The application of three-dimensional profiling to the measurement and characterisation of screen printed fine lines.

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University of Wales Swansea

The application of three-dimensional profiling to the measurement and characterisation of screen printed fine lines

By

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Thesis submitted to the University of Wales Swansea in fulfilment of the requirements for the degree of Doctor of Philosophy.

University of Wales Swansea

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Summary

Screen printing is used for printing fine lines in the electronics industry, as the process is able to print a large ink film thickness, enabling a variety of resistances, and it is capable of printing onto inflexible surfaces. The cross-sectional area of printed lines determines the electrical characteristics of the line. Presently, line cross-sectional size is determined by measuring line width, as the shape of a screen printed line is assumed rectangular and line height is assumed known from other screen printing process parameters. However, for fine lines this assumption may not be true. The aims of this project have been to ascertain the effect of screen printing process parameters on line quality and investigate the relationship between line width and cross-sectional area for fine lines.

A large experimental programme has been undertaken that investigated the influence of the screen printing process parameters on line width, cross-sectional area, line continuity and cross-sectional shape. The screen printing process parameters investigated were the squeegee parameters, the ink type and the screen. The effect of the orientation of the lines to the print direction has also been investigated.

A new measurement system has been developed to extract and evaluate the appropriate information from the printed images and allow full analysis of the results. A new parameter, the rectangular index, was developed specifically to understand the correlation between line width and cross-sectional area for fine lines.

The measurement system has been used to analyse the results, investigating repeatability, orientation, line cross-sectional size, line continuity and line cross-sectional shape. The line continuity, line edge quality and ink transfer were linked. Sufficient ink transfer leads to good line edge quality and continuity. The ink type and line width were the only parameters to affect the line cross-sectional shape. A new model has been proposed that related line width and cross-sectional area for fine lines. This would permit the use of 2D image processing for on-line quality assurance as opposed to 3D measurement or functionality testing, both of which are slower and have to be used off-line.

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GLOSSARY

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Nomenclature

α	The angle between cone and plate, for a cone and plate viscometer
γ_{SA}	Surface tension of the solid air interface
γ_{LA}	Surface tension of the liquid air interface
γ_{SL}	Surface tension of the solid liquid interface
$\dot{\gamma}$	Shear rate
ρ	Resistivity
σ	Standard deviation
σ_{pop}	Population standard deviation
$\sigma_{\bar{x}}$	The standard deviation of the sample means (standard error)
θ	Contact angle
μ	Viscosity
ι	Shear stress
Ω	Angular velocity

A	Line cross-sectional area
A_E	Equivalent area
B	Peak to peak variation of line width
f	Frequency
H	Line height
L	Line length or length of a resistor
N	Number of points or samples
P	Largest peaks in a data set
R	Resistance
R_s	Sheet resistance
R_T	Total resistance

RI	Rectangular index
r	The radius of the cone, for a cone and plate viscometer
T	Torque
U	Wavelength of line patterning
V	Lowest valleys in a data set
W_{SL}	Work of adhesion between the solid and the liquid
w	Line width
w_{max}	Maximum line width
w_t	Total width of the line
w_c	The width of the curved part of a line
w_u	The width of the part of a line where the height is considered uniform
x	Co-ordinate across line width
y	Co-ordinate along line length

Glossary

Accuracy	The amount a mean value is from the correct value
Adhesion forces	Forces that exist between two different substances that hold them together
Addressability	The number of uniquely identifiable points of a field or image
Binarisation	The process of segmenting an image into 2 parts for further analysis
Cohesion forces	Internal forces within a liquid that hold the liquid together
Contact angle	Angle at the interface of a drop of liquid with a solid.
Deterministic data	Data that follows repetitive patterns and a value at any point can be predicted with sufficient knowledge of the data
Drying-in	Solvents from the ink can evaporate whilst the ink is on the screen. This causes dry ink to partially block the mesh. This process is called drying-in.
Edge rippling	High frequency patterning along the length of the line.
Evaluation length	The length, or number of points, of a sample of data.
Frame	A rectangular frame is used to hold the mesh and allows it to be tensioned to the required level.
Flowcoater	A piece of metal used to spread ink over the screen before the squeegee stroke
Greyscale	Brightness range for a digitalised image
Half-tone printing	Using dots to represent shades in printing
Line measurement settings	Instrumentation and measurement settings used to obtain data from the printed image
Line measurement parameters	Parameters used to describe the quality of printed lines
Line quality parameters	Characteristics of a line that affect its performance

Line size	Either the line width or cross-sectional area
Line width	The width of a line
Mesh	A woven fabric that is stretched over a frame and supports the stencil.
Mesh count	The number of threads per unit length of the mesh
Mesh marking	Low frequency patterning along the length of a line
Newtonian fluids	Fluids whose viscosity is not dependent on shear rate
Nominal line width	The line width on the stencil that is the intended line width.
Non-Newtonian fluids	Fluids whose viscosity is dependent on shear rate
Image segmentation	The process of splitting an image for further analysis
Ink	The fluid used in screen printing is call the ink
Open area	The area of the mesh not covered by thread and is defined as a percentage of the total area.
Optical density	Darkness of a printed colour
Paste	In stencil printing the fluid, which is printed, is often called a paste. It is thicker than in screen printing.
Precision	The spread or variation of a sample of data.
Print direction	The direction the squeegee moves during the print cycle
Print speed	The speed the squeegee moves during printing
Random data	Data where it is not possible to predict the value at any point within the data.
R-squared	A measure of how well one set of data can be predicted from another.
Rectangular index	The ratio of actual cross-sectional area to the cross-sectional area if a rectangular cross-section was assumed
Rz	Measurement of surface roughness
Sampling length	The length, or number points, of a sample of data.
Sampling interval	Spacing between consecutive points of discretely sampled data
Screen	The mesh, the stencil and the frame together are known as the screen.

Screen profile	The height of the mesh and the stencil combined
Screen printing	The process of reproducing an image from a stencil supported by a mesh.
Screen height	The height of the mesh and the stencil combined
Screen tension	The tension of the mesh
Sensitivity	The ability of a measurement system to detect small changes.
Snap-off gap	The distance between the screen and the substrate
Squeegee	A piece of polymer used to push the screen onto the substrate
Squeegee angle	The angle, to the vertical, of the squeegee
Squeegee hardness	The material used to produce the squeegee
Squeegee speed	The speed the squeegee travels during the print cycle
Squeegee pressure	The pressure used to exert the squeegee onto the screen during the print cycle
Stencil	A photo-polymer layer put onto the mesh that creates the image
Stencil printing	A form of printing, very similar to screen printing, but no mesh is used to support the stencil
Standard deviation	A measure of the spread of a data set
Standard error	A measure of the spread of sample means obtained from a population
Substrate	The object onto which the image is printed
Surface tension	Forces on a liquid that prevent it from forming a new surface
Thread diameter	The diameter of threads used to manufacture the mesh
Threshold	The value used to segment an image in image processing
Viscosity	A measure of a fluids resistance to flow.
w_c	The width of the curved part of a line
w_u	The width of the part of a line where the height is considered uniform

Wettability	How easily a fluid wets a surface
White light interferometry	A method of measuring relative distances using the interference patterns, or phase shifts, of light

Chapter 1

Introduction

1.1 Introduction to fine line screen printing

Screen printing is one of the oldest forms of printing. It is based on stencil printing, where a pattern is cut into a sheet of material, such as paper, to produce a stencil. The stencil is placed onto the substrate and ink is brushed over the top of it. This reproduces a positive of the image on the substrate. Screen printing is a development of this process that uses a mesh to hold the stencil allowing more complicated patterns.

Screen printing has several important advantages over other printing processes in terms of ink deposit and flexibility. It can print a wide variety of inks onto most substrates, including substrates with simple contours. Screen printing can also print on flat inflexible surfaces such as glass. Its ability to lay down large ink film thickness, print viscous inks and to print on rigid substrates makes it ideal for the electronics industry. A large ink film thickness enables a large range in resistance and other functions of printed lines or components. Its ability to print viscous inks is ideal for the printing of solder pastes and functional inks with high solid content.

Industrial screen printing is mainly the printing of lines for sensors and electronic circuit boards. It is distinguished from graphic screen printing by the inks having a function other than their look, thus the term functional inks. Competition within the industry drives manufacturers to produce smaller and smaller products. This means finer lines need to be printed, to reduce the size of printed circuit boards. For finer lines, the interaction of the mesh and the screen is more significant on the release of the ink from the screen. Thus, it is harder to accurately produce the functional properties of the line.

The cross-sectional area of the line is critical to the performance of functional inks, e.g. for resistance when printing conducting inks. The cross-sectional shape of a line is assumed to be rectangular, with the height dependent on the ink type and screen. Therefore, only line width is required to find the area, since line height is assumed. However, for fine lines, the assumption that the height of the ink is uniform across the width may not be valid. Also, the performance of the functional circuit, with fine lines, would be more sensitive to discrepancies in cross-sectional area. Therefore, to accurately characterise the line quality of fine lines, the three-dimensional properties of the line are required to be measured. Figure 1.1 shows a schematic of a cross-section through a line detailing the measurement parameters.

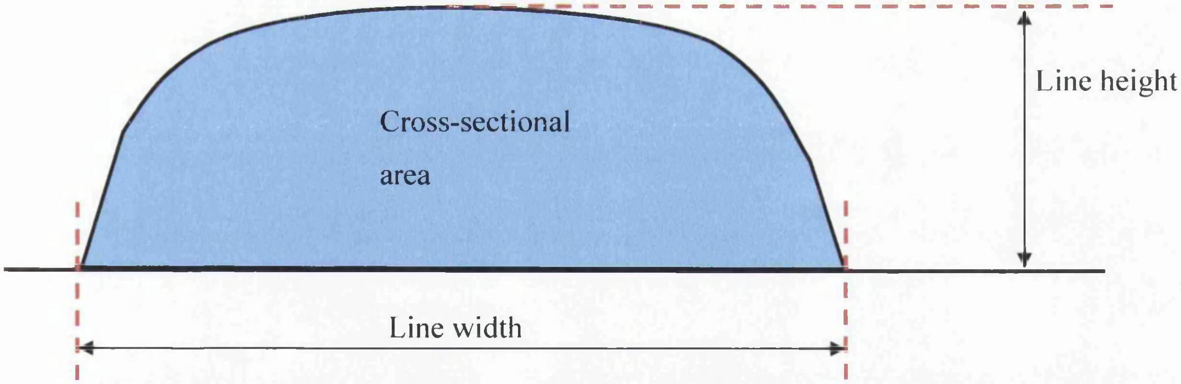


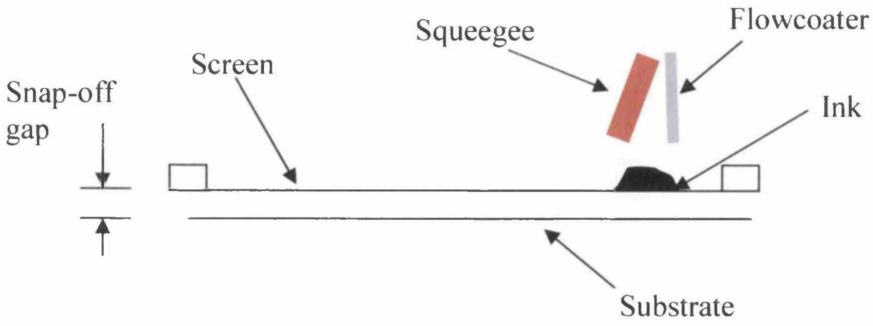
Figure 1.1 : A schematic of the line measurement parameters

The objective of this study was to investigate the effect of process parameters on line cross-sectional area and line width. Appropriate analysis algorithms were developed and applied to controlled experiments. The correlation of the line width and cross-sectional area was investigated to establish if a more accurate method to determine the cross-sectional area, than assuming a uniform distribution of line height across the width of the line, could be developed. This would permit the use of 2D image processing for on-line quality assurance as opposed to 3D measurement or functionality testing, both of which are slower and have to be used off-line.

