Characterisation of Fine Lines

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Abstract

The printing of functional inks, such as for sensors, conductive tracks and semi-conductors, is generally a combination of solids and fine lines. Functional fine lines require a consistent cross sectional area as well as a consistent width and edge profile and an absence of breaks and voids to optimise their properties. This paper describes the development of quality characteristics and tolerances for functional inks. Fourier and statistical techniques were used to obtain quantifiable measurements of the line quality characteristic. These measurable line properties have been correlated with process parameters. Initially 2-D techniques based on image processing were developed for examining the line width, edge profile and breaks. The effect of thresholding was found to be significant effect on the quality of the measurements. To reduce these anomalies, white light interferometry was used to evaluate the line height and cross sectional area. The quality characteristics have been related to performance criteria for reactive inks.

Introduction

Screen printing is commonly used for the fabrication of functional components, such as medical bio sensors, printed circuits, automotive sensing units and visual displays. Screen printing's ability to deposit a controlled thick film of ink makes it an ideal method for mass manufacture of such devices. The complexity of the components now being manufactured is increasing with the number of layers within the components increasing and conductive track thickness and track spacing reducing.

In many instances the performance of the component being printed is reliant on the successful deposition on fine lines. Where the ink film is being used to conduct electricity, any variation in its width, height and cross sectional area will have an effect on its resistance and subsequently the product performance.

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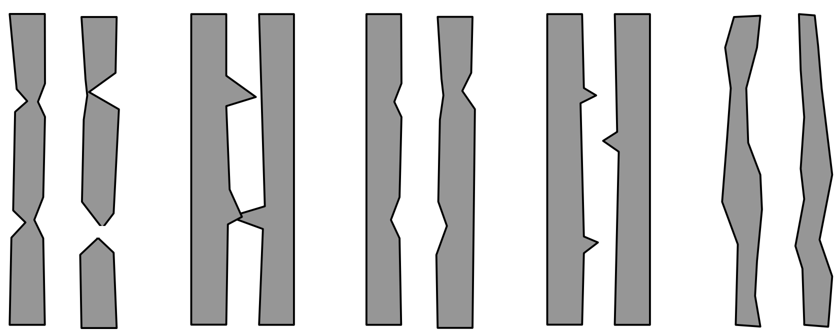
If the edge quality is such that two adjacent lines touch then a short circuit may result. If a dielectric is being used then changes in the geometry of any of the conductive / insulating layers will alter the component capacitance.

Measurement methods for halftone graphic reproduction already exist using densitometric techniques and analysis methods are in development for the optical measurement of halftone images (Lind & MacPhee, 2000, Malmquist et al, 1999). The aim of the work is to develop methods which can be used to provide a subjective measurement of fine lines.

Measurement of line quality

Previous studies on the role print parameters on screen and stencil printed products attempted to define the printed line quality. Webster (1975) used a 'defect criteria' to examine for good or bad lines. He made three points about the importance of any measurement system. The inspection should be done visually, since the small width of the conductors made manual electrical probing too time consuming. The defects must be described in quantitative terms, enabling the use of computer analysis. The measurement system should highlight the most significant problems encountered in fine line printing. This led to the definition of five defect criteria, which are described below and illustrated in Figure 1.



Opens: Voids in the line extending for more than 80% of the width

Shorts. Intrusions of conductor material extending more than 80% into the space between two lines.

Partial opens. Voids in the line extending between 40 and 80% of the width

Partial shorts. Intrusions of conductor material extending between 40 and 80% into the space between two lines.

Insufficient paste. Repetitive opens and partial opens along a length of a line.

Figure 1 : The line quality criteria developed by Webster (1975)

Rocak (1995) used a visual inspection system giving a mark out of three. The visual inspection was performed by the human eye. The thickness of the paste applied and the line width before and after firing in an infrared furnace was measured.

