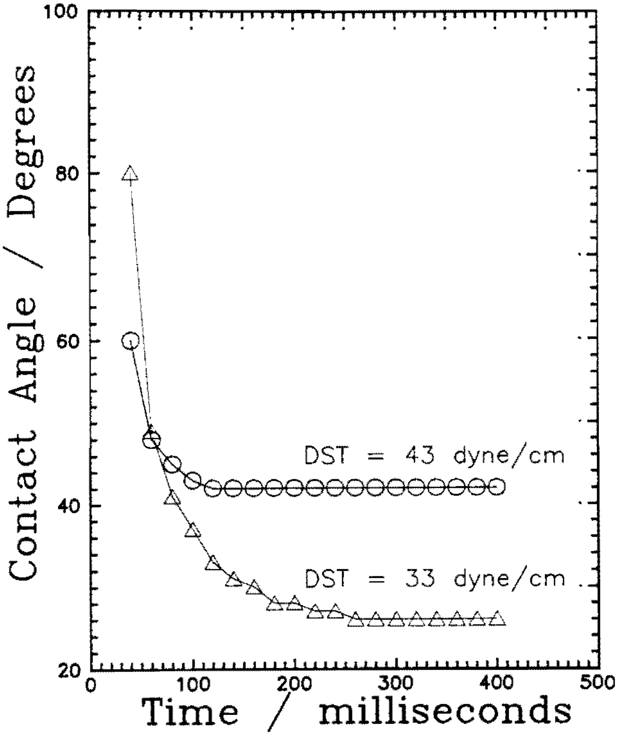

Fig. 2. Contact angle vs. time; LWC paper; two inks of different DST.

dot gain for two types of gravure cells - normal and elongated - engraved with a 130 diamond stylus. The description of the process of ink transfer and spreading on paper will start from the exact moment of ink doctoring by the doctor blade.

It was shown before (Kunz, 1975) that during wiping a small amount of ink is pulled out of the cell by the doctor blade. The amount of "pulled ink" depends on the wetting properties of the wiping material, rheological properties of the ink and press speed. This process results in excessive ink accumulation in the segment of the cell contacted last by the doctor blade - see Fig. 3. In addition, a few other factors such as ink inertia, press speed, air turbulence and gravitational field will cause the ink to flow in the direction opposite to the direction of the gravure cylinder rotation. The contribution from gravity decreases, gradually, as the cell approaches the nip. In the nip this contribution is equal to zero because the cell is now in a horizontal position. At some point between the doctor blade and the nip the shape of the ink meniscus in the cell is determined by the balance between all of the forces mentioned above. Shape of the cells e.g. conventional gravure vs. mechanical engraving will also affect the ink meniscus in the cell. Surface tension of the ink will counteract such surface deformation and try to make the meniscus more uniform.

