Print line quality in the gravure process.

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Abstract
Rotogravure is commonly used printing process in flexible packaging and is well suited for the microelectronic production method due to its speed and recilience of the image carrier. This study examines the reproduction of the most basic electronic component, namely a line, in terms of its printed width and gap which can be obtained between the lines. The investigation was carried out using the black separation of a conventionally engraved cylinder on a automatic viscosity controlled commercial printing press printing nitro-cellulose resin based graphic inks to 80gsm one side highly coated paper. By studying the process with a reliable commercial graphic ink the process is being examined under current optimised best practice operation and thus its capabilities are not being limited by development materials. This paper examines the effect of press speed, viscosity and line orientation on the printed line thickness and on the printable gap between lines. The lines were capture by CCD based microscopy and analysed using custom software. Line quality was quantified by the average line width, line porosity, line edge definition and number of edge satellites. The viscosity and line orientation had a significant effect on the printed line width with lines printed in the direction of print being the highest quality and less sensitive to changes in viscosity. The minimum printable line whose consistency would potentially offer sufficient continuity through the line was between 100 and 150 μm, with reducing viscosity improving the rendition of finer lines. All lines were subject to edge variation as a result of the cylinder diamond engraving with higher viscosity lines producing satellite areas of ink which were independent of the main line body. The line width gain was found to vary with the specified line width with lines less than approximately 250 μm being smaller than that specified and those above approximately 250 μm increasing in width. The gap between adjacent regions of ink was found to be larger than that specified with reducing viscosity bringing the gap width closer to that specified. The results have implications for the understanding of the wiping action of the doctor blade and the subsequent transfer of ink to the substrate.

1. Introduction
Rotogravure is the premier printing process used for high quality graphics and packaging. Its primary advantages being speed, quality and robustness of the image carrier. As such it is a potential method for the micro manufacture of electronic materials, smart packaging and RFID. It offers significant improvements in terms of speed, resolution and productivity compared to screen printing and traditional electronic manufacturing.

The viscosity of the inks for the gravure process is generally low and may contain up to 80% solvent which therefore lends itself to thin ink films and the solvent laden solutions required by many organic semiconductors, [1]. This may not be ideal for particulate laden conducting inks, which may typically be 75% particulate by mass, [2] and subsequently may be of too high a viscosity.

The robust image carrier in rotogravure is a distinct advantage over other processes as it is not subject to phenomena such plate swelling (flexography), plate wear (offset litho) or screen wear and tension loss (screen). Although the engraved cylinders can be engraved accurately, the reproduction of the features on the printed substrate is a subject to wide variety of variables including press speed, substrate characteristics, ink viscosity and doctor blade settings, [3, 4, 5].

One of the principal factors which will determine is suitability for micro manufacture is the dimensional characteristics of printed features; the simplest of these being a line. Laboratory experiments on printability testers of conductive materials have found the process to be conducive to the printing of particulate conductive materials as well as conducting polymers, [6, 7, 8]. This investigation examines the potential of rotogravure for printing fine lines appropriate for the manufacture of printed electronics on a full scale commercial press. This was conducted using a graphic ink which enabled easier evaluation yet had similar rheological and drying properties to the organic semiconductor inks.

2. Method

A full factorial experiment was carried into the effect of viscosity (at three levels of 16s, 19s and 22s as measured by a Zahn 2 efflux cup) and production speed (at three levels of 1.67, 3 and 5 m/s). The investigation was carried out on an automatic viscosity controlled commercial printing press printing nitro-cellulose resin based graphic inks to 80gsm one side coated paper. The viscosity of the ink was set by addition of thinner and the press was allowed to stabilise for 5 minutes after each change of viscosity. The speeds and viscosities chosen lie within the normal operational limit of the process.