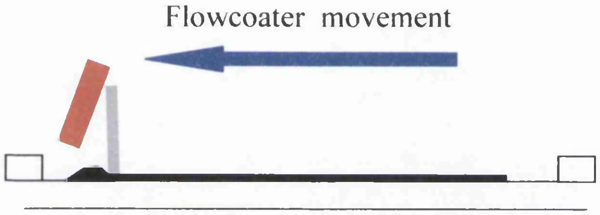
1.2 The screen printing process

Screen printing is a process that forces ink to transfer through a fine mesh onto a substrate. The physical process that allows this to happen is outlined below.

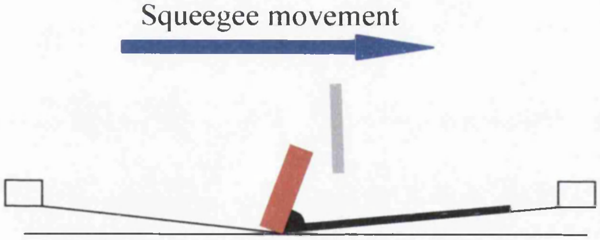
Before a print cycle begins, the press is set up as shown in the schematic in Figure 1.2(a). A piece of metal called the flowcoater then moves across the screen at a small height above it. This leaves an even layer of ink spread over the whole image area of the print. This is shown in Figure 1.2(b). The squeegee, which is a flexible polymer, is then pushed down, forcing the mesh onto the substrate. The squeegee is drawn across the screen until it reaches the end of the print length (Figure 1.2(c)). This transfers the ink through the screen onto the substrate. The tension of the screen pulls the stencil off the substrate behind the squeegee. The squeegee is released and the press is returned to the position in Figure 1.2(a) ready to begin another cycle.



(a) The parts of a screen printing press at the beginning of a print cycle



(b) The flowcoater spreads a thin layer of ink over the image area of the screen



(c) The printing stroke

Figure 1.2 : The screen printing cycle, showing a cross-sectional view through the screen

1.3 Screen printing parameters

Many parameters influence the screen printing process, a list of these is given in Table 1.1 (1). This section describes their role in the screen printing process and the way each parameter can be varied.

Table 1.1 : Parameters affecting the screen printing process (1)

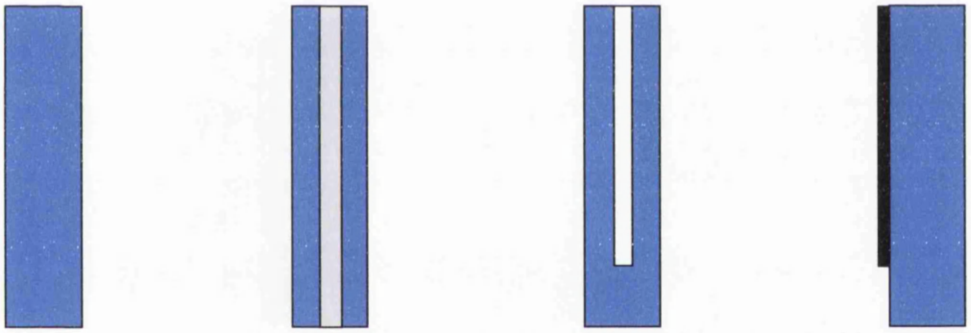
Printing Process	**Substrate**	**Screen**	**Squeegee**	**Ink**
Squeegee pressure	Cleanliness	Mesh count	Squeegee material	Viscostiy
Squeegee angle	Surface energy	Thread diameter	Shape of edge	Solid content
Print speed	Surface Roughness	Mesh opening	Squeegee backing or stiffening	Particle size
Snap-off distance	Planarity	Mesh height		Shear strength
Print stroke length	Geometry size	Mesh material		Homogeneity
Paste quantity on screen		Emulsion thickness		Adhesion
Flowcoater height		Stencil roughness		Stability and consistency
Flowcoater speed		Stencil type		Surface tension
		Screen tension		

1.3.1 Press parameters

The position and use of the press parameters is shown on Figure 1.2. The snap-off gap is the distance between the substrate and the bottom of the screen. This affects the angle between the mesh and the substrate at the point of printing. It also affects the distortion of the image since the further it is stretched the more distortion there is in the image.

The flowcoater is a piece of steel used to spread a layer of ink over the screen before printing. This ensures an even covering of ink over the screen and that all of the printing cells are filled.

The squeegee is a flexible polymer that is used to transfer the ink through the screen onto the substrate. Squeegees are manufactured to different flexibilities. This property is called hardness within the screen printing industry and is measured using the Shore A scale. This is more a measurement of how easily the squeegee deforms than its hardness. Typical squeegees vary from about 60 to 90 Shore A. The simplest design is made from only one compound. More complex designs have been developed to increase the rigidity of the squeegees along their height, so the angle set on the press is closer to the angle between the squeegee and the screen. These include having a steel back on the squeegee, making the squeegee with a hard polymer in the centre of the squeegee and making the squeegee with a piece of fibreglass in the centre. Examples of these are shown in Figure 1.3. On the press, it is possible to change several attributes of the squeegee. These are squeegee angle, squeegee pressure and print speed. These all affect the hydrodynamic pressure in the ink roll in front of the squeegee.



(a) Conventional (b) Trilayer (c) Fibreglass centred (d) Steel backed

Figure 1.3 : Cross-sections of the alternative squeegee designs

1.3.2 The screen

The screen is made up of three parts: the frame, the mesh and the stencil, as shown in Figure 1.4. The frame is a rectangular structure that is used to support the mesh. The mesh is made from tightly woven threads, of either a synthetic polymer or metal, and is used to support the stencil. The stencil is a photopolymer layer that defines the image to be printed. An illustration of a cross-section throught the screen showing the mesh and stencil is shown in Figure 1.5.

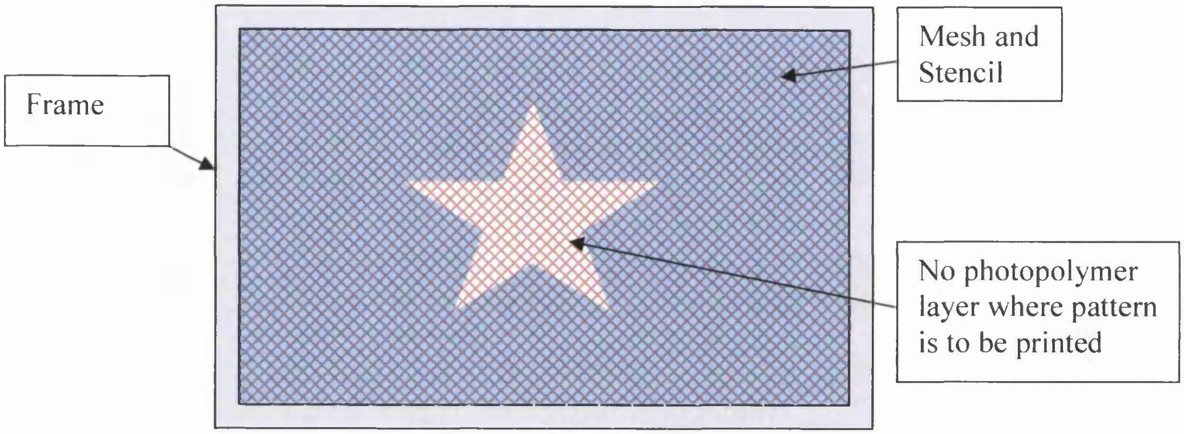


Figure 1.4 : An illustration of a screen for screen printing

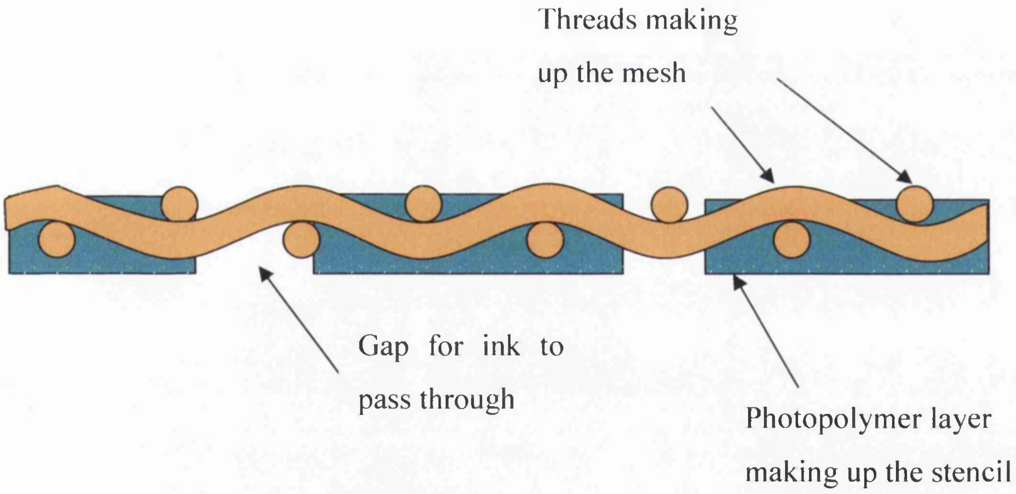


Figure 1.5 : Cross-section through the screen showing the mesh and the stencil

The defining characteristics of a mesh are the mesh count and the thread diameter. The mesh count is the number of threads per unit length. Tensioning a mesh distorts the thread diameter and mesh count so that the mesh height is approximately 1.6 times the thread diameter. The open area, or mesh opening, is the part of the mesh not covered by the threads. It is defined as a percentage of the total area. Typically for screen printing this is about 25%.

The stencil controls the image on the screen. There are three main types of stencil (2); direct emulsion, indirect emulsion and capillary film. The production methods for the types of stencil are described followed by a discussion of their advantages and limitations.

Direct emulsion uses a viscous light-sensitive emulsion. This is spread evenly over the screen. Several coats can be laid onto either side of the mesh. The number of coats on each side of the screen is normally used to describe the coating regime. For example, a 1+1 direct emulsion would have one coat on each side of the screen and a 2+2 direct emulsion would have two coats on each side (2). A positive of the image is placed on top of the screen and is exposed using UV light. This hardens the non-image areas. The uncured parts of the stencil are then washed out and the screen is dried. The quality of the stencil is determined by the evenness of the coating of the emulsion. The more coatings applied, the thicker the stencil and more ink transfer is obtained.

Indirect emulsion differs from the direct method in that the processing of the stencil is done away from the screen. The stencil comes as a thin photosensitive film. This is exposed using UV light. The stencil is then chemically hardened and the uncured film is washed out. The film is transferred wet to the mesh and carefully pressed onto it (2), as it dries it adheres to the mesh.