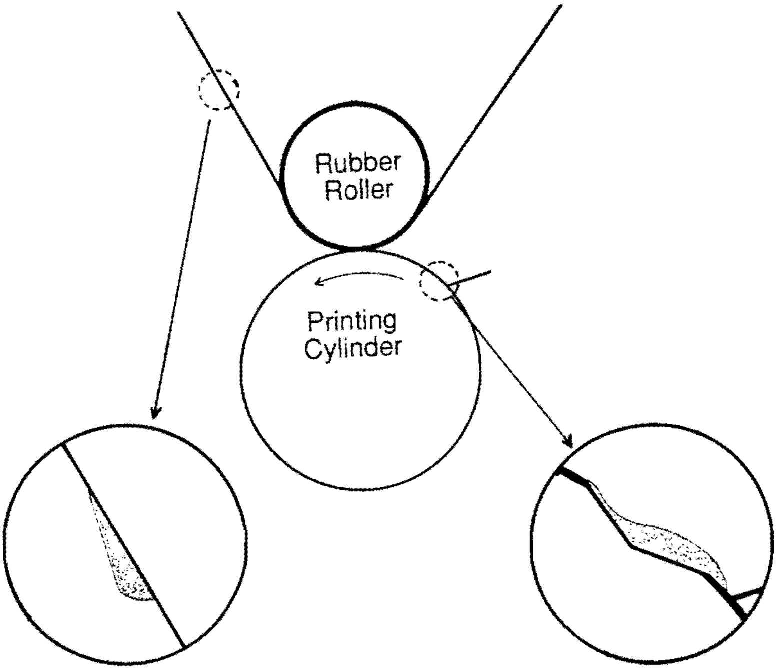

Fig. 3. Gravure printing unit

When the cell filled with the ink enters the nip zone ink transfer begins at the first instant of physical contact between ink and paper. The process of transfer is very fast and for high speed presses (e.g. 2500 fpm) it lasts only about 2-3 milliseconds. After transfer the ink deposited on paper travels "up-side down", on the almost vertically positioned web, towards the dryer. Assuming the distance between the nip and a dryer to be about 3 feet long the time needed for the web to travel this distance is about 70 milliseconds. Only during such a short time period can additional ink spreading and ink/paper interactions take place. To avoid the negative effect of water on paper properties like surface roughening due to paper fiber swelling this time should be as short as possible.

In other words water based inks should print better on high speed presses. This may, however, require changes in the configuration of dryers to dry the ink adequately.

The spreading of the ink can take place only when the contact angle value for a given ink is higher than its advancing contact angle. As results from Fig. 2 show those values are 42 and 26 degrees for the inks with DST 43 and 33 dyne/cm, respectively. Assuming maximum ink transfer to be 50% (Jeske, 1990), and taking into account cell shape and diamond stylus angle of 130°, it was found that "free" spreading of the ink deposited on paper is very unlikely in any direction for the ink with a DST = 33 dyne/cm and impossible for the ink with a DST = 43 dyne/cm. In this analysis we assumed also that the cell touches the paper with its whole perimeter simultaneously and all of the ink is inside the cell. Some degree of "free" spreading can be expected for compressed cells and for diamond stylus angles lower than 130° . On the real press some deviations from the above calculations are possible due to nonuniformity of ink distribution in the cell and gradual transfer of the ink from the cell. Possible sagging of the ink deposited on paper in the areas of large enough cells can also occur - see Fig. 3. If sagging of the ink takes place then the local value of contact angle can exceed the value of advancing contact angle of the ink on the given substrate and ink can spread in the direction opposite to the direction of printing. All the factors involved in the ink transfer process should also affect the quality of the print - shape of the dot and ink distribution within the single dot.

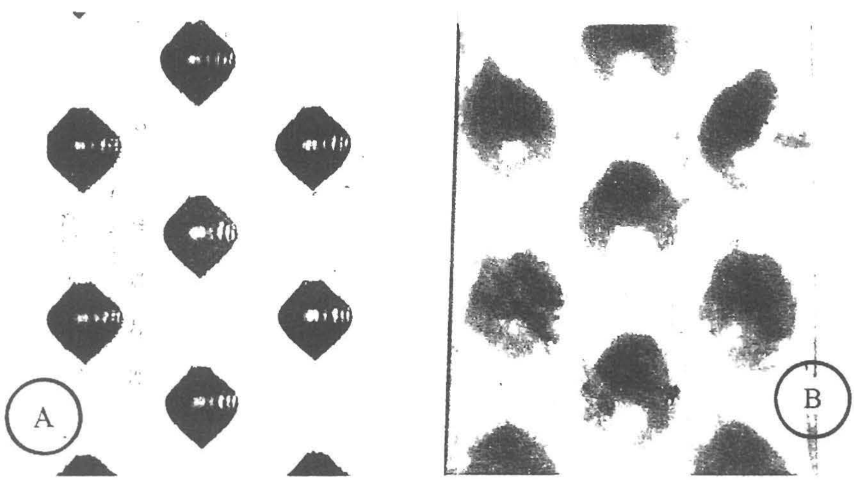

Fig. 4. Microphotographs of gravure cells (A) and dots(B); normal cells.

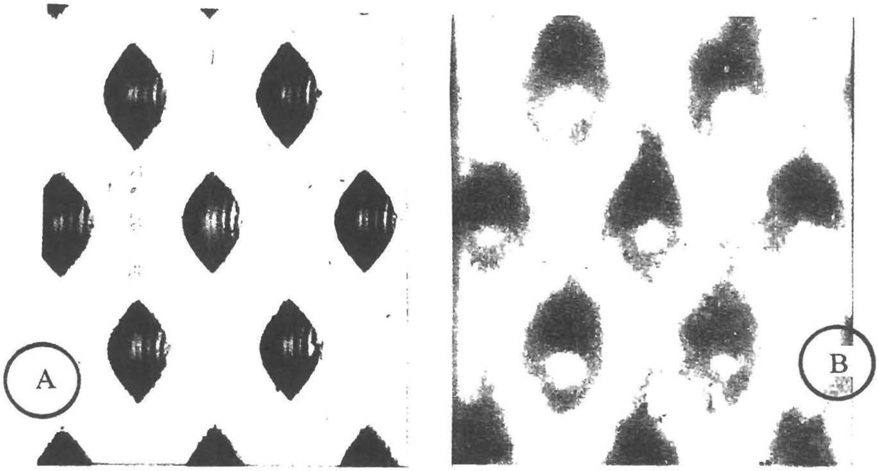

Fig. 5. Microphotographs of gravure cells (A) and dots (B); elongated cells.