Pan et al (1995) examined fine line printing of a paste in screen printing. Measurement of the height of the lines was attempted, but this was unsuccessful due to the equipment capability. The paper focused on the space width, the distance between two adjoining lines, and a visual inspection for connections between two lines. The space width was found using a microscope. A mean and standard deviation were found from a total of 10 points measured at two places for each line width on each print.

Rodriguez and Baldwin (1999) examined the solder release mechanism in stencil printing. To do this a camera was used to film the action of printing and the quality of the final prints was examined. The characteristics of the print measured were average height, wetted surface area and cross sectional area of the solder deposit. This was done using a non contact laser metrology. The actual quality of the print was evaluated using the percentage volume of paste deposited on the substrate. This is calculated from the ratio of the printed volume to the aperture volume on the stencil. Thus the measured parameter examined ink transfer rather than the actual quality of the printed image.

Several techniques have been used to measure the quality of fine line reproduction. The basic measurement parameters are line width or height and variations of these, although some studies have examined other factors. It is important to produce a repeatable method for the evaluation of lines. A visual analysis and simple grading system, using the human eye, is unlikely to be repeatable, especially from person to person. Using a machine to measure lines improves repeatability, but results are likely to be dependent on the instrument used. It is, therefore, important to give information on the measurement method used and specifics of the instrumentation.

Most of the systems used have chosen to examine the quality of the printed image. Most have done this by examining the printed line width or space width. The five defect criteria described by Webster produce a good system for statistical process control. These parameters, or similar, should be considered in any measurement system. Rodriguez and Baldwin (1999) took a different approach, by examining the actual amount of ink printed compared with the hole size in the stencil. This examines the printing process rather than the finished product, although the two should be related. This is useful for scientific value to further understand the process. This is especially true when trying to develop a model of the process as Rodriguez was. There are, though, more standard ways to measure the quality of the printed image.

Analysis methods

Two measurement methods were used to assess the quality of the lines; a high magnification optical microscope fitted with a high resolution CCD monochrome camera and a white light interferometer. A monchrome Pulnix TM-865 camera and microscope were used to capture an image of a line. through Leica MZ 2125 micriscope. A stabilised xenon light source was used to illuminate the image. White light interferrometry is a non contact surface profiling method which generate a three dimensional map of a surface over a 2 dimensional area.

The basic principle of interferometry is that a beam of light is sent through a beam splitter, with half the being sent to the surface and half to a reference surface. The reflected beams are then recombined and interference caused by the beams travelling a different distance is used to measure the height of the test surface. The main advantages are that a large area of the sample can be measured quickly. It is a non-contact and non-destructive method and can measure wet and dry ink samples, Veeco (1998).

An initial analysis found that, in general, the edge definition of screen printed lines can possess three distinct characteristics (Figure 2). When correctly printed, the lines possess straight edges (Figure 2a). Edge rippling is characterised by high frequency variations in the line width while mesh marking results in lower frequency variations in the line width (Figure 2b & c). The mechanism for edge rippling is usually associated with stencil roughness, excess ink transfer. Mesh marking is usually associated with line / mesh orientation and insufficient ink transfer.

One critical parameter which can have a significant effect on any geometrical measurement is the threshold value (Lind & MacPhee, 2000, Malmquist et al, 1999). The threshold value is used to determine what can considered to be ink and what can be considered as substrate, converting the original image to its segmented equivalent (Figure 3).

