Preferred citation: J.F. Oliver. New insights into structural properties of paper used in new marking technologies. In **The role of fundamental research in paper-making**, *Trans. of the VIIth Fund. Res. Symp. Cambridge, 1981*, (Fundamental Research Committee, ed.), pp 851–859, FRC, Manchester, 2018. DOI: 10.15376/frc.1981.2.851.

NEW INSIGHTS INTO STRUCTURAL PROPERTIES OF PAPER USED IN NEW MARKING TECHNOLOGIES

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Introduction

The image quality, paper handling and archival specifications of non-impact printing technologies such as ink jet, electro-photography, thermography, etc. impose special requirements on the substrate. For economic and practical reasons, paper will continue to be the substrate predominantly used. This situation presents new opportunities for the paper industry at a time when traditional markets, such as newsprint, are being eroded by the proliferation of electronically-accessed data bases.

The most important feature of these new reprographic technologies is their `electronic front end' character. This means that image-wise digital input creates the printed page in the same fashion as a blank sheet contacting a rotary press. The acceleration in reprographics is the result of disc storage and the micro-electronic revolution. Computer-driven, non-impact printing engines are creating business forms, special reports and government documents on demand. Disc storage and computer-generated signals provide the input for demand printing which allows avoidance of printing over-runs and inventory space.

Each type of electronic printing imposes its own special demands on the paper. Consequently, there is a need for special paper structures to give optimum performance in any given reprographic technology. For example, ink jet uses aqueous based ink while the dry or liquid toner of electro-photography is hydrocarbon based. The latter poses special fixing challenges while the former poses wetting challenges. Direct thermal printing requires a coated sheet containing reactive pods and the state-of-the-art is only just acceptable from a resolution point of view. On the other hand, transfer thermal printing has both archival and image quality but requires a donor sheet or transfer step from a master.

Not all grades of paper are suitable for these reprographic processes. Furthermore, the lack of basic understanding of the ink/paper interaction in relation to image quality has been a serious handicap for the paper-making and reprographic equipment manufacturer. To meet this new challenge, various dynamic and static experiments are performed which allow image evaluation. In this note, a dynamic sorption apparatus to study spreading and penetration of an aqueous ink is described. Some qualitative findings on ink/paper interactions related to ink-jet printing will be presented.

Dynamic Sorption Experiments

Spreading and penetration experiments of ink-jet drops were conducted in a dynamic sorption apparatus which is shown schematically in Figure 1 and described in more detail elsewhere(1).

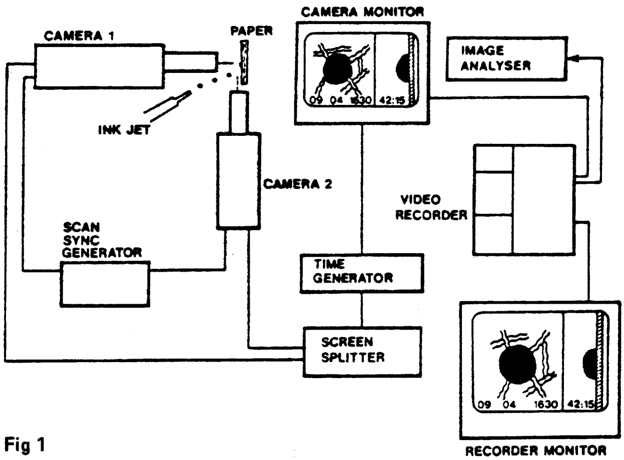

Fig 1

The apparatus is capable of observing localised wetting phenomena at microscopic resolutions in situ. Its essential features include: a video/optical system which enables simultaneous top and side-view observations of sorption phenomena: automated data acquisition via a video recorder interfaced with an image analyser: and in this case, an ink-jet printer which ejects reproducibly-sized drops ranging from 250 to 400 μm in diameter.

Two aqueous dye-based ink jet inks of low and high surface tension (γ) were studied on a wide range of commercial uncoated and coated printing papers.