The capillary film stencil again comes as a photosensitive film. It differs from the indirect method in that the film is placed onto the mesh before exposure. The stencil is put onto a wet mesh and then exposed and washed out the same as the direct emulsion (2).

Stencils are characterised by their surface roughness on the print side and the extra height added to the mesh. Rz is used to measure the roughness of the stencil. Rz is the average of the difference between the five largest peaks and five lowest troughs within a data set and is a measurement of low frequency undulations of a surface. It is defined in the Equation 1.1.

$$R_z = \frac{1}{5}\left[\sum_{j=1}^{5} P_j - \sum_{i=1}^{5} V_i\right] \qquad \text{Equation 1.1}$$

Where,

P_j = highest peaks in data set
V_j = lowest valleys in data set

The direct emulsion method produces a rougher surface on the bottom of the stencil than the other two methods. The consequence of this is that direct stencils do not produce as good line definition or as much control on print quality. The application of more layers of emulsion reduces the surface roughness of emulsion screens, thus improving the line definition. Although this in turn produces a thicker stencil and, therefore, more ink transfer.

Direct emulsion screens put down more ink than capillary or indirect screens, since they have thicker stencils. Thicker stencils hold more ink and, therefore, more ink is transferred onto the substrate. This is especially true if several coatings of emulsion are used. The control over the thickness of emulsion stencils allows good control, or ability to vary, the ink film thickness compared with the other two methods.

Capillary and indirect screens are used to create high definition work with very good line definition. They are also more repeatable between screens. Indirect stencils produce a slightly better line definition than capillary film stencils. This is because light is reflected by the mesh in the capillary film method, during exposure of the stencil, and slightly distorts the image. However, it is very easy to crease or break an indirect stencil whilst transferring it to the screen. This means capillary films are more widely used.

1.3.3 The substrate and ink

One of the most important parameters in screen printing is the relative strength of adhesion between the substrate and the ink and the cohesive forces within the ink. Other factors affecting the process, that are associated with the ink and substrate, are the surface roughness of the substrate and the viscosity of the ink.

Within the literature review, stencil printing is considered as well as screen printing due to their similarity. The liquids used to print with in stencil printing are much thicker than in screen printing and are often called pastes. Within this work the term paste is used to describe the thick liquids used for stencil printing and ink is used to describe the thinner liquids used for screen printing.

The interactions at the interfaces between the ink and mesh and the ink and the substrate, are important as it determines how the ink behaves during the printing cycle (3). These relationships are determined by the free surface energies of the ink, the mesh and substrate. How this influences the ink release is described in the Literature Review.

Surface tension is a measure of the cohesive forces within the ink. It is a phenomenon caused by the attraction between molecules at the surface of a liquid. In the bulk of the liquid, away from the surface, other molecules surround each other and the inter-molecule forces even out. At the surface, molecules are pulled inwards by the molecules in the bulk of the liquid. This force is balanced by the resistance to compression. This leads to free energy and is defined as the energy required to increase the surface by one unit area. The surface free energy of a liquid is called surface tension.

Viscosity is a measure of how easily a fluid flows, i.e. its resistance to flow. It is important in screen printing as the ink must pass through the screen onto the substrate. As a fluid flows, some parts of the fluid will flow faster than others, this occurs as particles close to boundaries are influenced by the boundary. An example of this is a river, where flow near the banks is slower than the flow in the middle, thus a there is a velocity gradient across the fluid. As a consequence, a shear force acts on the fluid and, thus, a shear stress exists. For many fluids, the shear stress is proportion to the velocity gradient within the fluid, these are called Newtonian fluids. The constant of this proportional relationship is viscosity and is defined in Equation 1.2.

Shear stress = viscosity x velocity gradient Equation 1.2

There are fluids where this relationship does not hold and viscosity is dependent on the rate of shear, these are called Non-Newtonian fluids. Shear thinning, or viscoelastic, fluids flow more easily as the shear rate is increased. Whereas, shear thickening, or dilatant, fluids increase in viscosity as shear rate increases. This is shown in Figure 1.6.

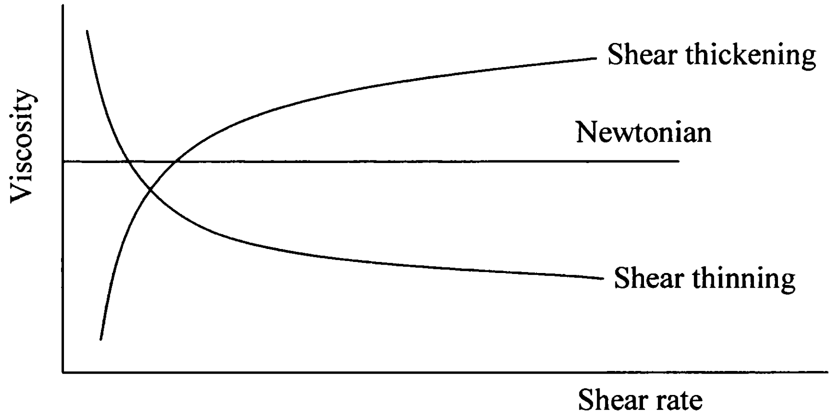


Figure 1.6 : Non-Newtonian fluids (4)

Screen printing inks are shear thinning and the viscosity of most are also time dependent, this is called thixotropy. The viscosity of screen printing inks can vary from a free flowing liquid to pastes that do not flow until a shear force is applied, such fluids are called Bingham fluids.

Bingham fluids have properties that resemble solids at very low shear forces and properties that resemble liquids at high shear forces. Solder pastes often have these properties, therefore they are characterised not just using parameters used for liquids, but also those used for solids such as yield point.

1.4 Screen printing fine lines

1.4.1 The development of thick film technology

After World War II, there was an increase in the availability and use of electrical appliances. At this time, circuits were hand soldered with wires connecting the components (5). Pressures on markets to reduce the size of the circuits led to technological breakthroughs in manufacturing techniques. Cost was not the driving force, since much of the funding for the early electronics industry came from the military (6). Thin film technology was one solution. This uses techniques of coating a thin film of conductive material on to a non-conductive substrate. Generally, the whole substrate was covered with a conductive layer and photolithoghraphy was used to produce the pattern of the wires. The components were then soldered onto the board (7). This meant that there was no need for connecting wires between components. This led to faster production and smaller circuits. More size reductions came with the introduction of thick film technology in the early 1960s (8). To produce a thick film, the conductive material was screen printed onto the substrate.

Thick film technology was born from the idea that resistors could be printed onto the substrate as well as conductive wires. The capability to print some of the components onto the circuit led to large reductions in size and increased reliability. The main difference between thick and thin film printing, apart from the manufacturing technique is the thickness of the deposit on the substrate. Thin film circuits are typically less than 1μm thick whereas thick films are about 25μm thick (7). This thickness makes possible a larger range of resistances for the printed wires.

There are some components that cannot be printed. These have to be added later. Also several packaged circuits can be connected onto one circuit board. These combinations of circuits and components are called hybrids and are commonplace in modern manufacturing techniques (7).

1.5 The aims of the investigation

The cross-sectional area of printed lines is of importance as it determines the electrical characteristics of the line. Presently, line cross-sectional size is determined by measuring line width, as the shape of a screen printed line is assumed rectangular and line height is assumed known from other screen printing process parameters. However, for fine lines this assumption may not be true.

The aims of this project have been to further the understanding of the reproduction of fine lines by the screen printing process, particularly by using three-dimensional measurement to ascertain trends in cross-sectional area, line width and cross-sectional shape. The correlation of line width, cross-sectional area and cross-sectional shape has been investigated to determine any trends that existed between these parameters for fine lines. This would permit the use of 2D image processing for on-line quality assurance as opposed to 3D measurement or functionality testing, both of which are slower and have to be used off-line.

An experimental programme has been undertaken and the influence of the screen printing process parameters on line width, cross-sectional area and cross-sectional shape has been investigated. New measurement methods have been determined to extract and evaluate the appropriate information from the printed images and allow full analysis of the results.

1.6 Structure of the thesis

The thesis is split into six chapters. Their content is outlined below and Figure 1.7 shows how the chapters link together.

Chapter 1	An introduction to screen printing and fine line printing.
Chapter 2	A review of relevant literature.
Chapter 3	Description of the experimental programme conducted, including the instrumentation used, to investigate the effect of screen printing process parameters on fine line reproduction.
Chapter 4	The development of measurement techniques to objectively characterise the size and continuity of a printed line. This enabled the investigation into the experiment described in Chapter 3.
Chapter 5	The investigation of process repeatability and effect of process parameters on fine line reproduction. Within this chapter the results are presented and discussed.
Chapter 6	Conclusions and recommendations.

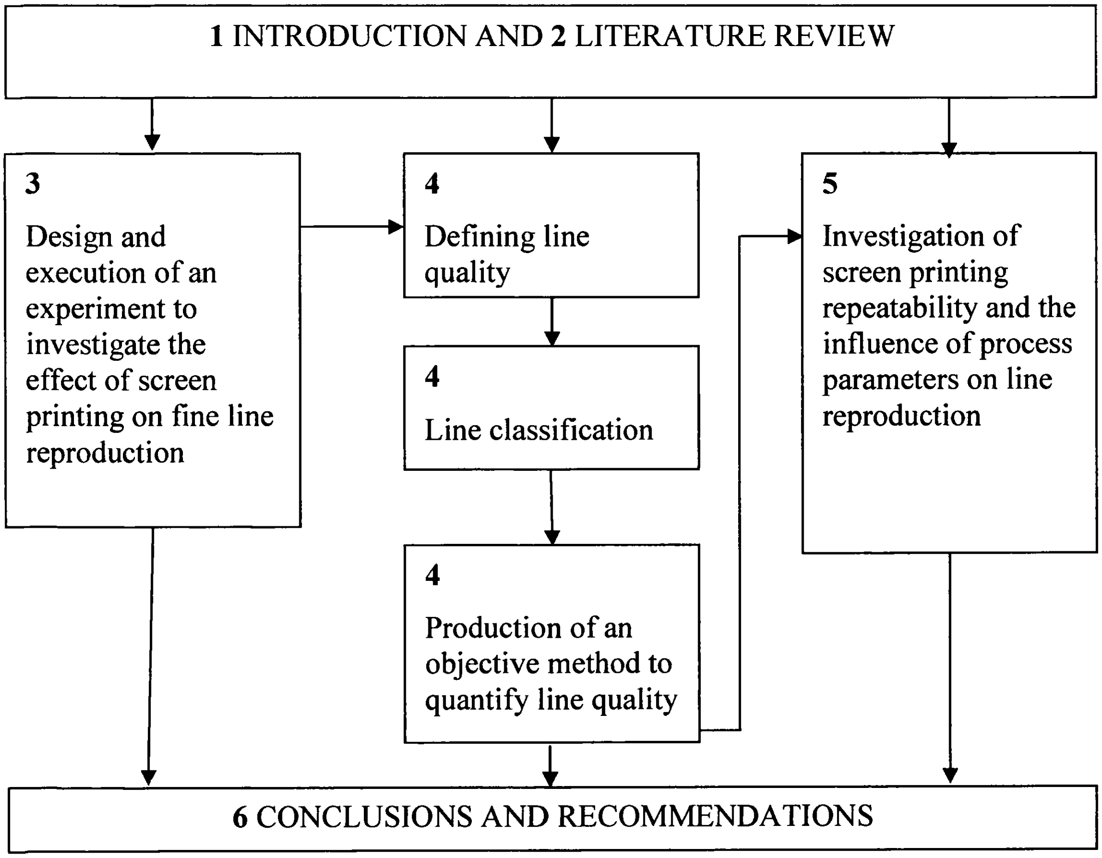


Figure 1.7 : The structure of the thesis

Chapter 2

Literature Review

2.1 Introduction to the literature review

This section describes and discusses previous work into screen printing and fine line reproduction. A knowledge of the current understanding into the screen printing process for the reproduction of fine lines is built up. This is used to determine the most appropriate screen printing process parameters to investigate within this study. The development of a full understanding of the screen printing process is required to determine the reasons for the patterns in the results obtained.

