Two and three dimensional characterization of screen printed Lines

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Abstract

Screen printing is frequently used in the manufacture of electronics and sensors as it can be used to print virtually any ink onto any substrate and produce a wide range of ink film thickness. During production the ink deposit may vary due to solvent evaporation due to the subsequent change ink rheology. Because of this variation quality assurance and analysis may require 100% inspection. An experimental trial into the effect of ink rheology and non contact measurement technique was carried out. The analysis highlights the limitations of a simplistic approach based on applying a geometry formula based solely on line width with line height inferred based on the screen properties. This difference can be attributed to the changes in the shape of the line's cross-section that are a function of process parameters. The paper infers that through an understanding of the process physics and in particular the influence of rheology, that the cross sectional area can be derived from the image processing. However, for quality assurance, rigorous process monitoring would have to be included to compliment the image processing.

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1. Introduction

Screen printing is commonly used for the manufacture of electronic circuits and devices. It provides significant advantages over conventional etching techniques in that it is additive, has less process stages, it can be used on polymeric substrates and is economical for a wide range of production runs. The process is not however without a number of disadvantages. Is has a limited resolution and register, which limits feature density. For electronic fabrication, the process uses an ink which contains a high particulate proportion which acts as the active part of the ink. Where high conductivity is required, the use of conductor / polymer composites in the ink reduces the overall conductivity of tracks.

The ink is a combination of solid particles (either carbon- graphite or semi precious metallic conductors such as silver) which are the active part of the ink, a polymer which is the binds the particles together and to the substrate and a solvent which dissolves the polymer. In order to improve the conductivity of the printed tracks there is the potential for increasing the solid conducting particulate proportion of the ink. This however has the effect of increasing the material viscosity, which might reduce the printed ink volume due to process ink transfer mechanics and increasing the ink cost considerably as the metallic conductors tend to be the expensive ingredient of an ink formulation. There is therefore a balance in formulation where the amount of solid particulates must be optimised for maximum conductance at minimum cost and best definition.

The printed "ink" is has highly complex rheological material with pseudoplastic and visco-elastic properties, [Amery, 1997]. This is to be expected as the formulations may contain up to 80% particulate content by mass and thus there is considerable interaction between the individual particles and between the particles and carrier resin.

A number of authors have investigated the ink transfer in screen printing and have suggested a transfer mechanism based on the development of hydrodynamic pressure at the squeegee tip which pushes the ink into the substrate, Reimer [1990], Huner [1994].

Others, primarily working in the solder paste printing industry, have promoted a "pull" theory where transfer occurs as the adhesion between ink and substrate overcomes the cohesive nature of the material, Messerschmitt [1982], Abbot [2000]. In heavily particulate laden systems, many of the assumptions made in both theories, such as zero ink elasticity are invalid. As such there is little scientific reasoning behind the ink transfer and no simple way in which predictions of effect of process parameters, particularly ink rheology have on print deposit.

In production, the passage of the squeegee and flow coat over a thin layer of ink on the screen produces the ideal conditions for solvent evaporation. Solvent evaporation reduced the ink solvent content and increases the viscosity of the ink which is sufficient to produce an appreciable difference in ink deposit, Jewell [2003], with increasing ink deposit as ink viscosity increases.

With solvent evaporation being an important factor, another aspect of circuit manufacture which is important is the quality assurance in a production environment. In a practical production environment some inspection would be required in order to provide measurable quality characteristics. For electronic PCB manufacture it is common practice to measure resistance of each printed board using custom designed jigs which place probes at key measurement points on the circuit board surface. This provides true functional data but is relatively slow, requires expensive jigs to be manufactured for each board design, the measurement hardware is expensive and as it is a contact measurement cannot be carried out on uncured ink films. An alternate solution is the use of image processing to measure the printed features.

The aim of this paper is to investigate the effect of ink material rheology on printed fine lines and the means by which these can be measured.

2. Method

The print trial to establish the effect of ink rheology on print performance was carried out on a small format printing press with 10 prints being produced for each condition; four of these being selected for analysis by each measurement method. The image printed consisted of series of lines at three orientations to the print direction.

In order to vary the shear conditions at the printing junction an investigation into the effect if mesh type and printing speed was carried out. A variation in the print speed can be directly related to the shear rate of the ink between the squeegee and screen and shear rate through the screen as the print contact time is reduced. A change in the mesh specifications results in a changing shear regime as the ink passes through the mesh as mesh aperture opening varies. This was achieved using two polyester and two stainless steel meshes, Table 1. The ink volume percentage is calculated by considering a square sided volume within the mesh and multiplying the percentage open area by the thickness of the mesh material. Stainless steel mesh is preferred where high dimensional tolerance and higher ink weights are required while the polyester mesh provides more durable and lower cost mesh material.