The cylinder used was electromechanically engraved with diamond and engraving pattern suitable for the black separation. Although lines are being printed, which do not require screening, the limitations of the mechanical nature of the engraving process mean that some degree of screening is always required. This also reduces high localised wear of the doctor blade or cylinder. The black separation was chosen as it has the highest detail rendition and also has the 45 degree screening pattern which does not give preference to lines printed in the horizontal of vertical direction.

The measurement was carried out optically using a high resolution monochrome CCD camera, stabilised Xenon light source and bespoke image processing software. This allowed 576 sample pixel scans to be taken along the length of each line. Being black lines on a white substrate the lines were easily segmented using a mid peak greyscale histogram method and analysed in custom written software.

The line quality was defined in terms of width, edge roughness (by standard deviation of the width) and percentage solid. This last characteristic is considered important as it is the microstructure of the line which is important and not simply the visual macroscopic reproduction of the line. Typically line reproduction in rotogravure is subject to internal voids within line where the ink fails to transfer or fails to flow out after printing. This leads to a internal and external failures of the lines, Figure 1.

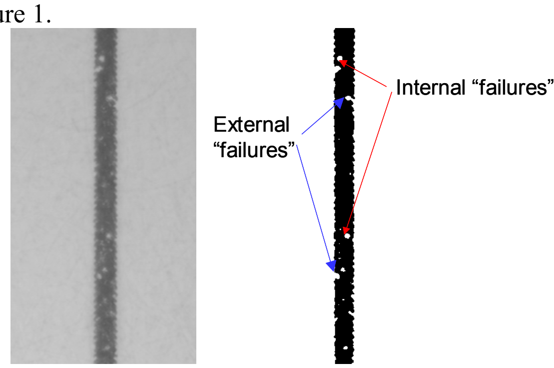

Figure 1: The lines as printed and segmented image highlighting the general failures in reproduction.

In addition, towards the edges of lines it is possible that the smaller more shallow engravings form “satellite” areas of ink which are not bound physically into the line structure at all. In this instance the ink has transferred to the substrate but has been unable to flow to form a coherent solid ink film. From a macroscopic viewpoint, these contribute to the width of line but have no contribution to make to the microscopic properties of the line, e.g. for conduction. The measurements of lines and voids could be

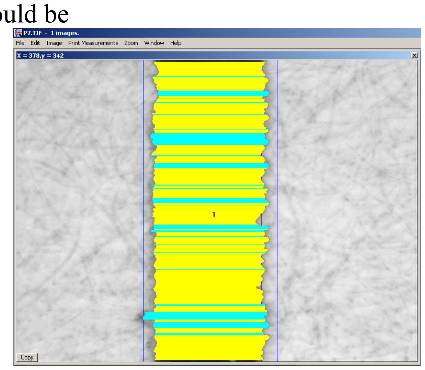

Figure 2: Segmentation and detection on voids & satellites in the lines

The integrity of the line was calculated by examining the proportion of unprinted area within the boundary of each line over the sample length and is expressed as %solid. The % solid for each line of pixels is defined between the boundaries of the line as :

$$\%solid = \frac{\text{Black pixels}}{\text{White pixels} + \text{black pixels}} \qquad (1)$$

An overall mean is obtained by taking the average for line of pixels in the image. Thus a value where 100% indicates a line with no inner voids (or failures). Lower values of %solid indicated increasing number of internal failures within the line structure.

The line quality characteristics were measured on four 300 micron lines at angles of 0^o,45^o, 90^o and 105^o to the print direction, Figure 3. For each angle the camera orientation to the line was altered such that the line was vertical within the frame. This ensured a consistent measurement length and that differences in the digitisation of the line played no part in differences between the print angles.

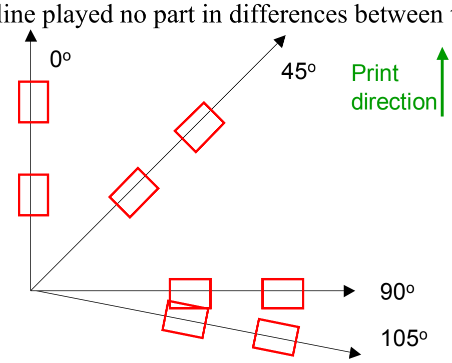

Figure 3 : The measurement areas investigated.