The work is described in four sections; the effect of process parameters on ink transfer, the effect of process parameters on fine line reproduction, fine line measurement techniques and the mechanics of ink transfer in screen printing.

2.2 Ink transfer and image quality in the graphic screen printing industry

The work described here concentrates on practical experiments to show the effect of screen printing process parameters on ink transfer conducted for the graphic screen printing industry. This work is included as knowledge of parameters affecting ink transfer are equally important to graphic and industrial screen printing. The work into image distortion was related to phenomenon found by this research project.

2.2.1 The effect of process parameters on ink transfer

In the graphic screen printing industry ink transfer is measured, in the main, by using optical methods. The two parameters used are solid density and tone gain. Solid density is a measure of darkness (absorption of light) of the printed region, whereas tone gain is a measurement of the increase of ink laid down compared the required amount (10, 11). The ink height is also used as a physical measurement of ink transfer.

The mesh is considered by most screen printers to have the greatest effect on ink film thickness (11). The mesh can be considered to be an array of cells, created by the gaps in the weave of the mesh. A simplistic explanation of screen printing is the flowcoater fills the cells with ink and the squeegee then forces the mesh onto the substrate and ink is drawn out of the mesh as it snaps-off the substrate. Thus, changing the size of the cells affects the ink transfer; more ink held in each cell equals more ink transfer. Therefore, a mesh with thicker threads and a larger open area produces a larger ink film thickness. Changing the thickness of the stencil also alters the thickness of the screen, although only for half-tone and fine lines. In practice, this can only be achieved for direct emulsion stencils; with the more layers applied the greater the ink film thickness.

Holh and Hunt (12) carried out an investigation into ink film thickness. In their study, they examined the use of nine meshes and printed using ultra-violet cured ink. The ink film thickness was plotted against the mesh count, this is shown in Figure 2.1. Up to a mesh count of 250 threads per inch, a decrease in ink film thickness was found. At higher mesh counts the ink film thickness hardly decreased. The study did not examine mesh height and a closer examination of the results shows that the thread diameter changed a lot for the meshes with mesh counts up to 250 threads per inch, but changed by only small amounts for the higher mesh counts. A better way to analyse the results would be to consider the effect of mesh volume or height on ink film thickness (12).

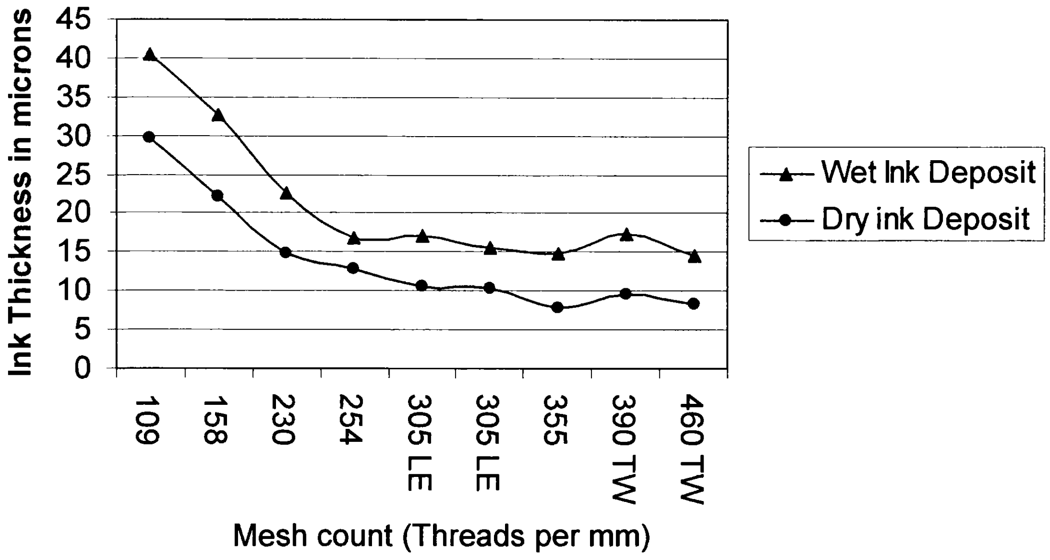


Figure 2.1: Mesh count and ink film thickness (12)

T Barden examined the effect of screen printing parameters on ink film thickness and ink transfer (13). The screen printing process parameters investigated were ink type, stencil type, mesh tension, squeegee hardness, snap-off gap, squeegee angle, squeegee speed and squeegee pressure. The ink type was the most significant of the parameters investigated. Other parameters that had an effect were (13):-

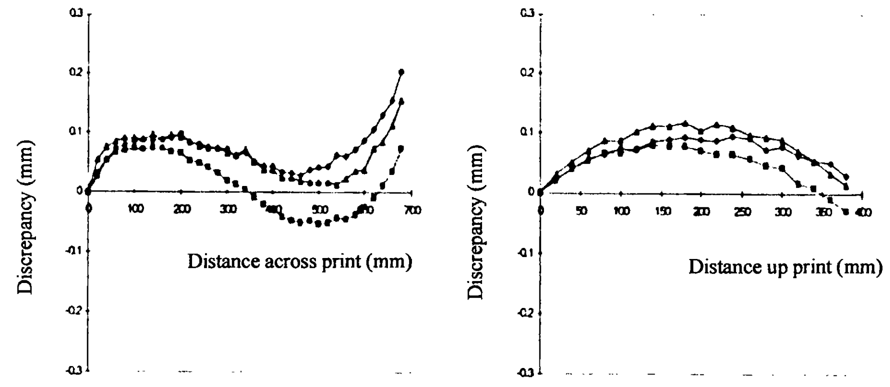
- The squeegee angle. Angles closer to the horizontal produced more ink transfer.
- Squeegee type. Soft squeegees produced more ink transfer than hard ones.
- Increasing the squeegee speed and pressure increased ink transfer but by a lesser extent than changing the angle.

2.2.2 Image distortion in screen printing

Donald Marston, in an article in Screen Printing magazine, discusses the use of Rz, defined in Chapter 1, as a method to measure surface roughness to quantify the quality of a stencil (14). Rz is a measure of the underlying waviness of a surface. It was suggested that to obtain good edge definition, a stencil must have a low Rz value; less than 10 microns and that capillary film stencils are within this range. To obtain a smooth surface using direct emulsion stencils several layers must be applied to the underside of the screen. The study compared different coatings of direct emulsions and capillary film stencils. It concluded that capillary film stencils had lower Rz values, than the direct emulsion stencils, no matter how many coatings were applied.

Claypole et al studied the screen printing process to determine the significant process parameters on image distortion (15). The parameters examined were mesh tension, print speed, mesh ruling, squeegee angle, the ink and squeegee hardness and pressure as a combined variable. The size of the printed image was compared to the original film image by accurately measuring the positions of cross-hairs on the print. This was achieved for the print and transverse directions and the discrepancy in the position between the printed sample and the original image on the film was calculated.

Figure 2.2 shows representative trends found for the discrepancy in the transverse and print direction. Large positive strains were found in the print direction, but the strain was small or negative in the transverse direction. This work highlighted the differences between the transverse and print direction and shows that the problem of image distortion is not a one-dimensional effect.



(a) Transverse direction

(b) Print direction

Figure 2.2 : Representative plots of discrepancy in image

2.3 The effect of process parameters on fine line printing

Previous work investigating the influence of screen printing and stencil printing process parameters is reviewed within this section, due to the similarities of the two processes. The main differences, being the screen as there is no mesh in stencil printing, just a stencil. Also the thickness of the liquids used to print with. Stencil printing tends to use a much thicker liquid, with a higher solid content, than in screen printing and is often called a paste.

2.3.1 Squeegee and press parameters

In 'Squeegee deformation study in the stencil printing of solder pastes' Hannan, (16), concentrates on the role of the squeegee in the stencil printing of solder pastes. Specifically, the study examines the deformation of the squeegee into the stencil aperture and how this affects the height of the solder paste printed. It was assumed that when the squeegee passes over the stencil it is pushed slightly into the top of the aperture. This scoops out some of the paste in the aperture, thus reducing the amount of paste deposited onto the substrate. This occurs since the amount of ink in the aperture directly affects the amount of paste deposited onto the substrate.

Six squeegees were examined. These were one metal blade squeegee, three squeegees of differing shore A hardnesses, and two which had stiff material along the length, but soft tips. All the squeegees were set at a nominal angle of 60 degrees to the stencil. The height of the printed paste was measured for several aperture widths, lengths and pitches. The line orientations used were parallel, perpendicular and 45 degrees to the print direction and readings from all three orientations were averaged.

The experimental study found that the softer squeegee produced less paste height and, thus, more scooping. Also, metal and hard squeegees were consistent for all aperture sizes, but the softer squeegees produced erratic heights at several aperture sizes.

Hastlehurst, (17), used an orthogonal array to examine many parameters in the stencil printing process. The aim of the study was to find the most significant parameters and examine the interactions between them. Parameters associated with the printer and the stencil were investigated. All the parameters were set to two levels. The same paste was used for the whole experiment. A correlation between mass of paste and line height was also investigated. The same initial mass of paste was used before each of 16 runs. Measurements of line height at two fixed places on each deposit were taken. Also, the mass was found of each board before and after printing.

The results were analysed by analysis of variance analysis (ANOVA), (18). The study found that there were five main process parameters. These are aperture width, print direction, squeegee pressure, aperture orientation and pitch. Aperture width was the most significant process parameter. Hastlehurst suggested this was due either to paste being trapped in the small apertures or they were not filled properly. This would result in less paste being transferred to the substrate. Also, pressure was a significant parameter. Too much squeegee pressure, as described previously (16), produces scooping of the paste, thus reducing line height. Lines placed parallel to the squeegee blade produced larger line heights than those placed at ninety degrees. The pitch also had an effect. The closer pitch lines were not as high. This implies that the paste roll may be affected by line pitch. The study also investigated interactions between the parameters, but these were found to be insignificant compared to parameter effects.

Pan, (1), examined the effect of four press parameters on the screen printing process. These were squeegee pressure, squeegee hardness, snap-off gap and squeegee speed. These were examined using orthogonal array techniques, (18), to examine each parameter at two levels. An experiment with all the parameters set to a middle level was also printed. The test image contained parallel lines of equal width and spacing, at 0.125mm, 0.2mm and 0.25mm, placed parallel and perpendicular to the print direction. The space width, and its deviation from the mean value, was used to examine the lines. This is the distance between two adjacent lines. For lines perpendicular to the squeegee direction, there were too many connections between the printed lines to take repeatable readings.