(a) Straight edge

(b) Edge rippling

(c) Mesh marking

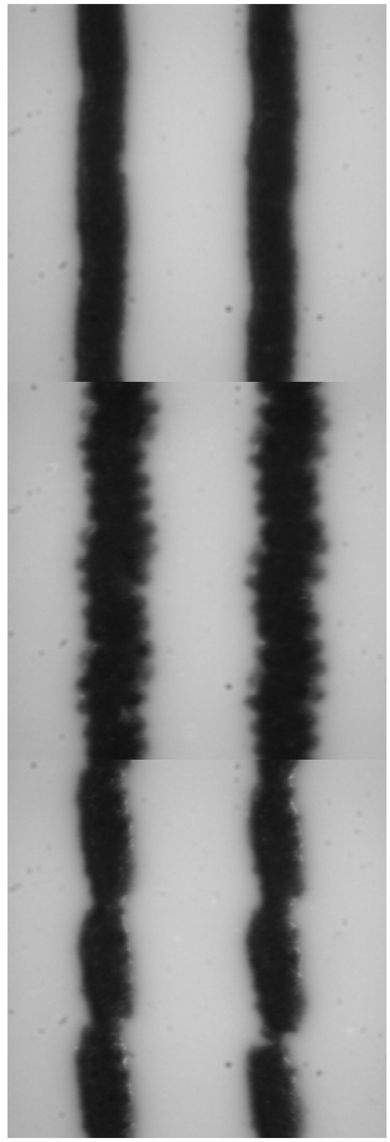
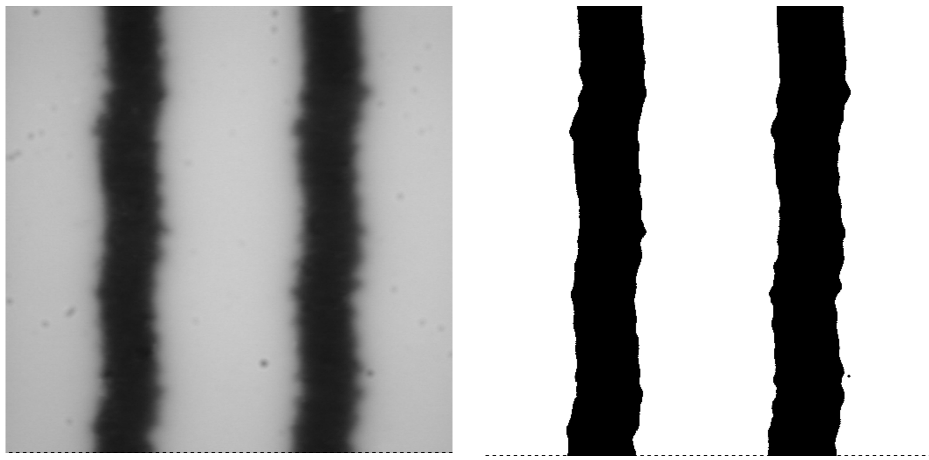


Figure 2 : Typical edge characteristics of screen printed lines.



(a) Original image (b) Segmented image

Figure 3 : The original image and segmented image when the correct greyscale threshold value is applied.

The threshold when image processing is defined using a grey value. This is usually obtained from the grey scale histogram (Figure 4). Automatic methods by which the threshold value are set include the mid point between the peaks, the point of minimum gradient between the peaks and the point of minimum value between the peaks (Lind & MacPhee, 2000, Malmquist et al, 1999).

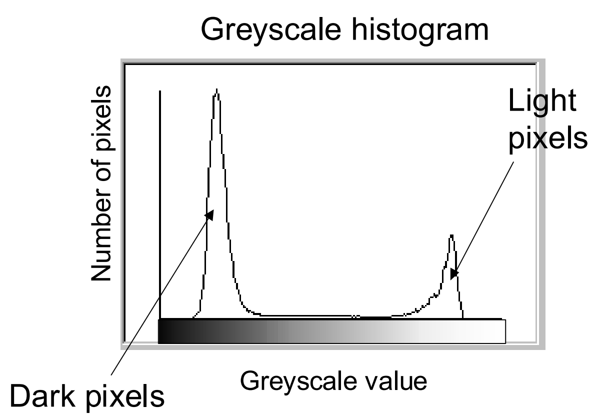


Figure 4 : A typical greyscale histogram.