3. Results

Statistical analysis of the lines showed that there was little difference in the line quality of successive prints over the 32 samples measured. This is in line with other studies on rotogravure, [3], which reported that the process is inherently stable over short time periods. Measurement along each of the lines also showed minimal variation along the length of the lines. Thus although there may be significant difference in line width along the line, the variation is repeatable and periodic. Measurement of 5 samples was deemed sufficient to record all important features of the printed lines.

The edges of the lines for all samples showed significant variations along the length of the lines, with a regular variation which corresponded to the individual engraved cells. The printed thickness, edge characteristics and integrity of the lines were found to highly dependent on orientation to the print direction with lines parallel (0^o) to the print direction being the thickest and least sensitive to changes in viscosity and speed. Perpendicular (90^o)to the print direction the effect of speed and viscosity were significant with variations of up to 40 micron in line width, Figure 4. All lines were measured thinner that specified in the digital file. Reducing the viscosity of the ink increased the printed width of the lines as a result of the low viscosity ink "spreading" during printing or due to improved release of the ink from the cells. The effect of the speed on line width was small compared to the effect of the ink viscosity.

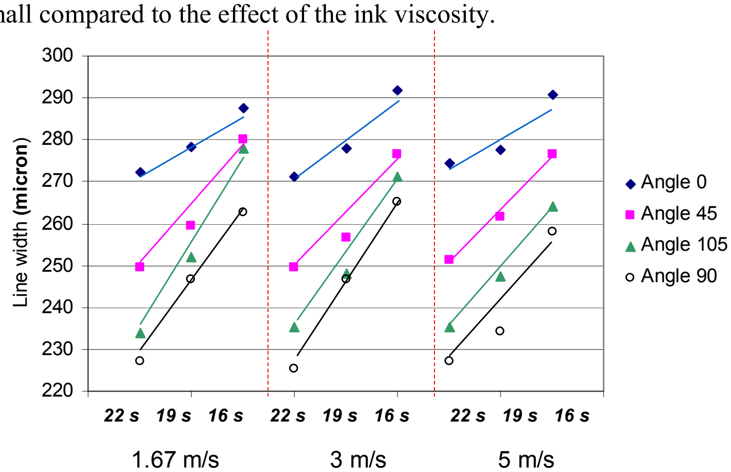

Figure 4 : The effect of viscosity and speed on the measured line width
At four angles of orientation relative to the print direction.

Lines printed in parallel to the print direction were significantly more uniform than those printed perpendicular to the print direction, typically having only a standard deviation of 1.5 micron over the experimental range compared to 2.5 micron for lines printed at an angle to the print direction, Figure 5. Increased speed resulted in a poorer quality line, particularly perpendicular to the print direction. Reduced viscosity improved the line edge quality at all speeds. This can be attributed to the ink spreading to fill the undulations at the edge of the lines.

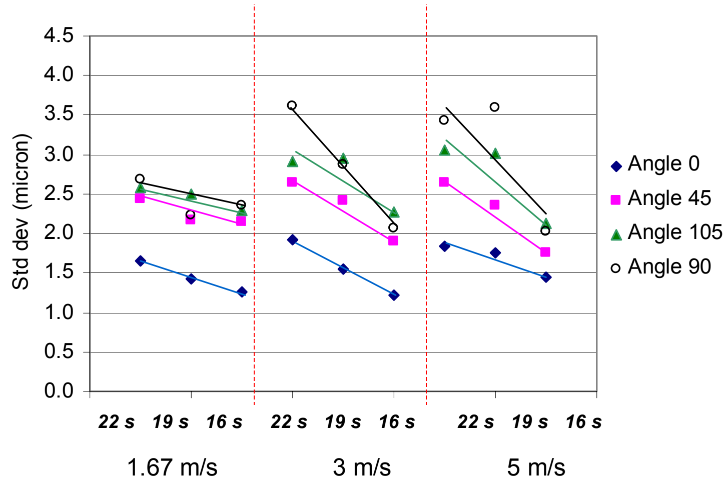

Figure 5 : The effect of viscosity and speed on the measured line edge roughness at four angles of orientation relative to the print direction.