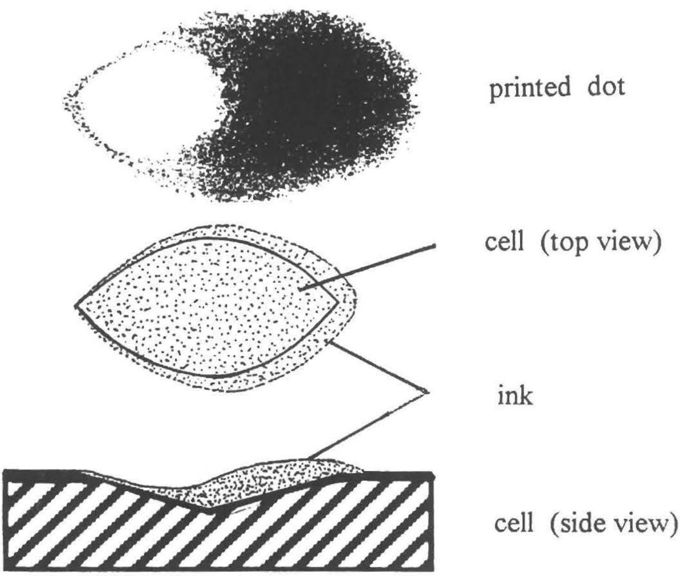

Fig. 6. Real gravure dot (microphotograph) and postulated distribution of ink in the cell.

The microphotographs of the example gravure cells and the respective dots are presented in Figs 4 and 5 for normal and elongated cells, respectively. All the dots were asymmetrical "doughnuts" of similar shape to the respective cells but the ink distribution within the single dot was very uneven. As observed from Fig. 3 the part of the cell with the ink depression (underfilled) prints first. This explains why the dots have a "doughnut" shape with only a small amount of ink transferred to the paper around the hole. Most of the ink is transferred to the paper when the convex meniscus touches the paper surface. The part of the cell printing last is overfilled with ink. Part of the ink will then be squeezed and rolled out between the paper and land area of the printing cylinder with maximum color strength being observed in the area where an ink filament was formed (Kunz, 1975). A comparison between the ink distribution within the real dot and the postulated ink distribution in the cell is presented in Fig. 6.

As shown in Figs 4 and 5 the dots are considerably bigger than the respective gravure cells. A comparison of the contours of the cells and the dots between elongated and normal engravings is presented in Fig. 7. It can be seen that the gain in "a" size is smaller than in "b" size and this results from two different mechanisms of dot gain in "a" and "b" directions. Dot gain in "a" direction is due to both ink spreading in the grooves formed between the printing cylinder land area and the web and mechanical squeezing of the ink on the land areas between printing cylinder and impression roller in the nip.

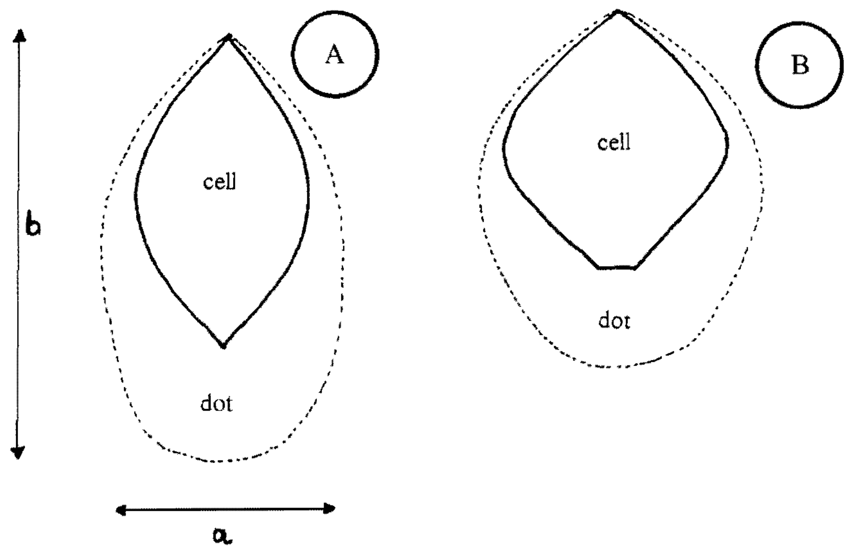

Fig. 7. Contours of the gravure cell and respective dot; (A) - elongated cell; (B) - normal cell.