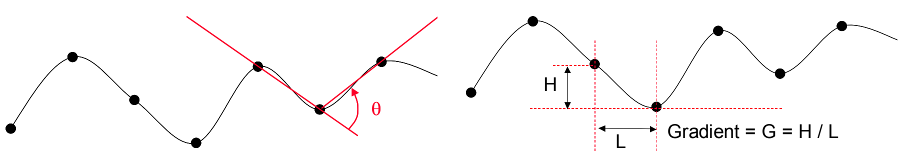
In 3D surface profiling the choice of threshold value is usually easier, provided that the substrate is smooth and flat. As the measurements are absolute, the threshold can be set to a nominal value. During initial trials a value of 0.5 µm was found to provide the correct balance between defining the vast majority of the line area while reducing the possibility of introducing non image areas into the segmented data.

Once a suitable thresholding value has been chosen it is possible to clearly define the boundaries of the line. The analysis of these boundaries can now be carried out using statistical and signal processing techniques.

Amongst the parameters which can be used evaluate the width of the line are the average line width, the line width gain (the difference between the printed width and the film width) and the percentage line width gain. One of the simplest statistical method which can be used to asses the line edge quality is to examine the standard deviation in the line width. A line whose thickness is consistent along its length has a small standard deviation and vice versa :

$$\mathrm{SD} = \sqrt{\frac{\sum(\text{Avarage width} - \text{width at each point})^2}{\text{Number of points}}} \qquad (1)$$

Other line edge quality characteristics that can be calculated include an analysis of the gradient and change in angle between successive measurement points on the line. The parameters measured along the length of the line are depicted in Figure 5.



(a) The change in angle between successive points on the line

(a) The gradient between successive points on the line

Figure 5 : The (a) change in angle and (b) gradient used to define line edge quality.

In order to generate a single statistical value for the edge quality, the data along the edge of the line is average in accordance with the equation (2) and (3).

$$GQ = \sqrt{\frac{\sum_{i=1}^{N}(G_i)^2}{N}} \quad (2)$$

$$CQ = \sqrt{\frac{\sum_{i=1}^{N}(\theta_i)^2}{N}} \quad (3)$$

Where GQ and CQ are gradient quality and curvature quality respectively. Simple statistical methods are unable to differentiate between the mesh marking and edge rippling phenomena as the most visible dominant distinguishing feature between the two is the frequency of the patterning. In order to detect and evaluate the frequency, Fourier methods were employed. Using the variation in line width from an average centreline it is possible to evaluate the frequency of the variation (Figure 6).

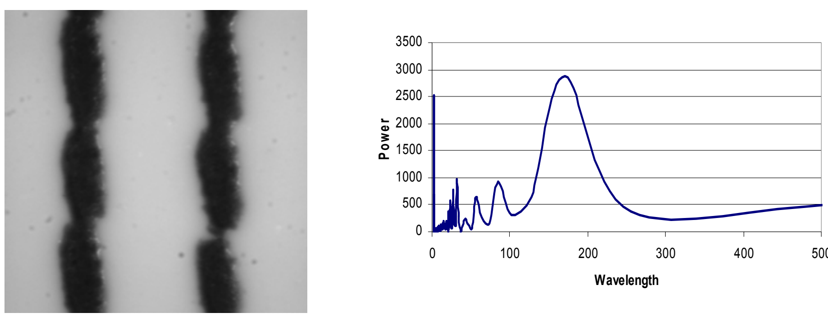


Figure 6: Printed lines showing mesh marking and their complimentary width Fourier analysis showing the peak at peak wavelength.

The width frequency spectrum *W(f)* is calculated using equation 4.

$$W(f) = \int_0^l w(y) e^{\{-i2\pi f l\}} dy \quad (4)$$

Where w is the width of the line at position y. The numerical values of the dominant peak of the FFT may vary according to the sampling length, resolution and mesh ruling. In order to evaluate the degree of mesh marking or edge rippling a method was developed which defined a mesh marking index. A mesh marking index of 100% is defined when the mesh marking wavelength (L) is twice the mesh pitch (x) (Figure7).