Thus, this study showed that there was a difference between different line orientations, but was unable to quantify it. The results were examined using analysis of variance analysis (ANOVA), (18), to find the statically significant parameters. This technique showed that squeegee hardness and speed had a significant effect with a 95% confidence level. For lines parallel to the print direction, squeegee speed was significant on space width deviation. Higher squeegee speed increased the space width deviation. Squeegee hardness is the most significant parameter and hard squeegees are best for fine pitch printing. Snap-off and squeegee pressure had no significant effect, but may be affected by different screen tensions.

2.3.2 Ink, Substrate and screen

Bertrams, (19), undertook an experiment to examine line width and concluded that the screen and ink influenced the screen printing process more than the press settings. Betrams considered the influences on the ink for all parts of the process from the movement of the squeegee to the ink drying on the substrate. During the movement of the squeegee the viscosity of the ink is important as the ink has to flow, and fill, into the mesh. Viscosity is also important to enable good separation of ink from the mesh.

At the point of ink transfer three forces act on the ink. These are the adhesion forces between the ink and screen, the adhesion forces between the ink and substrate and the cohesion forces within the ink. These forces are shown in Figure 2.3. The balance between these forces determines the quantity of ink that is pulled from the mesh and is left on the substrate after printing.

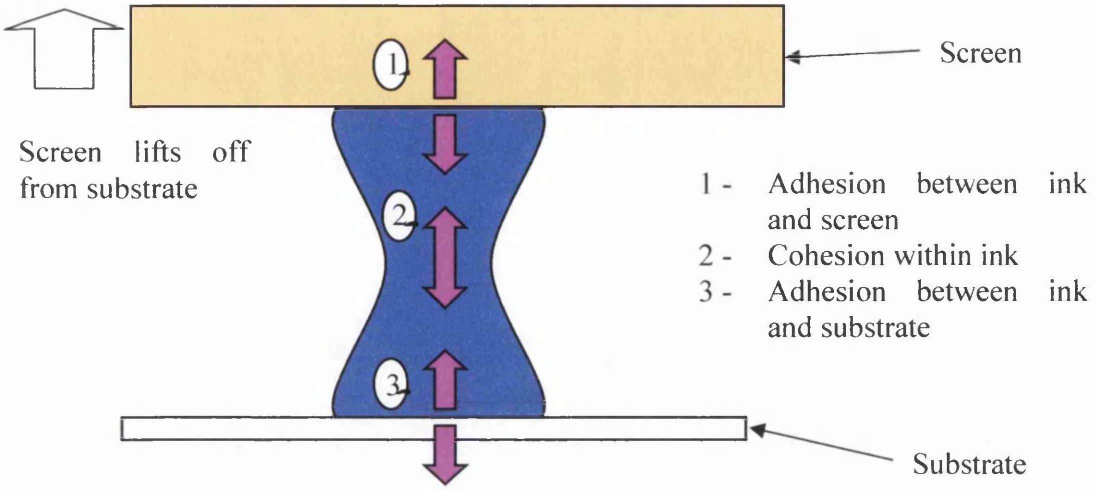


Figure 2.3 : Schematic of Forces that exist as the screen pulls away from the substrate

After printing gravity and surface tension affect the height and width of the printed line. Betrams gave a coefficient of spread, S_c, to define the spreading of the ink after printing, Equation 2.1, although this is Dupre's Equation (20), where S_C is actually the work of adhesion between the solid and the liquid. This is the work required to separate the liquid and solid interface.

$$S_C = \gamma_{SA} - (\gamma_{SL} - \gamma_{LA}) \qquad \text{Equation 2.1}$$

Where,

γ_{SA} = Surface tension of solid in air

γ_{SL} = Interfacial tension of solid and liquid

γ_{LA} = Surface tension of liquid in air

Liang examined the effect of surface energies on the resolution of screen printing, (3). The wetting effect of the ink on the substrate is important in screen printing. If the ink runs too freely then the line will spread increasing its width. This leads to parallel lines, printed closely together, connecting and thus reducing the printable resolution. In contrast, if the ink does not flow sufficiently freely, the ink will not take up the gaps caused by the mesh and there will be gaps in the line, or large reductions in width. A liquid with a low surface energy will wet a substrate with a high surface energy. The study examined 3 inks printed on 6 types of substrate. This gave a large range of relationships between the surface energy of the solids and the surface tension of the liquids. Six line spacing widths ranging from 100μm line width and gap to 250μm line width and gap were used to examine resolution. Lines of a design width of 150μm were used to examine line width.

Several conclusions followed from Liang's work. A reduction in the wettability of the substrate and ink can improve screen printing resolution. For high surface energy substrates, where wetting occurs readily, the use of high thixotropic inks will improve line resolution. For low surface energy substrates, wettability is more important. High line resolutions can still be achieved, even with low viscosity inks, if the critical surface tension of the substrate is less than the surface energy of the ink, (3).

In 'Solder Paste for Fine Line Printing in Hybrid Electronics', Rocak, (21), examined 4 solder pastes for fine pitch printing. The pastes were initially tested for solder balling, wetting, slump, corrosion and insulation resistance. The pastes were then printed to examine their effect on line quality. Two variables were examined, these were print speed and stencil thickness, both at two levels. A visual inspection, using the human eye and giving a mark out of three, was used to assess line quality. The thickness of the paste applied and the line width before and after firing in an infrared furnace was measured. The results showed that, for a higher squeegee speed, the thickness increased, for most of the pastes. This effect was found to be greater for the larger stencil thickness.

Rodriguez and Baldwin investigated the fundamentals of the stencil printing process, (22). Their aim was to analyse and expand the knowledge of the paste release mechanism. Their objective was to identify critical factors and produce a model to estimate printed volume. Two phases of the experiments were completed. The first was designed to find the significant parameters. The second was to examine the important parameters for interactions. Six parameters were identified for the first phase, these were stencil thickness, aperture shape (circle and square), area ratio, paste viscosity, separation speed and particle size. Area ratio is the area of the aperture divided by the area of aperture walls. A two level fractional factorial experiment was used. The stencils were printed using a metal squeegee set at 45 degrees. The prints were measured using a non-contact laser metrology tool. This was used to find the height, the width and the cross-sectional area of the lines, but the prints were evaluated by examining printed volume compared with the volume in the aperture as a percentage.

The three most significant factors were area ratio, stencil thickness and particle size. The experiment was designed to investigate the limiting factors on solder paste release, so the aperture size was designed so that adhesion forces of the paste to the stencil and substrate were similar. There are two modes of stencil release. If the adhesion forces to the substrate are greater than the adhesion forces to the stencil then a large proportion of the paste is deposited. If the adhesion forces of the substrate are less than the adhesion forces to the stencil then much of the paste remains in the stencil and a small proportion of the paste is deposited. The two aperture ratios chosen for this study represent these two conditions. Particle size and stencil thickness were also significant. An increase in particle size leads to a decrease in printed volume. An increase in stencil thickness leads to an increase in printed volume. The ratio of particle size to stencil thickness is the important factor. Studying the interactions, the study shows that the particle size needs to be less than one third of the stencil thickness to produce a ninety percent deposit. This was also shown by Morris and Wojcik (23). The shape of the aperture was also shown to be significant. For a square aperture, paste can be trapped in the corners, allowing less paste to be released.

Morris and Wojcik examined solder paste for stencil printing and produced five tests to characterise the properties of the paste at different stages of the printing process (Figure 2.4). Test 1 measures the shear stress before a rheological break down. This determines how squeegee parameters affect the viscosity and the printing process. Test 2 measures the thixotropy, the ink must shear thin so that it flows into the small spaces in the stencil. Test 3 measures the cyclic thixotropy. Tests 2 and 3 together measure how easily, under printing conditions, the paste fills the stencil prior to printing. Test 4 measures the yield point of the paste. This measures how easily the ink will fracture as it is drawn out of the stencil. Test 5 measures the inks dependency on temperature.

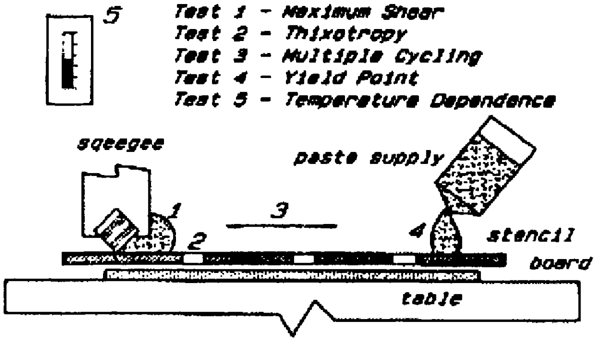


Figure 2.4 : Rheological tests for solder pastes and their relationship to the stencil printing process (23)

2.3.3 Discussion

Although stencil printing is very similar to screen printing, some of the basic differences mean that parameters have different effects on the two processes. Squeegee hardness is one of these. In stencil printing, the scooping caused by soft squeegees produces less ink transfer. In screen printing, softer squeegees produce more ink transfer. This is due to the bending and changing of the angle of the squeegee. Squeegee pressure is also a parameter that has the opposite effect for screen and stencil printing, again this is due to scooping.

The aperture size is a parameter that has a similar effect for both processes. If the hole that is being printed through is too small then the ink will not release from the hole. The ink and substrate interaction is another parameter that has a similar effect on both process. The importance of matching the surface tension characteristics of both the ink, or paste, and substrate apply equally for screen and stencil printing. It can be concluded that the similarities between screen and stencil lie only in the mechanism of ink release and spreading after printing, not the filling of the screen or stencil. For factors that apply to the ink release and spreading, observations from processes can be applied to screen printing.

The screen printing press parameters examined for their effect on the process were squeegee pressure, squeegee hardness, squeegee speed and snap off gap. These were only examined for the space width and not the actual size of the line printed. A notable omission is the squeegee angle, that was shown by experiment (13) to have a large effect on ink transfer and tone gain. For this reason, it is expected to have an effect on fine line reproduction and should be examined. Most of the work on press parameters was also only in two-dimensions, but it is necessary for fine lines to examine cross-sectional area, not just line width. The orientation of the lines was shown to have an effect, but this was not characterised.

The ink and substrate have been characterised for screen and stencil printing. The ink viscosity and surface tension are some of the most significant parameters on the process. It is important to match the surface tension of the ink and surface energy of the substrate to ensure good release of the ink, without too much spreading after printing. If this is achieved line resolution for screen, or stencil, printing can be optimised. The printing process can be broken down into three stages that can be used to characterise the ink.

1. **Squeegee movement.** During the print stroke the viscosity or thixotropic properties of the ink are significant. The reduction of the ink viscosity during the print stroke helps the flow of ink into the mesh. This is shown in Figure 2.5.

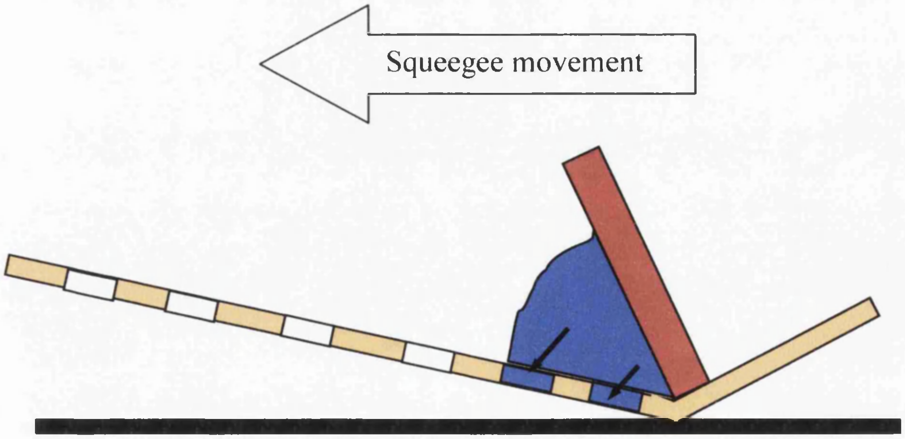


Figure 2.5 : Flow of ink into the mesh.