Frame by frame analysis of video recordings of the drop contact line and profile history were used to measure or calculate several parameters. Of importance in this discussion are: drying time (t_d), the time elapsed between the first video frame, $t_o \sim 0.03$ sec., and the disappearance of the drop beneath the surface: drop diameter (D): average contact line velocity (v): and the initial contact angle (θ_o) measured on the first video frame.

Drop Profile and Contact Line development

The detailed experimental account of drop profile and contact line development revealed the complexity of the surface and porous structure of uncoated and coated commercial papers. Contact line spreading contours and corresponding drying times (t_d) for the various systems studied are shown in Figure 2 for uncoated papers. With the exception of K and P, the initial contours for samples A,H, J and V remained near-circular and smooth. This is presumably due to the much lower θ_o, and hence more rapid spreading prior to the initial period, for K and P. However from then on, with the exception of V which was relatively smooth and had a higher θ_o, the development tended to be similar for all these samples. For plain papers F and D_b, which showed the most prolonged drying, contact line development was negligible up to t_d. This behaviour is consistent with the

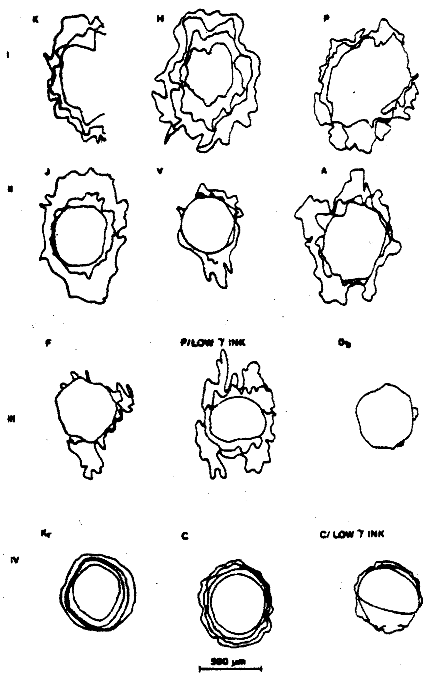

Fig 2

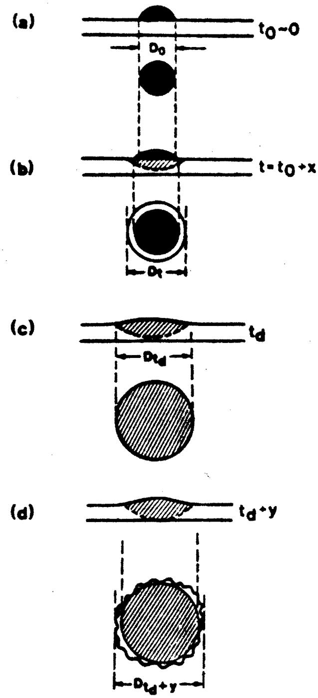

Fig 3

high θ_o value and the degree of sizing. Subsequent post-drying development (see Figure 3(d)), particularly with F, produced considerable deterioration in image quality. With the ink of lower surface tension, the sizing is no longer effective, as indicated by low values of θ_o and hence t_d. In fact without sizing and/or with a lower γ ink, image quality on plain paper is no better than on the aforementioned uncoated structures (compare F/low γ ink with any other uncoated paper in Figure 2).

In contrast, the coated structures K_r and C produced by far the highest quality images, i.e. approximately circular contact lines free of large-scale irregularities and show-through. Even with the lower γ ink, with a much lower t_d value, the image quality was more or less preserved for sample C.

Sorption Mechanism

Despite the complexity and wide variability among the systems studied, the consistent pattern of events outlined in Figure 3 seems applicable. Initially, significant lateral liquid drop spreading is in evidence for systems with very low t_d values (see Figure 2(i)). Lateral spreading quickly diminishes as bulk capillary forces take effect. This was verified, at least for coated paper, by drop radius data computed according to Cheever′s equation[1,2], a modification of the Lucas-Washburn equation to describe radial spreading through open slit capillaries. During this stage the drop surface skims over and substrate penetration is negligible. The corresponding extent of spreading, expressed as the percentage increase in D_o, was negligible for highly sized papers (D_d and F), but appreciable for more absorbent papers. The important initial spreading stage therefore plays a critical role in terms of two essential ink-paper properties:

(i) on impact, in association with drop kinetic energy, it governs the initial drop contact area, which in turn determines the ratio of liquid concentration to available pore volume. Thus for a system with slow pore filling, e.g. F/high γ ink, the surface wettability must be increased as, e.g. in F/low γ ink, in order to reduce t_d to an acceptable value.