Spreading in the grooves takes place on both sides of the nip and is illustrated schematically in Fig. 8. The process depends on the groove shape, surface tension of the liquid and its viscosity. The details can be found elsewhere (Rye et. al., 1996).

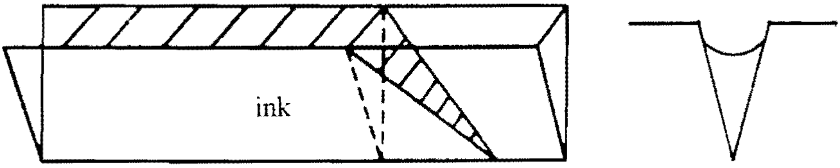

Fig. 8. Schematic representation of ink spreading in a groove.

Based on the dot gain in "a" direction it is possible to evaluate the lateral (in "a" direction) ink spreading for a given press speed. It was found that the spreading of both inks (43 and 33 dyne/cm) in "a" direction is roughly about 5 µm/millisecond of dwelling time. Lateral ink spreading speed can be also estimated based on the dot gain in "a" direction at different press speeds. The dots printed in the same tonal area at different press speeds are presented in Fig. 9 with average dot sizes "a" and "b" presented in Table 1.

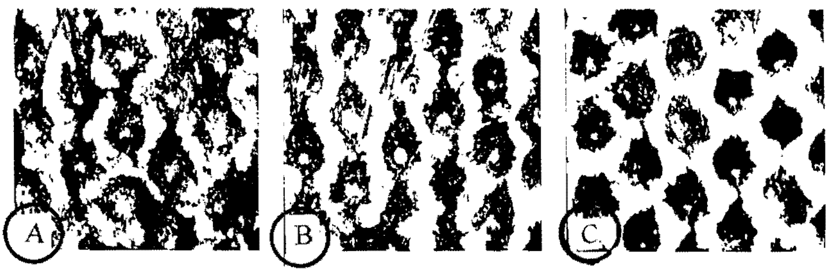

Fig. 9. Microphotograph of gravure dots printed at different press speed:
A - 10,000 imp/h; B - 23,000 imp/h; C - 30.000 imp/h.

As seen from Fig. 9 the higher the press speed the better the print quality (less lateral spreading). Knowing the cylinder circumference and assuming that the dwelling zone is about 0.5 inch wide the dwelling time can be calculated for a given press speed.

Table 1 - Dot Size as a Function of Press Speed

Press Speed (m/s)	*Average Dot Size (μm)*	
	"a"	*"b"*
2.5	115	118
5.7	100	115
7.7	90	115

The dot gain in "a" direction as a function of dwelling time can then be determined. An accurate determination of the contributions of two processes responsible for dot gain in "a" direction is, however, very difficult. The distance of penetration in the grooves is a linear function of $\sqrt{t}$ and can be evaluated based on ink properties (γ_{la} and θ values) and groove shape (Rye et. al., 1996). The amount of ink that spreads on a land area and its distribution around the cell may vary depending on the press speed and ink surface tension. Therefore, it is very difficult to evaluate the contribution to the dot gain caused by the squeezing process.

Squeezing of ink between the printing cylinder and impression roller is the main mechanism responsible for the dot gain in "b" direction. The higher gain in "b" direction than in "a" proves that the ink meniscus deformation in the cell, as well as the amount of ink that could spread onto the land area of the cylinder (see Figs. 3 and 6), can be quite significant. It is expected that the amount of ink spreading onto a land area is higher for the ink of lower surface tension. This was, indeed, found using dot gain analysis - see Table 2. In addition, ink sagging may also contribute to the dot gain in "b" direction. Possibility of ink sagging was discussed previously (see also Fig. 3).