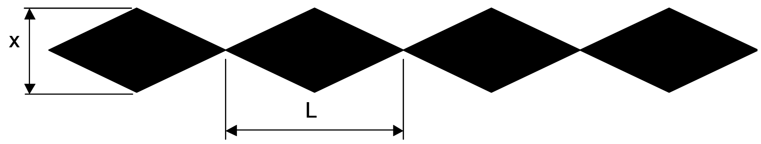


Figure 7 : A 100% mesh marking value was defined when the

Test analysis

Using optical techniques, the measured thickness of the nominally 160 micron lines is dependent on the grey value threshold (Figure 8) irrespective of the line edge characteristics. The automatic threshold value (by the mid point method) also varies with the sample.

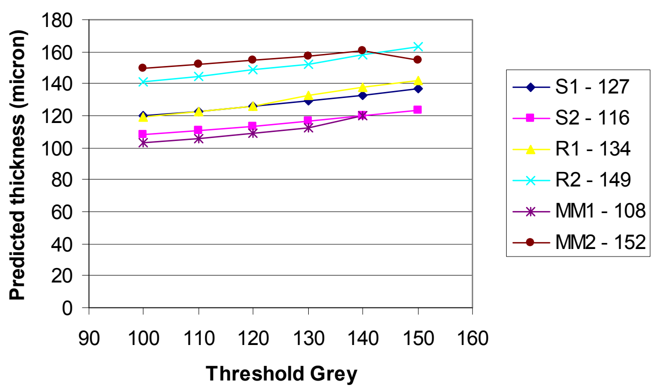


Figure 8 : The measured line thickness as the grey scale value for smooth (S), edge rippled (R) and mesh marked printed lines (MM). Automatically calculated threshold values shown

As the effect of thresholding can result in error measurement, white light interferometry was used for the remainder of the analysis. The repeatability of the surface profiling when measuring a nominally 140 micron line, for a selection of line samples from an orthogonal array experiment, can be seen in Figure 9. The measured line width is lower than that specified and has a maximum variation of around 4 micron.

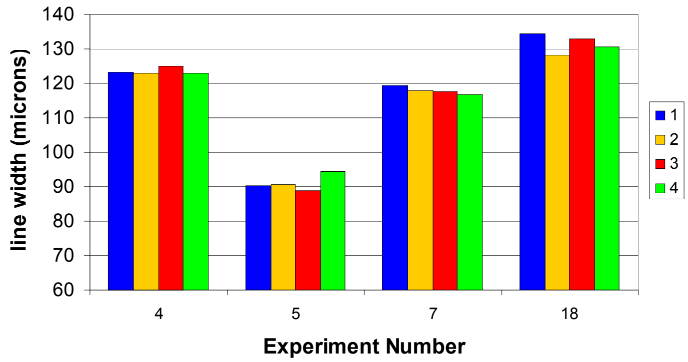


Figure 9 : Repeatability of the surface profiling method.

A comparison of the two methods highlights a significant difference between them. The image analysis method consistently predicting a line approximately 30 microns wider (Figure 10). The reasons for this discrepancy and the implications of it are discussed later.

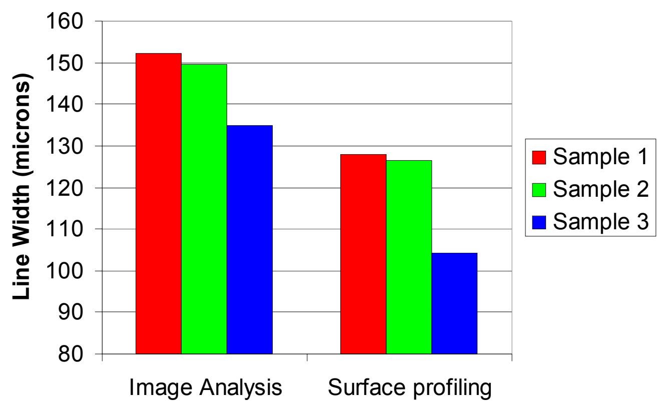


Figure 10 : A comparison of the measurement methods

Measurement of a number of sample lines showed that similar results are produced when a sample of rough edge (R1 to R4) and smoother edge (S1 to S4) lines (Figure 11). The methods employed clearly identify the differences between the smooth and rough lines and produce a objective numerical value which was related to the visual appearance of the lines.