The viscosity had a significant impact on the integrity of the printed lines with increasing viscosity increasing the number of voids present in the line, Figure 6. Increasing speed increased the number of voids present in the line, particularly perpendicular to the print direction. This can be attributed to the failure of individual cells to transfer resulting in visible omissions of cells within the line.

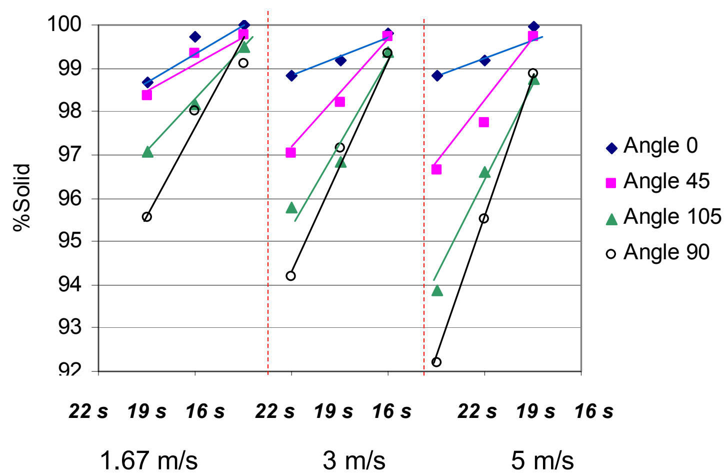

Figure 6 : The effect of viscosity and speed on the measured line integrity at four angles of orientation relative to the print direction.

Visual inspection of the lines printed clearly shows the characteristics displayed in previous figures. All lines showed regular patterning along their lengths due to the engraving stylus method used to manufacture the cylinders, Figure 7.

Parallel to the print direction there is no discernable difference between either side of the line. Significant variations in line edge quality were observed between the leading an trailing edge of lines printed perpendicular to the print direction. At the trailing edge, the ink from individual cells can be seen on the substrate, while the voids were more or less uniformly distributed through the line, Figure 7.

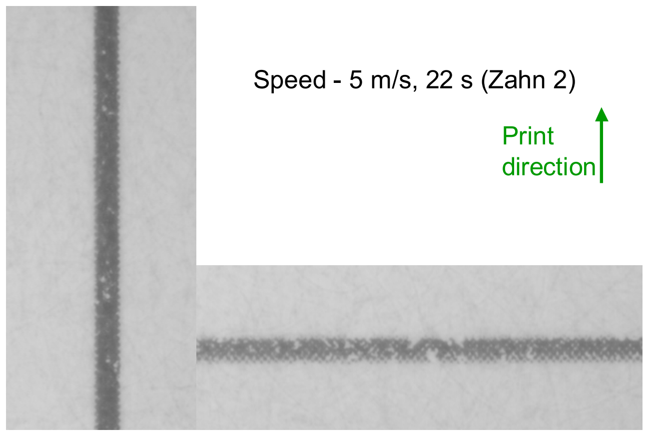

Figure 7: Microscope images of the printed lines showing the difference between lines printed in the orthogonal directions

An interaction existed between the press speed and viscosity. The width of the lines with the lower viscosity inks were the most sensitive to changes in press speed. The press speed affected the edge roughness of the lines to an equal degree for all ink viscosities. The number of voids present in the lines increased significantly as the press speed increased for the highest viscosity ink but remained constant for the low viscosity inks.