Ink spreading in the grooves and mechanical squeezing between the printing cylinder and impression roller can, on paper, create a very thin liquid ink film around the contour of the cell - see Fig. 7. Ink transferred from the inside of the cell to paper can easily spread over this area covered with liquid ink film because the contact angle of the ink on the wet ink film is zero. However, a very thin ink film will dry very fast and drying will inhibit further spreading. This type of spreading will not contribute to the dot gain because ink will never flow beyond the contours of the dot created during ink transfer in the nip. This process can only affect the ink distribution within the single dot.

Table 2 - Dot Gain in Different Tonal Areas

for Two Inks of Different DST

Tonal Area	*Dot Gain in "a" Direction (μm)*		*Dot Gain in "b" Direction (μm)*	
	DST=43 dyne/cm	**DST=33 dyne/cm**	**DST=43 dyne/cm**	**DST=33 dyne/cm**
1	18.8	20.3	15.0	27.9
2	19.8	18.1	18.3	32.0
3	18.0	20.0	17.5	35.4
4	25.8	25.6	29.3	38.0
5	31.5	33.0	43.8	44.0

So far surface tension of the ink was the only force that counteracted ink meniscus deformation and forced ink flow from the cell in the direction opposite to the direction of printing. This picture is true only in the absence of the electrostatic assist (ESA). When ESA is "on" the ink in the cell experiences significant dielectrophoretic force in the close vicinity of the nip. This attractive force is the result of a polarization effect in the non-uniform electric field.

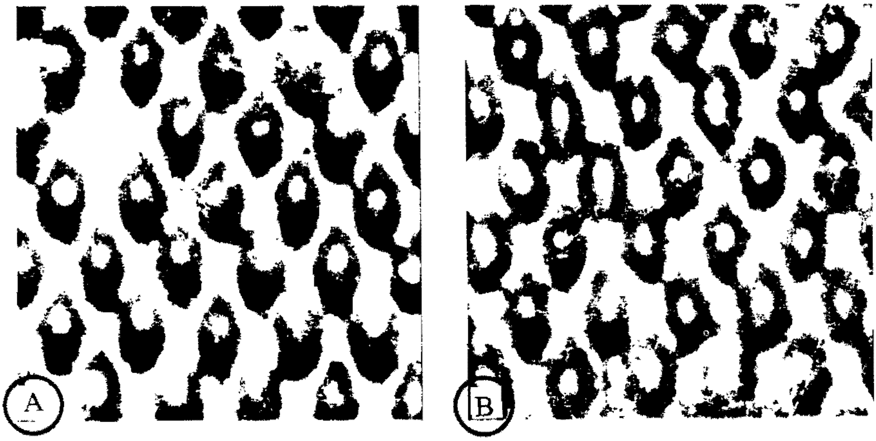

Fig. 10. Effect of ESA on ink distribution within the single dots; A - ESA "off"; B-ESA"on".

The force acting on the object in such a field depends on the volume of the object, its polarizability, local electric field and field gradient (Moore, 1982). Because of the liquid nature of the ink the dielectrophoretic force will cause the ink to flow towards the nip which should have a positive effect on the uniformity of ink distribution within the dot. The positive effect of ESA on the reduction of missing dots is well known and is due to enhanced meniscus deformation of the ink at the edges of the cell. Such deformation makes the physical contact between ink and paper more probable even on rough substrates. The effect of ESA on the ink distribution within the dots is presented in Fig. 10. As seen the dots with ESA on are much more uniform "doughnuts" than those printed with ESA "off". Electrostatic assist affects the printability of inks in a very complex way. This effect depends on the ink and paper properties as well as press speed and voltage(current) applied (Birkett and El Sayad, 1973).

CONCLUSIONS

1. Presence of sharp edges and mechanical barriers on the paper surface has a negative effect on ink spreading.

2. Calculations showed that for typical engraving used for water based inks no "free" spreading of ink transferred to the paper surface will occur except for the possible local spreading due to ink sagging, which may occur between the nip and the dryer.

3. Forced spreading of the ink on the paper surface is due to capillary flow in the grooves which are formed between the land area of the cylinder and the paper in the nip. Mechanical squeezing of the ink between printing and impression rollers contributes also to this spreading.

4. Because of the concave-convex deformation of the ink meniscus in the cell dots have the shape of un-symmetrical "doughnuts".

5. Electrostatic assist reduces not only the amount of skipped dots but also improves the uniformity of ink distribution within the dot, making it more symmetrical.

6. Speed of printing has a very significant effect on print quality. The higher the speed the better quality - less dot gain and paper distortion.

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