(ii) in contrast to (i), greater wetting to spreading ratio increasingly exposes the inherent irregularity of the paper structure (i.e. wicking) at the expense of image quality.

From the view point of optimum image quality it thus appears that one or other of these critical properties must always be sacrificed. In addition the initial spreading stage also plays a critical role in terms of drop placement and image quality since it influences `fill-in´ or coalescence of adjacent (multiple) drops.

The relatively short initial spreading stage is followed by image development (Figure 3b), during which absorbed liquid undergoes subterranean spreading and/or re-emerges on the surface ahead of the drop. In addition, occasional local capillary channeling along individual fibres is evident on some papers. These localised sites serve to nucleate further irregular development in the image shape for a relatively long period after t_d, i.e. post-drying (Figure 3(d), so that the final image is considerably more ragged (see e.g. F.V. D_d in Figure 2). This complex behaviour is also evidenced by significant variations in optical density around the drop periphery. As noted in previous studies[3] the width of the band of absorbed liquid indicates the relative importance of these phenomena to image development.

In the subsequent second and, in a few systems, third stages (Figures 3b and c respectively), liquid spreading terminates and penetration predominates. On the basis of contact area and profile development data[2] none of these systems exhibits penetration rates consistent with the Lucas-Washburn capillary model; rather they show more prolonged spreading and complex behaviour. Among the principal factors contributing to this apparently increased porous resistance (or decreased liquid permeability) are the effects of: sharp fibre edges: pore tortuosity: build-up of air pressure particularly in `dead-end´ pores: break-down in liquid supply to spreading front: and fibre swelling which tends to diminish the average pore size. Increased penetration rates shown by several systems during post-drying, stem from subterranean absorption processes e.g. the interconnection of partially filled pores and localised surface fibre wicking. This final stage reflects a lag in the equilibration of bulk and surface capillary forces. In addition, shortly before the drop disappears, many paper samples become irreversibly swollen (see Figure 3c). With the high γ ink the amount of swelling is quite appreciable for uncoated papers.

Effects of the structure of paper

A further complication prevalent among all the papers studied is their structural anisotropy, both parallel and perpendicular to the plane of the paper. In contrast to coated papers, which maintained almost circular image development (see C and K_r, Fig. 2), contact line development on uncoated paper was invariably anisotropic and manifested to varying degrees the inherent structural directionality of these commercial papers.

On many samples the shape of successive drop images was distinctly different, indicating the sensitivity of individual ink jet drops to the structural variability of paper. Evidence for the latter was also revealed by differences between machine (MD) and cross-machine (CD) spreading velocities caused by fibre directionality, the spreading resistance of fibre edges, and fibre surface morphology(3).

Estimates of the transverse spreading velocity (v_t) of the penetrating liquid front during the incipient stages (see Figure 4) were several orders of magnitude less than for lateral (MD or CD) spreading. For a coated paper (Figure 4a) v_t was 50-