The effect of reducing the viscosity is to increase the positive line width gain, Figure 8, i.e. the lower viscosity inks are more prone to spreading. Similar trends were observed at the other two print speeds. Thinner lines tend to print thinner than that expected while wider lines to print wider than expected. For the middle ink viscosity, this switched from line loss to line gain occurs at approximately 400 μm.

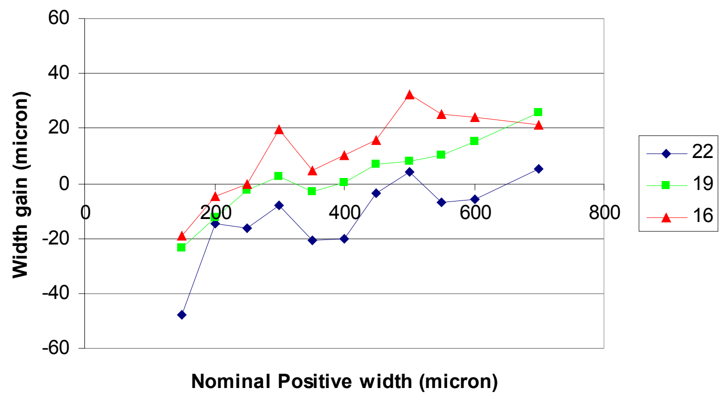

Figure 8 : The effect of viscosity on positive line width gain at 1.67 m/s

Reducing the ink viscosity causes a reduction in the positive printed line edge roughness, illustrating the flow out of the ink at the line edge, Figure 9. There is a marked trend where the edge roughness of the wider lines is higher than that observed with the thinner lines. This trend was observed at each viscosity and at each speed.

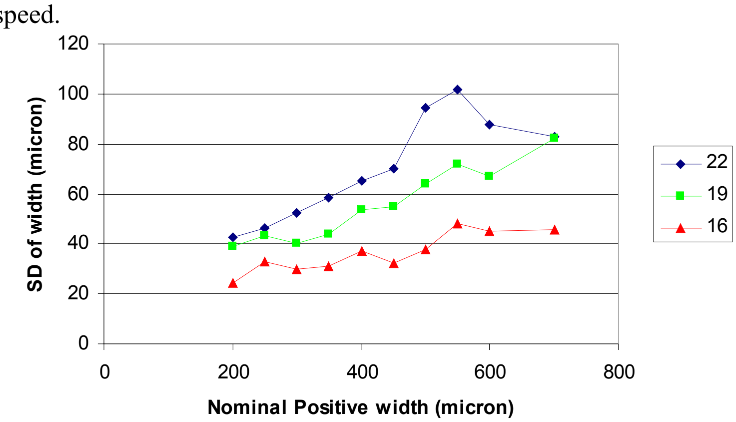

Figure 9 : The effect of viscosity on positive line width edge roughness at 3 m/s

All the gap widths were larger than that specified with reducing viscosity resulting in gaps which were closer to that specified, Figure 10. Similar results were obtained at all 3 printing speeds