2. **Point of snap.** As the screen pulls away from the substrate, there are three forces that are significant; adhesion between ink and screen, cohesion within ink and adhesion between ink and substrate. Thus, the important characteristic of the ink is surface tension.

3. **After printing.** The surface tension of the ink, compared to the free surface energy of the substrate, will affect the amount of spreading after printing.

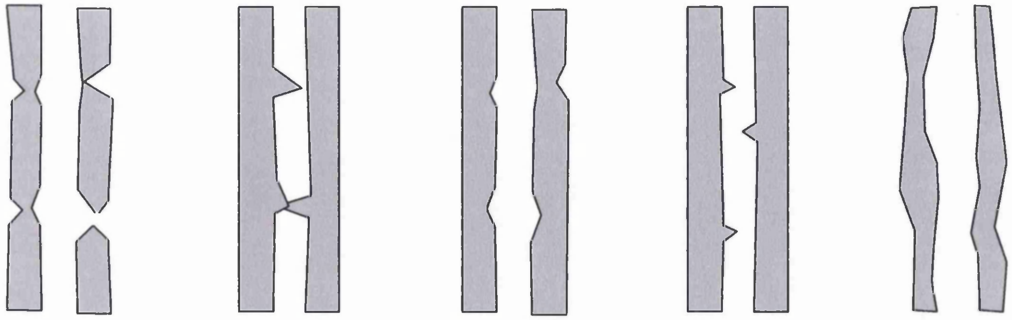
The screen or stencil is used to hold the ink or paste prior to the release of it onto the substrate. It has a large effect on ink film thickness. A thicker screen can hold more ink and will therefore deposit more onto the substrate, with a higher ink film.

2.4 Line measurement techniques

2.4.1 Review of measurement techniques

Webster, (24), used a 'defect criteria' to distinguish between 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 2.6.

- 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.



Opens Shorts Partial opens Partial shorts Insufficient paste

Figure 2.6 : Illustration of Webster's defect criteria, (24)

Bertrams, (22), examined the increase in width of the dried conductor line compared with the mask line width on the screen. This difference was called the line widening. No mention is made of the method used to measure the line width, whether it was visual or physical, or any apparatus used. The number of readings taken or the length along the line was also not mentioned, only that an average was taken.

In 'Solder Paste for Fine Line Printing in Hybrid Electronics', Rocak, (21), 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 examined fine line printing for screen printing, (1). Measurement of the height of the lines was attempted, but this was unsuccessful due to the limitations of the equipment available. 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 examined the solder release mechanism in stencil printing, (22). 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 carried out using a non-contact laser metrology tool. The actual quality of the print was evaluated using the percentage volume of the paste deposited on the substrate. This is calculated as 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.

2.4.2 Discussion of measurement techniques

Several techniques have been used to measure the quality of fine line reproduction. The basic measurement parameters are line width or line 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 line quality parameters 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 achieved this by examining the printed line width or space width. The five defect criteria described by Webster, (24), would be a good system for statistical process control. These parameters, or similar, should be considered in any measurement system. Rodriguez, (22), 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 are be related. This has a scientific value, to further process understanding, especially when trying to develop a model of the process as Rodriguez was. There are, though, more simple ways to measure the quality of the printed image.

The majority of the measurement techniques have been in two dimensions (line width), but to examine fine lines a measurement of cross-sectional area is necessary and this requires the three-dimensional measurement of the line profile. It is important to measure both the line size and the continuity of the line along its length. An objective three-dimensional measurement system is required to be designed. This must be a repeatable and reliable method of characterising fine lines.

2.5 Review of mechanics of ink transfer and screen printing models

2.5.1 Introduction to the mechanics of screen printing

Screen printing can be considered to have two stages; the filling of the screen with ink and the release of the ink from the screen onto the substrate. The first two papers described concentrate on the release of the ink from the screen. In the years following this, most of the work carried out concentrated on the flow of the ink into the mesh and the pressure in the bow wave in front of the squeegee. Attention then turned back to the ink release.

2.5.2 Review of theories on ink transfer in screen printing

The first of Riemer's papers analyses two parts of the screen printing process (25). The mesh and stencil were investigated to determine their effect on ink transfer, as well as the forces on the ink at the point of ink transfer.

Riemer consider the screen to be the major influence in ink transfer and other parameters are ignored. First, the mesh was examined to determine the volume of ink it can hold. This is assumed to be the ink volume printed. From this, the height of the ink film can be predicted. This is based on the complete transfer of ink from the mesh. This is not an accurate estimation of the ink printed as ink is left on the screen and it assumes the squeegee does not deform into the mesh and that the threads do not distort under tension.

The effect of the stencil was also examined and Riemer predicts a one to one scale of the thickness of stencil to the increase of ink height printed, i.e. a 1 micron increase in stencil thickness would produce a 1 micron increase in printed film height. Edge effects of the stencil are described. He states that ink height is less away from the stencil because the mesh height is less than the height of the mesh and the stencil.

Riemer, also, considers the mechanics of ink transfer. The printing process is described in two parts

- Filling the mesh during the squeegee stroke
- Ink pulled out of the screen during the snap-off

For good ink transfer, the forces between the ink and the substrate have to be strong enough to pull the ink from the mesh. Riemer considered the ink elongates as the mesh pulls away from the substrate and at the thinnest point in the ink, the maximum tensile strength is exceeded and the ink separates. For good ink transfer, the ink is required to stick to the substrate. This is known as ink wetting and is a function of surface energy. Although, if the ink sticks well to the substrate, the ink will also stick to the screen. The physical evidence for this is that some of the ink is left in the mesh after printing. It is, therefore, reasonable to conclude that the ink separates within itself, not from the mesh surfaces. The position of the minimum thickness will determine the amount of ink released. Riemer derives a formula for the ease of ink release. An ink is given a number dependent on mesh count and mesh thickness. For good release, an ink should have a high adhesive strength to the substrate and a low tensile strength.

Messerschmitt (26) considered why ink does not separate totally from the screen and adheres to the substrate. Previous theories are examined.

- The breaking of the bond in the ink does not happen due to the relative areas of the screen and mesh. The area of the screen in contact with the ink is much larger than the area of the substrate.
- The ink does not flow through the screen because of the pressure from the squeegee, as ink can not flow under the screen due to the seal between the stencil and substrate.

- Ink release does not occur due to gravity, since screen printing can be carried out up side down.
- Ink release has little to do with air pressure and the ink being sucked out of the screen, since screen printing can be carried out in a vacuum.

Having discredited these theories Messerschmitt describes his own.

Messerschmitt's argument is based on the importance of tensile fracture of the ink. The squeegee fills the mesh with ink. The mesh is divided into cells, which hold the ink, called cups. The top surface of the ink is created by the squeegee and surface tension. At the point just after the squeegee, the mesh and substrate are held together by the ink. Three forces are present at this point; adhesion between the ink and substrate, adhesion between the ink and mesh, and the surface tension on the top surface of the ink. As the mesh is drawn up, during the snap-off, the ink acts as a ductile solid. The adhesion forces between the ink and mesh and substrate are great and do not break. The raising of the mesh induces flow in the ink as it tries to maintain a constant volume because of the internal cohesion forces in the ink. This changes the shape of the ink. As the mesh is drawn up, further tensile forces holding the ink to the screen oppose the cohesion forces in the ink. This creates a shear stress in the ink near the mesh. The shear forces tear the ink away from the mesh leaving only a small amount of ink on the screen.

Both Riemer and Messerschmitt put forward arguments on how ink is released from the screen onto the substrate. Riemer considered tensile properties of the ink to be more important, whereas Messerschmitt considered shear stresses in the ink to be the most significant. In the years following the concentration of research was on the ink flow into the screen and mesh, and not the release of ink onto the substrate.

Riemer wrote three papers from 1985 to 1988, (27, 28, 29), concentrating on ink flow into the screen. The first, (27) examines the use of the Navier-Stokes equation to derive a solution to the pressure distribution within the bow wave of the squeegee. The movement of the squeegee generates hydraulic pressure in the ink in front of the squeegee. The screen printing process was assumed to be an inclined plane moving over a high viscosity fluid on a stationary horizontal surface. Riemer considers this pressure important in screen printing as it pushes the ink into the mesh and supports the squeegee. If the hydraulic pressure was increased, then the squeegee would bend more. This would result in a thicker print since the squeegee would not penetrate the mesh as much. Thus, press parameters that caused an increase in hydraulic pressure would increase the ink film.

Riemer extended this work in 1987 and 1988 (28, 29). Riemer postulated a theory to explain why more ink is left on the substrate than in the screen. The mesh was considered as an array of small tubes. Ink particles were concentrated in the centre of the tubes, due to collisions that occur in the ink that pushed the particles to the centre of the tube. During the printing process a vehicle rich layer stays attached to the mesh, lubricating the flow of particles in the centre of the tubes. To provide evidence for this Riemer examined the particle content of the ink on the substrate and on the mesh after printing. This showed a larger particle content on the substrate than in the mesh. Riemer also described a release mechanism for the ink. This was based on a vacuum forming under the mesh threads during snap-off. Although, Messerschmitt had already discredited vacuums as the reason for ink release in the screen printing process (26).

Huner examines screen printing as a blade coating process (31). His study describes the theory of blade coating and then the similarities between this and screen printing. The blade coating process consists of a substrate moving under a short inclined plane. The coating liquid flows under the plane, due to the movement of the substrate, and is tapped at the height of the blade. This is shown in Figure 2.7. Huner decides to use Newtonian fluid for his models. The solution is based on the Navier–Stokes equation in 2 dimensions for Newtonian flow. This was solved to find the height of the ink left on the substrate after the coating process. Results showed that the height of the flow is dependent on the geometry of the system and not on the speed or viscosity of the inks.

It is known that the ink characteristics and the speed of the squeegee are some of the more significant parameter effects in screen printing (1, 9). This leads to questions on the validity of assuming screen printing to be similar to blade coating. The next part of Huner's study examines the differences between screen printing and blade coating theory.

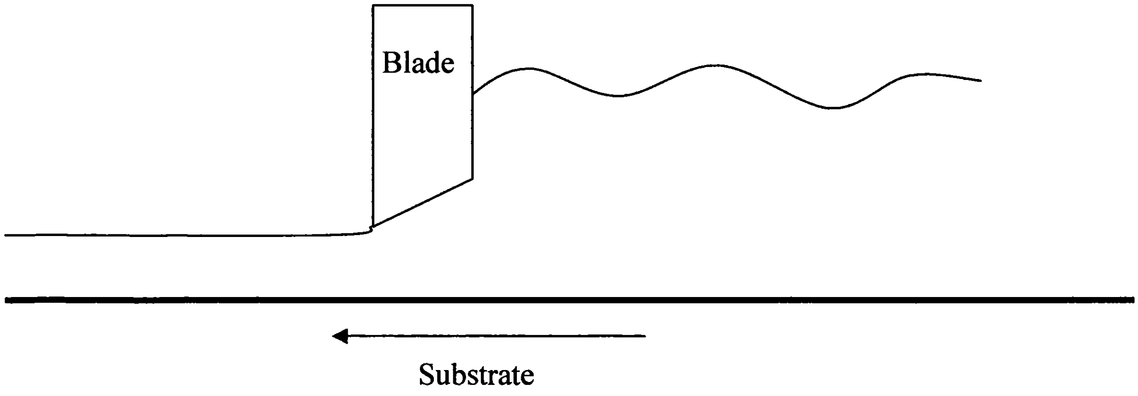


Figure 2.7 : The essential features of a blade coating apparatus (31)

Huner argues that if the mesh count is low and the screen has a high open area, then the screen only acts to separate the squeegee from the substrate. Thus, ink is not considered to flow through the mesh and blade theory should apply to screen printing. Huner does note that this is not the case near the stencil and will only work in areas of open mesh. Huner then goes on to examine Riemer's theory using the Taylor solution of the Navier – Stokes equation to the wedge flow problem and compares it with the conditions that exist in the ink roll in front of the squeegee.