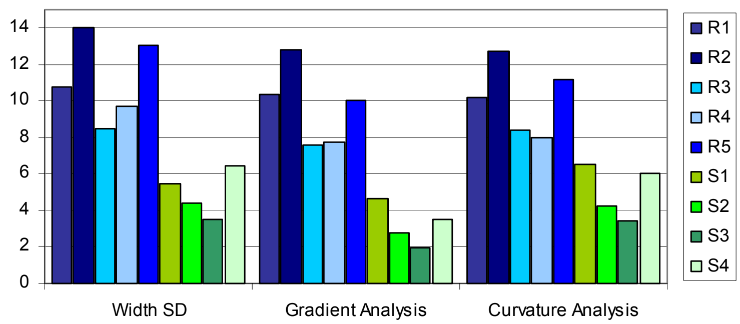


Figure 11 : Statistical methods can be used to establish the line edge quality.

The source of the line edge quality is correctly identified by the Fourier analysis carried out on the fluctuations in the line width (Figure 12).

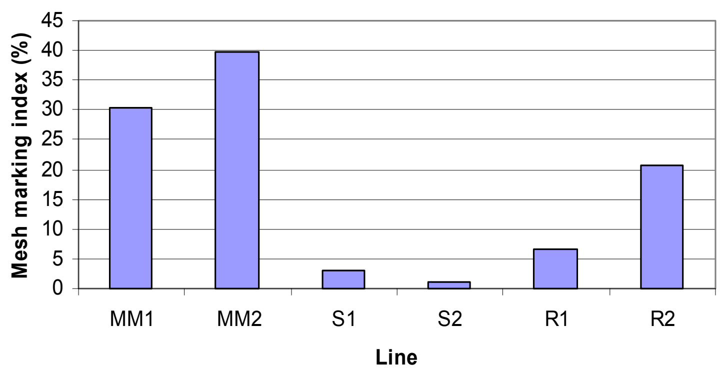


Figure 12 : Fourier techniques identified the difference between mesh marking (MM) and edge rippling (R)

Discussion

In all instances the line width measured with using image processing techniques was higher than that measured by surface profiling. As the film thickness measured is of the order of 14 microns and the level of magnification high, some of this difference can be attributed to the difficulty in ensuring that the entire depth of the line is in focus. Any “out of focus” results in blurring of the image and subsequent grey levels at the edge of the line are not distinct. The thick film thickness can also result in difficulties when optically defining the line boundary as a shadow can be cast by the line itself. As interferrometry is not subject to these errors, this is likely to be the more accurate.

The deficiencies in optical methods are likely to be reduced as the thickness of the printed film is reduced. In general however, the efficiency of the majority of sensors improves as the film thickness increases, and resistance decreases. Other factors, which will play a significant part in the success of image analysis techniques, are the consistency of illumination and calibration such that an accurate threshold can be established.

The analysis methods were employed “offline”, in that the measurements were made after the print run. With the advancement in image processing speeds and reduction in costs, the algorithms employed could be incorporated into an in line print measurement system. This would allow quicker evaluation of changes in print quality.

The methods employed in the study are also applicable as quality analysis tools to other printing process where fine lines must be reproduced, such as the bar codes, currency printing or geometric half toning techniques.

Conclusions

A robust measurement method for the evaluation of printed line quality have been developed which are able to distinguish between the various characteristics of screen printed fine lines. The analysis methods used can be used with optical and surface profiling. There is considerable scope for utilising similar analysis for line characterisation in other printing processes.

Acknowledgements

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