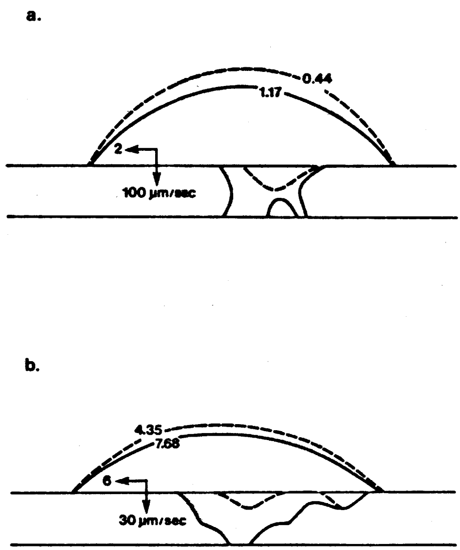

Fig 4

fold greater than v_{MD} whereas for an uncoated paper (Figure 3b) the difference was 5-fold. Differences between lateral and transverse spreading rates reflect variations in the effective pore size (r), and as noted by other workers[4,5], follow the trend $r_{MD} < r_{CD} << r_t$. Although the rate of penetration increases as pore size decreases, conversely, according to Poiseuille's equation, the resistance to flow is much higher for smaller pores. Thus the net effect is for lateral spreading to predominate. However, when the capillary resistance is lowered, as for example in the system C/lowγ ink (see Figure 2), v_t/v_{MD} is substantially lower and lateral vs. transverse spreading anistropy lessened.

One further important consideration in this context, revealed through high-speed cinematographic studies[6], is the effect of multiple drop impacts on single drop sorption dynamics. Clearly liquid permeability and drop concentration have a strong bearing on modifying the sorption dynamics but experimentally this remains to be quantified. As observed with other porous materials[7], depending upon the local moisture level some paper/ink systems may exhibit spontaneous wetting response on initial drop contact and substantial liquid resistance with further drop impacts.

Conclusions

These studies have revealed profound differences in the porous natures of uncoated and coated paper structures and in the relative capillary resistance to lateral and transverse spreading of inks with different surface tensions. Among the structures examined only coated papers produced acceptable images within requisite drying times. On plain papers either slow drying times, or the highly irregular and anisotropic images produced by high and low surface tension inks respectively, indicate the need for further studies to develop commercial paper structures which meet the stringent requirements of ink-jet printing.

Acknowledgement

The author is grateful to Dr. R.H. Marchessault for his encouragement and Xerox Corporation for granting permission to publish this article.

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Transcription of Discussion

Discussion following Dr.J.F.C.Oliver's Prepared Contribution

Dr. R. Brown, English Clays Lovering and Pochin Ltd., UK

Have you found any significant differences between the effects of neutral diketene sizing on the Xerographic process and those of the standard Bewoid acid sizing?

Dr. J.F.C. Oliver

I am not directly involved with work on the xerographic process, but I happen to know that IBM presented a paper last month at the ACS Colloid Symposium(1). They found significant effects on toner fuse-fix which relates to the type of sizing process.

Dr. R. Brown

Where the laser printing type apparatus is used, have you ever found any volatile condensation effects in continuous use?

Dr. J.F.C. Oliver

I'm sorry, I have no knowledge about this activity. The only laser application that I am aware of is optical character generation of images on the xerographic photoconductor drum in high-speed printing.

Dr. M.B. Lyne, Paprican, Canada

Your film indicates that you have the ability to measure the dynamic contact angle of the liquids on the surface of paper. Do you use this technique for dynamic interfacial tension studies?

Dr. J.F. C. Oliver

Presumably you mean the adhesion tension since the interfacial tension is a unique property in that there is no acceptable independent experimental method whereby it might be measured. Even for the adhesion tension (as defined by the Young-Dupré equation(2)) the system is much too complicated for that. Apart from problems arising from the roughness and porosity of paper, one would have to use a vehicle alone, since the ink is also a complex material and impurities may affect the surface tension.

Dr. M.B. Lyne

Have you done any studies on the differences between super-calendered and machine-calendered papers?

Dr. J.F.C. Oliver

I only included one calendered sample. I have not explored that variable as such.

Prof. K.I. Ebeling, Helsinki University of Technology, Finland

Have you used other liquids, such as water? If so what are the competing structure-swelling processes preventing further fluid absorption likely to be?

Dr. J.F.C. Oliver

The inks are in fact 85% water-based so we are inevitably observing swelling.

Prof. K.I. Ebeling

Can you comment on whether the absorption is due primarily to inter-fibre or intra-fibre absorption?

Dr. J.F.C. Oliver

Either could take priority depending on the paper grade. In very open structures such as newsprint grades it is an inter-fibre pore-filling phenomenon. For other grades it could well be inter-fibre phenomena which are important. However, since for most grades the total pore volume largely comprises inter-fibre voids, the role of intra-fibre voids may well be obscured in the absorption process.

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