Huner discredits Riemer's theory on two counts. Riemer assumes the screen to be smooth and impermeable satisfying no slip boundary conditions. This may be true of an almost completely masked screen. This does, though, produce a pressure singularity at the squeegee tip unless stress is relieved in some way. Riemer states that this is relieved due to turbulence and Non-Newtonian behaviour of the inks. Huner argues that turbulence is a high speed phenomenon and does not occur with Navier-stokes equation. Hydroplaning is a better solution but, in order for hydroplaning to occur, then a gap must appear at the squeegee tip. This would no longer satisfy the Taylor solution. The Taylor solution also breaks down at the edge of the ink roll. Here inertial effects are significant and are neglected in the Taylor solution. Huner, therefore, postulates a new theory to examine the pressures and ink flow in screen printing. For this purpose he splits the ink roll into three regions

- The squeegee tip
- A middle region where the Taylor solution applies
- An outer region which includes the free surface of the ink

Huner's paper tries hard to discredit Riemer's theory, but neglects many key aspects of screen printing. Huner argues that the open area of the mesh is large and that the screen only acts to separate the squeegee and substrate. This is a large assumption, especially since most meshes have an open area of less than 25 or 30 percent. The screen for most applications is probably more similar to Riemer's approximation to a smooth and nearly totally masked screen, especially when printing fine lines, than Huner's idea of an almost complete open mesh. Huner has completely neglected the Non-Newtonian aspect of the screen printing process. Riemer uses Non-Newtonian flow to relieve the stress in the squeegee tip causing infinite pressure at this point. Huner's idea of the three regions of the ink roll is used in several of the next papers on ink flow, but neglecting the shear thinning effect of the ink is a large assumption.

Owczarek and Holland (32) wrote a paper examining the screen printing process and tried to improve Riemer's theories on ink flow in the ink roll. He examined flow patterns and concluded that ink was pushed through the screen ahead of the squeegee. Physical evidence and tests backed this up. Interrupted printing tests were performed. The squeegee was stopped suddenly during the print stroke and removed. The print was examined by a profilometer to show the height and shape of the ink on the print. This suggested that there was pre-printing through the mesh in front of the squeegee. Using this profile, the deformation of the squeegee into the mesh during printing was estimated. The study used the original formula postulated by Riemer (25) in 1971 to find the ink held in the mesh. This time, though, the deformation of the squeegee into the mesh was taken into account.

Huner examined the deflection of the squeegee along its length in two further studies (33, 34). He modelled the squeegee as an inclined cantilever beam clamped at one end and a force applied at the other end exerted at an angle. This force is dependent on the force of the squeegee on the screen, the frictional drag force and the normal and tangential fluid stresses. These are reduced to two main forces; the force at the squeegee tip and the fluid pressure. Analysis of this produced an equation with no analytical solution. The equation was, though, in 2 parts, a part relating to the elastic stresses on the squeegee and a part relating to the squeegee speed and ink viscosity.

Jewel examined the hydrodynamic and drag forces that occur during the movement of a squeegee in screen printing (35). This was achieved by solving the problem of Non-Newtonian hydrodynamic lubrication. The parameters analysed were squeegee hardness, ink viscosity and squeegee load. Experiments were performed on a rig consisting of a rotating belt onto which a squeegee could be pressed. The report found that the drag force dominated the hydrodynamic forces. Thus, increasing the squeegee load had a greater effect on the drag force than increasing the squeegee speed. Increasing either squeegee angle or ink viscosity increased the drag force. Softer squeegees produced higher hydrodynamic pressure at low speeds. Hydrodynamic force decreased with an increase in speed and increased with squeegee angle.

Fox et al. examined a new idea of using a roller instead of a conventional blade squeegee (36). A model was produced to predict the deposit thickness of halftone coverage. It examined the hydrodynamic pressure created in the nip junction between a compressible roller and a porous screen. This relies on a fluid film existing between squeegee and screen. One conclusion found by comparing data between a rigid blade squeegee and a roller squeegee was that the roller squeegee produced a higher pressure at the nip. The model showed good a agreement to experimental data from actual prints up to 50% halftone. For the actual prints the deposit height for 50% halftone to a solid remained constant. From this Fox concluded that the height of the deposit was governed by the hydrodynamic pressure in the tip up to about 50% halftone. Above this the hydrodynamic action does not govern the process since the fluid film fails to exist. The squeegee rests on the screen and the height of the thickness is governed by the height of the screen.

The work done by Fox can be used to examine the theories put forward by Riemer (27, 28, 29) and Huner (31). Riemer considered the screen to be reasonably impermeable and capable of sustaining a fluid film similar to hydrodynamic lubrication. Huner considered that the mesh exists only to maintain a gap between the squeegee and the screen. Fox has shown that at low coverage, Riemer's theory seems to hold true and that, when printing high coverage, Huner's theory seems to govern the process. Fox found that for the roller squeegee, the transition took place around 50% coverage. This, though, may be different for a blade squeegee, which is not capable of sustaining the same hydrodynamic pressure. Image resolution is likely to have a large effect on this as well.

The idea of the squeegee working as a hydraulic pump and affecting the printed image has been examined thoroughly. The next two papers examined describe models that assume the squeegee exists only to push ink into the screen and press the screen onto the substrate. The important forces of ink transfer occur at the point the screen snaps off the substrate. This is a return to the initial theories postulated by Riemer (25) and Messerschmitt (26).

Having completed an extensive experimental program, Rodriguez and Baldwin put their work into a model to predict the volume deposited in stencil printing (22). Through their experimental work, they identified three modes of paste release.

- The complete release mode occurs if the adhesion of the paste to the stencil was significantly less than the adhesion of the ink to the substrate. For this mode, most of the ink is deposited. It occurs if the area ratio of the aperture is large. In practice, it is recognised by the paste trying to separate completely from the aperture walls.
- The shear release mode occurs if the adhesion of the paste to the stencil is stronger than the adhesion to the substrate. A necking of the ink precedes splitting of the ink. Failure occurs due to shear stresses within the ink becoming larger than the ultimate

tensile strength of the paste. In this case it was considered that the paste behaves more similarly to a solid than a liquid at the point of release.

- Adhesion failure release mode occurs if the squeegee pressure is too small to properly wet the substrate.

The aim of the study by Rodriguez and Baldwin was to produce a model to predict paste volumes for the shear release mode. To do this, the forces that occur in the paste during the release of the paste were analysed. The forces are considered in a similar way as Riemer in 1971 (25). The three main forces examined were adhesion between substrate and stencil, cohesion within the paste, and adhesion between the paste and substrate. A detachment force is considered, which is the force required to detach the paste from a surface. If the detachment force is greater than the adhesion force then the paste will detach from the surface. During the release mechanism, the detachment force is applied parallel to the surface, thus frictional forces also play a part. The static and dynamic forces are different. For slip between the paste, and the surface first a detachment force has to be applied that is greater than the adhesion force. The force required to maintain slip, which needs only to overcome friction, is smaller than the force required for detachment. Thus, once the paste has begun to slip over the aperture walls, the stress at the interface reduces and the paste slips more easily.

The shear release model uses the existence of a yield stress and the viscoplastic tendencies of the paste. The paste is assumed to be rigid until a force is applied that produces a shear stress greater than the shear yield stress of the paste. At this point, the slip shear stress will act on the stencil walls rather than the adhesion stress. The slip stress is smaller than the adhesion stress. Once this occurs then the paste is released completely from the stencil. Elemental stress analysis is used to build up a model of the paste release to predict the percentage volume of paste deposited. The model shows a good approximation to experimental data.

Abbot (37) uses the idea formed by Messerschmitt that the dominant forces in ink transfer occur during the snap-off of the screen to create a model to predict ink transfer for screen printing. Abbott describes the process of ink transfer as 'infiltration of a free surface through a three-dimensional structure'. The model uses the theory of the formation of meniscuses to predict the amount of ink transferred. Several assumptions are made to simplify the model.

- The flow is only considered in 2 dimensions.
- The threads are considered to be cylindrical.
- The liquid is considered to be incompressible.
- The squeegee blade is rigid and fills the screen completely with no deformation into the screen.

The model assumes that the free surfaces of the ink conform to their radius of curvature and ink splitting occurs when the free surfaces meet. This is shown in Figure 2.8. The data obtained from the model was compared to SPTF (Screen PrintingTechnical Federation) data on ink deposit verses mesh count (12). The model was found to predict results reasonably compared to the experimental data.

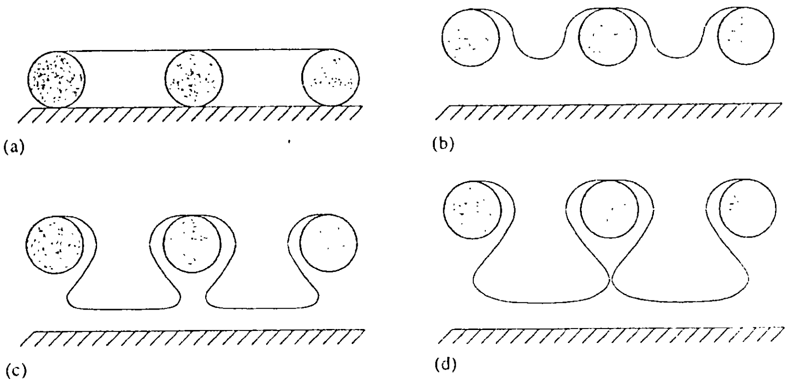


Figure 2.8 : The predicted evolution of the meniscus as it travels through a mesh (37)

Rodriguez and Abbot took different approaches to the idea that the main influences on screen printing occur as the screen snaps off the substrate. Rodriguez examined three cases of ink release dependent on the size of the aperture and thus the ease of ink release. For fine lines, the shear release mode occurs, involving the necking of the ink as the screen is pulled off the substrate. Rodriguez modelled this by elemental stress analysis of the shearing of the ink. His assumption that the shear release mode is present during fine line printing is backed up by the work carried out on inks by Bertrams (19) and Liang (3) on the effect of surface tension on the release of the ink. Abbott did not use the adhesion and stresses within an ink, but the size of the meniscus formed as the mesh is pulled off the screen. Both of these theories have been verified under some screen printing conditions, but they cannot produce a complete model, since they do not take into account the filling of the screen. Thus, models that solely examine the release of the ink from the screen do not take into account some press parameters such as squeegee angle, pressure and type. These have been shown experimentally to affect ink transfer in screen printing (13).