Table 1 : Mesh types investigated.

	Material	Mesh ruling (threads/ cm)	Mesh diameter (μm)	Ink volume (cm^3/m^2)
1	Stainless Steel	125	32	24
2	Stainless Steel	78	40	43
3	Polyester	77	48	28
4	Polyester	61	64	30

In order to asses the impact of ink rheology (and by inference the process variation due to evaporation), 6 commercial ink formulations were printed and analysed. Each contained the same base resin but varied the conductive carbon graphite content. Although metals such as silver are commonly used where conductivity is required, carbon graphite provides a more cost effective material, particularly for disposable electronics and also provides a better method for the comparison of measurement method. The black carbon graphite ink provides the necessary optical contrast between the black ink and the white substrate.

Metallic elements in the ink can lead to specular reflections which could result in measurement error.

The printed lines were measured using digital image capture and by white light interferrometry. A monochrome Pulnix TM-865 camera and microscope were used to capture an image of a line. through Leica MZ 2125 microscope. A stabilised xenon light source was used to illuminate the image. Segmentation of the images was achieved using a the mid point between peaks in the greyscale threshold. Further details of the analysis methods used can be found in [Jewell, 2003].

White light interferrometry (WLI) is a non contact measurement technique for surface topology characterisation. WLI 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]. Typical output from a WLI of a printed line is shown in Figure 1.

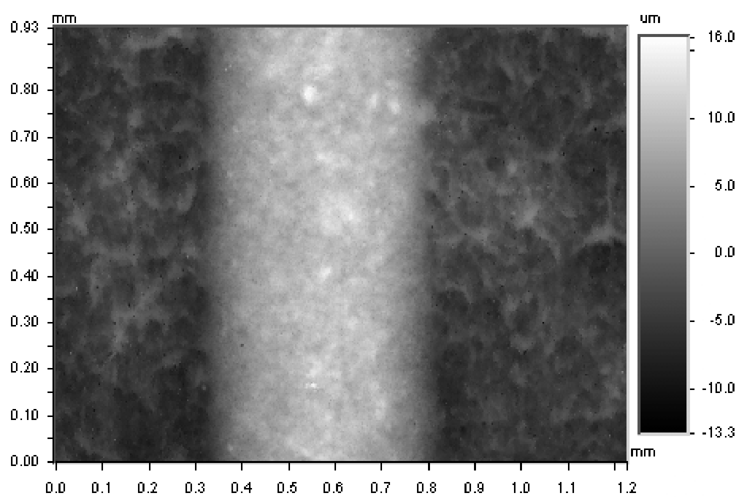


Figure 1 : White light interferrometry measurement of a printed line, where the grey scale value indicates film height (white is highest).

In order to obtain the full information on the printed line, macros were written to calculate that the cross sectional area for all points along the line length, using a

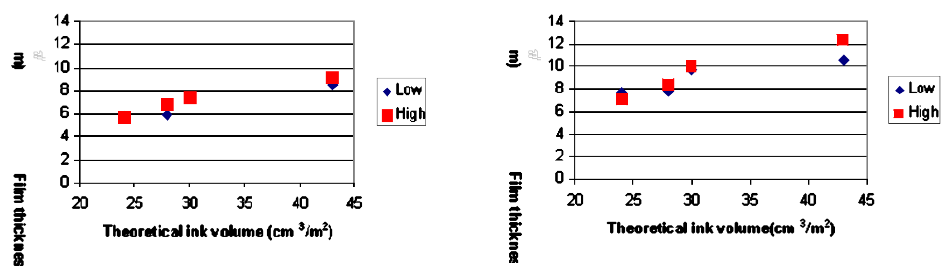
Simpson’s rule approximation. Satellite ink droplets were ignored during the analysis. The polyester substrate had an Ra of 0.2 μm and thus determination of the exact substrate level was prone to error, although software masks reduced this considerably.

Measurement of the ink rheology was carried out on a Haake cone and plate rheometer suitable for shear only QA measurements and on an ARES variable and oscillating rheometer fitted with a parallel plate geometry. This unit is considerably more complex and costly and is capable of measurement of non Newtonian and complex visco-elastic properties.

3. Results

3.1 Print trial results

The ink deposit was measured by considering the an area within an are of solid within view of a reference substrate. With the 38% carbon ink, there is a increase in ink deposit with theoretical ink volume while increasing the print speed increases the printed film thickness a small amount for almost the screens, Figure 2(a). Similar behaviour is seen at 42% carbon. The increase in transferred ink volume is typically 50% of that which is predicted by the theoretical ink volume. This highlights the limitation of this statistic as an indication of ink transfer ability. It also shows a significant proportion of ink, assuming the screen is filled, remains in the mesh as the screen is raised from the substrate.