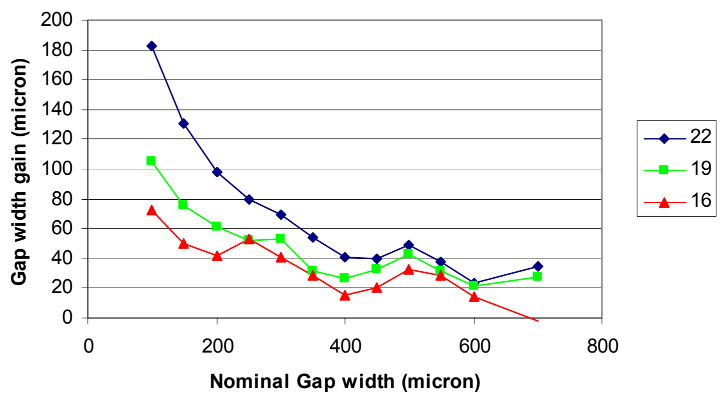

Figure 10 : The effect of viscosity on gap width gain at 1.67 m/s

4. Discussion

There is a significant difference between the perceived macroscopic line quality and the microscopic structure of the lines. Such differences are visually subtle but would have a significant impact on the functionality of the lines of electrically active material. The reduction in line quality seen at higher viscosities does bode well for inks with a high viscosity ink (as a result of high particulate loading) which may need to be used to provide the necessary good conductive properties.

The findings have implications for micro manufacture by gravure printing but are also applicable for graphic applications where fine lines must be printed, e.g. in the printing of bar coded labels. Although some of the intra line voids may be associated with the paper substrate used in the study, the smooth coated nature of the substrate would suggest that the voids produced are a function of the gravure ink transfer mechanism when higher viscosities inks are removed from the cylinder at high speed. The true reproduction of the cylinder engraving pattern seen at the edge of the lines on the print shows the high intrinsic reproduction quality of gravure but highlights that when true straight lines are required in micro fabrication by print, there may need to be alter the engraving method, e.g. laser engraving. Reducing the viscosity of the ink improves the edge quality of the line at the expense of line spreading. This may not be viable when lines are to be printed close together.

At first glance, Other printing technologies such as flexography may appear to overcome this limitation of good line definition but it is not without its own problems. One problems is line haloing which is usually seen around solid areas and can result in an ink profile with raised edges which are typically 25% higher than the film height in the bulk of the line, [9]. A further issue with flexography is the difficulty of printing narrow gaps as the impression pressure applied to the ink through the plate tends to cause significant line spread, [9]. Offset gravure may overcome some of the problems associated with direct gravure but problems with regard to ensuring the correct ink release from the offset roller and deformation of the offset roller are likely to become issues, [7,8].

In any electronic production system there is a need to reduce the line thickness and proximity of the lines (termed "track and gap" in the electronics industry) in order to reduce device size, improve performance and to place additional functionality in the device. A further area of study is required on the realistic track and gap obtainable with high speed rotogravure printing and the influence of printing parameters on this behaviour. The reduction in line height with reducing line thickness as a results of the reduction in engraving depth [7] will also have a determining role on functionality of the printed fine line as the cross sectional area of the ink reduces appreciably with finer lines

The investigation has used two dimension image capture techniques to investigate the lines. As the viscosity is controlled by the quantity of thinner (and hence percentage of solid content) an assessment of the lines should be carried out using a three dimensional measurement technique such as white light interferrometry in order to yield a true measure of the material transferred. This would be best measured on an impermeable substrate such as a polymer film as a reference substrate layer would be easier to establish, [5]. In addition any further studies should examine the effect of the semi porous nature of the lines on the electrical properties (conductivity, impedance etc).

5. Conclusions

An experimental investigation into the effect of ink viscosity, press speed and line orientation on line resolution in rotogravure printing has been carried out using a commercial printing press. Using image analysis, the main findings of the work are :

- The printed thickness, edge characteristics and integrity of the lines is highly dependent on orientation to the print direction. Lines parallel to the print direction are the thinnest and largely unaffected by speed and viscosity.
- The viscosity and speed has a significant effect on lines perpendicular to the print direction. Lines printed at high viscosity are most prone to voids within the boundary of the line.
- Of the two parameters, the viscosity has the most significant impact on the width and integrity of the printed lines.
- There is an interaction between the press speed and viscosity with the higher viscosity inks being the most sensitive to changes in press speed.

Further work should examine :

- The use of alternative engraving techniques which do not involve screening
- The use of flexography as a means of printing fine lines.
- The use of polymer film substrates and the electrically active inks
- Minimum track and gap potential of the gravure process.

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