(a) 38% (b) 42 %

Figure 2 : The effect mesh theoretical ink volume and print speed on cured film thickness for the 40% carbon ink.

At lower specified line thickness, there is a noticeable increase in the line thickness compared to that specified on the film, Figure 3. As the line thickness increases this increase tapers off and produces a regular increase in printed line width. This may be attributed to the slump of the lines after printing.

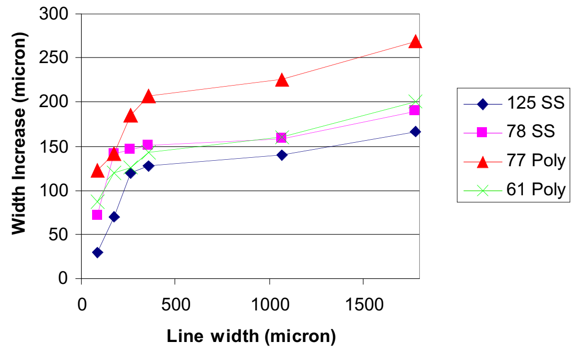
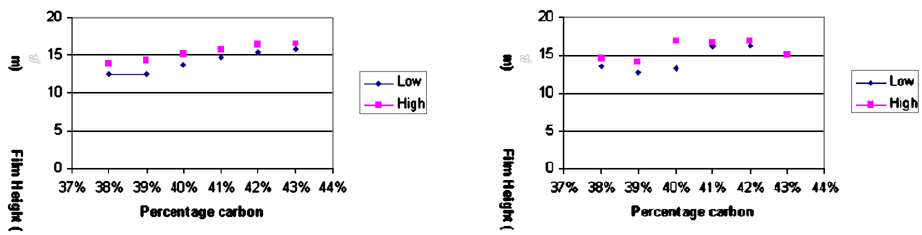


Figure 3 : The increase in printed line width for all screens
for one of carbons inks printed at high speed.

Increasing the percentage carbon increased the cured film thickness, Figure 4, almost linearly with the 61 threads/ cm polyester mesh while increases above 40% did not change the cured film thickness for the 77 stainless steel mesh. In both cases the increase in speed resulted in an increase in ink deposit.



(a) 61 Polyester mesh (b) 77 Stainless steel mesh
Figure 5 : The effect of carbon content on wet ink deposit at low and high speed.

3.2 Rheological assessment

The effect of carbon content on the high shear behaviour (above 50 s^{-1}) follows a consistent pattern. All the inks are pseudoplastic in nature with increasing carbon content increasing the viscosity of the inks, Figure 5. The effect of carbon content is most evident at low shear rates.

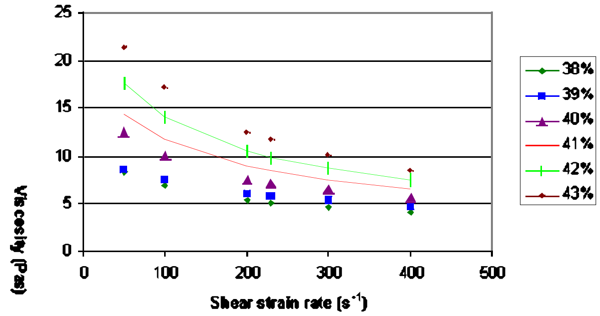


Figure 5 : High shear behaviour the inks under investigation.

Low shear oscillatory rheometry shows that the ink is highly elastic at low shear and becomes more viscous as the shear rate is increased as shown by the increasing phase angle in Figure 6. Although there is a general trend showing increasing phase angle with carbon content, there are instances when this trend is not followed clearly, e.g. the profile of the 38% carbon lies between the 42% and 40% carbon.

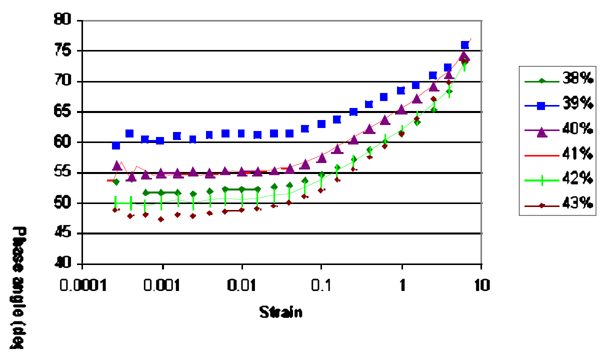


Figure 6 : The elastic / viscous phase angle for the each ink formulation.

3.3 Measurement methods

Measurement via WLI shows that the fine lines differ considerably in their cross sectional shape from the idealised rectangular deposit. For a nominally 120 micron line, the line exhibits a dome shape cross section with relatively flat "beach" areas on the side of the lines, Figure 7.

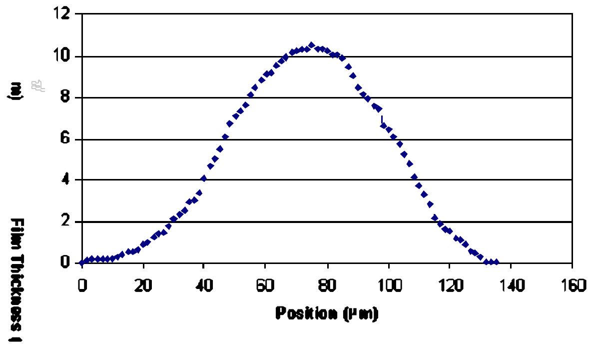


Figure 7 : The true cross sectional area of a printed fine line.

The effect of the shape of the lines on the resultant cross sectional area is significant for the finer lines. The true CSA obtained by integration is around 50% of that which is obtained if one assumes that the lines have a rectangular cross section over a broad range of line cross sectional areas., Figure 8. There are a number of reasons for the non rectangular nature of the lines including flattened areas of “beach” at the edges of the line, variations in the surface topology of the lines and substrate surface finish effects which would could make finding a substrate “level” difficult.

The line cross sectional profile highlights the need to take into account the non rectangular nature of the lines when examining screen printed fine lines. It has implications for the design of circuits as the gap between lines could become conductive as a result of these beach areas. Possible causes include slumping of the line post printing and the attachment of the ink to the screen which draws the ink away from the substrate.

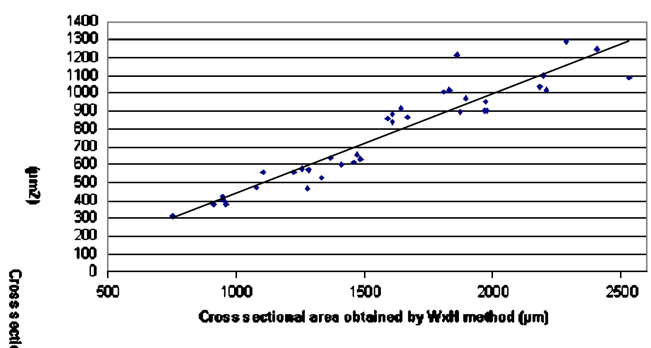


Figure 8 : A comparison of the cross sectional area calculated from integration and by the product of the height and width.

As the film thickness - density relationship is logarithmic, the flattened “beach” areas at the edge is detected optically although it adds little to the overall film CSA as the film thickness is small. There is subsequently a significant difference between the width of the line measured and the cross sectional area of the lines, Figure 9. There is little correlation between the two parameters which shows the problem in measuring the three dimensional line characteristics using a two dimensional imaging technique.

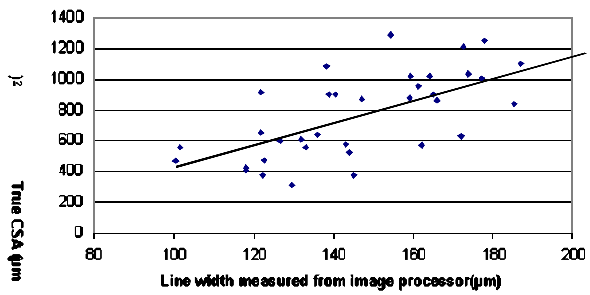


Figure 9 : The correlation between the line width measured by image processor and the line CSA.

There may be some scope for using a multi level image segmentation in order to pick up the small difference between the optical density of the main body of the line and the beach area. This would require accurate and stable lighting, a suitable software calibration for greyscale / ink film thickness and a CCD camera with excellent grey scale resolution in order to pick up the small differences in the greyscale values between the beach and main body.

4. Conclusions and recommendations

An experimental investigation into the effect of ink rheological parameters has been carried out

- A dominant factor which determines the quantity of ink transferred is the theoretical ink volume although the increases are typically 50% of that expected.
- 2 dimensional measurement of print characteristics do not provide the necessary means for measuring the cross sectional area, i.e. the functionality of the line.
- The rheological properties of the inks

Recommendations for further work are :

- To estimate true print to bulk resistivity, the true cross sectional area to print resistance measurements need to be carried out.
- The work should be expanded to examine the relationship between microscope image characteristics and other the ink deposit when other shaped objects are printed.

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