2.5.3 Discussion of ink transfer in screen printing

Two schools of thought have been described and discussed in this section. One considers models that examine the squeegee pushing ink through the screen, the other considers the ink is pulled out of the screen as it snaps off the substrate. Each of these theories alone cannot describe the whole screen printing process. Three stages of printing are used to describe the use of the theories of ink transfer.

1. **Squeegee movement.** The squeegee moving over the mesh is an action that determines the amount of ink held in the screen. The screen thickness and the deflection of the squeegee affect the amount of ink in the screen. The amount the squeegee deforms is dependent on the hydraulic pressure generated under the squeegee. The process parameters that affect this are the ink viscosity, squeegee angle, squeegee speed, squeegee pressure and squeegee hardness. Two conditions were shown to exist for the modelling of the squeegee movement. Huner considered the mesh as porous media, this applies more to large open areas. The mesh can be considered non-porous and the squeegee rides on a thin film on top of the screen. This was examined by Riemer and Fox. Fox showed that this assumption produced a good approximation to experimental data for low coverage areas.
2. **Point of snap.** As the screen snaps off the substrate the ink is drawn out of the mesh. This determines the amount of ink, which is already present in the screen, that is

transferred to the substrate. This is related to the amount of ink held in the screen, since it is not possible to transfer ink that is not held in the screen. This is affected by, the surface tension of the substrate, the surface tension of the ink, the yield stress of the ink, the snap speed and the screen tension.

3. **After printing.** No models reviewed have taken into account the amount the ink spreads once it is on the substrate. This is affected by the surface tension of the ink and substrate.

This assumes a perfect seal between the screen and the substrate. For rough screens or substrates, ink leakage can occur under the screen during printing.

2.6 Discussion of proposed work

2.6.1 Introduction to proposed work

Previous work into screen printing is discussed to show areas that require research. The effect of some screen printing process parameters on the line quality required consideration. These are discussed in the first part of this section. The investigation into previous work into the reproduction of fine lines using screen printing prompted the questions 'what is a good quality line?' and 'how line quality could be measured?' Therefore, this section considers how these two questions could be answered. Much of the previous research has been conducted assuming a rectangular cross-section, measuring width only. This present study will examine the validity of this assumption and consider alternative measurement methods.

2.6.2 Screen printing process parameters

The work in this study aimed to increase the understanding of the effect of the process parameters, as well as to develop a repeatable measurement method. The screen printing parameters were chosen for two reasons. Parameters of known effect were chosen to prove the use of the measurement and analysis techniques developed. This enabled a comparison of the results found using the measurement and analysis techniques to previous data. Parameters known to affect tone gain and ink transfer were examined to increase the understanding of the process. The choice of the parameters is discussed below.

As discussed in Sections 2.2 and 2.3, several parameters associated with the squeegee are known to have an effect on ink transfer (13). The most significant squeegee parameters are squeegee angle, type, pressure and speed. Squeegee angle has been shown to have a large effect on ink transfer (13), but has not been examined for its affect on fine lines. The squeegee type is the next most significant squeegee parameter after squeegee angle. The squeegee speed and pressure have a comparatively small effect on ink transfer. The squeegee speed was shown to be the least significant of the four parameters (13, 17). The effects of the squeegee type, pressure and speed for stencil printing of fine lines have been examined in the past (16, 17). However these studies were not specifically for screen printing and have been shown to have a different influence on stencil printing, as opposed to screen printing. Thus, the effect of the squeegee angle, speed and pressure on fine line screen printing still required thorough investigation, since they are known to have an effect on ink transfer.

Previous studies into ink type have shown that it is one of the most significant parameters of all the screen printing process parameters. This has been shown for fine line printing (3, 19, 22, 23). The viscosity and the surface tension are the two ink characteristics that effect the printing process, so these need to be measured for the inks examined. Even though the effect of the ink is well characterised, it is useful to examine the ink to show the effectiveness of the measurement system. The ink type may have as significant effect on cross-sectional shape as it has on ink transfer.

The important characteristics of the screen are the stencil height and roughness (12). The height has been shown to have an effect on the ink transfer. The stencil roughness has been shown to have an effect on the edge quality of lines (14). This knowledge can be used to evaluate the capability of a line quality measurement system. The stencil characteristics were also considered likely to have an effect on cross-sectional shape.

Orientation is the angle at which the line is placed relative to the print direction. The effect of this on ink transfer and line quality has been studied, but not quantified (1). A thorough examination would allow the effect of orientation to be quantified.

2.6.3 Fine line measurement

Previously, line quality had been measured in several ways, but no work has been carried out to find a repeatable and reliable method to characterise the quality of fine lines. 'What characteristics make a line good or bad?' is a question that requires consideration. Webster (24) considered this, but his work relied on a measurement of the two-dimensional size of the line. This is not reliable for fine lines where the cross-sectional shape is not rectangular. This is because a two-dimensional analysis of line size relies on the assumption that the cross-sectional shape of the line is a rectangle.

Variation of the line cross-sectional size along the length of the line is also important. Some of the previous studies made several readings of line width, but with no description of why a particular number of readings were taken. It is important to measure not just the cross-sectional size of the line, but how repeatable the cross-sectional size is along the length of the line. It is, therefore, necessary to consider any patterns that arise along the length of the line and to measure the variation of the line cross-sectional size along its length.

Assuming that the line has a rectangular cross-section may not be a good approximation for fine lines. There is a curved section at the edges of a cross-sectional profile that is not taken into account by this approximation. As the line width decreases the proportional affect of the curved section increases. Thus, the effect of the curved section and how it affects the cross-sectional area of the line needs to be examined. It would be useful to relate the cross-sectional shape of fine lines to the width or width and height of the line. This may allow the cross-sectional area of the line to be determined from the measurement of line width for fine lines.

2.7 Closure for the literature review

This section reviewed previous work on methods of measuring fine lines, the effect of process parameters on fine line printing and the mechanics of ink transfer. This was followed by a discussion of the proposed work to be carried out by this study.

The main conclusions from this review were

- A new measurement system was required to be developed that measured the parameters of the line that influenced the characteristics of printed lines and were affected by the screen printing process.
- The screen printing process parameters that required investigation were the squeegee parameters, the ink and the screen, as these were the most significant process parameters. The orientation of lines to the print direction was shown to affect line width, although this was not a quantified or a theory proposed as to why this may occur. A thorough investigation into line orientation should, therefore, be included within this study.
- The review into ink transfer showed that there were three stages to the screen printing process. These are ink flow into the screen, ink flow out of the screen just behind the squeegee and ink spreading after the ink was deposited onto the substrate.

Chapter 3

Experimental Programme

3.1 Introduction to the experimental programme

This chapter describes the instrumentation used to measure the ink characteristics and the instrumentation used to capture the required data from the printed image, followed by the experiments carried out to investigate the influence of screen printing process parameters on fine line reproduction. The screen printing process parameters investigated were the ink type, the squeegee angle, the squeegee type, the squeegee pressure and the screen.

3.2 Measurement of ink characteristics

3.2.1 Contact angle measurement

The contact angle of the inks was measured using a DAT110 contact angle measurer produced by Fibrosystems, shown in Figure 3.1. A drop of liquid is placed on to a substrate and a CCD camera records an image of the drop on the substrate. From the image the contact angle is calculated. The relationship between contact angle and surface tension is described is described below.

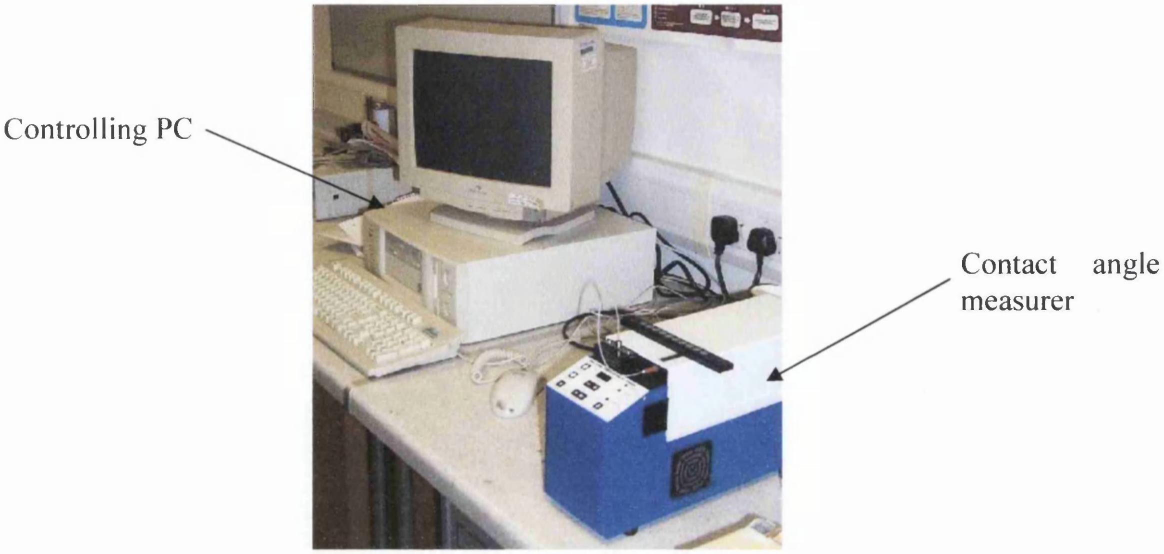


Figure 3.1 : DAT110 Dynamic contact angle measurer

Solids and liquids can be described as having a surface free energy and this is the ability of a solid to attract or repel a liquid. When a drop falls on a solid a new interface is formed between the solid and the liquid. The work of adhesion, between the solid and the liquid, is defined as the work required to separate the liquid from the solid surface. Dupre's Equation (Equation 3.1) relates the interfacial energy of the three phases (solid, liquid and gas) that occur at the boundary (20).

$$W_{SL} = \gamma_{SA} + \gamma_{LA} - \gamma_{SL} \qquad \text{Equation 3.1}$$

Where,

W_{SL} is the work of adhesion between the solid and the liquid

γ_{SA} is the surface tension of the solid air interface

γ_{LA} is the surface tension of the liquid air interface

γ_{SL} is the surface tension of the solid liquid interface

When the drop sits on the surface, it does so in a state of equilibrium with the forces due to the surface free energies balanced, this is shown in Figure 3.2. The angle at the boundary between the liquid and the solid is called the contact angle (Figure 3.3) and is a measure of the relative adhesion and cohesion between the solid and liquid. Figure 3.2 shows the force balance at the boundary, this is called Young's Equation (20).

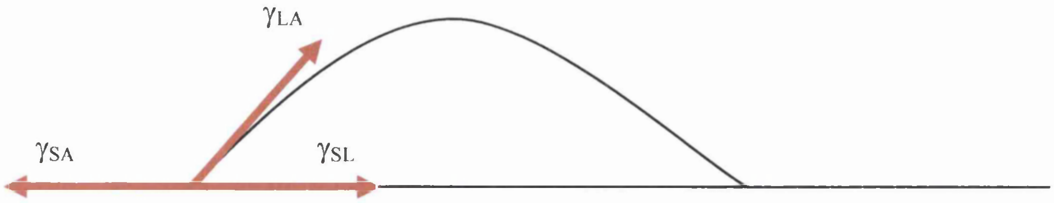


Figure 3.2 : Force balance at the boundary between a solid and a liquid

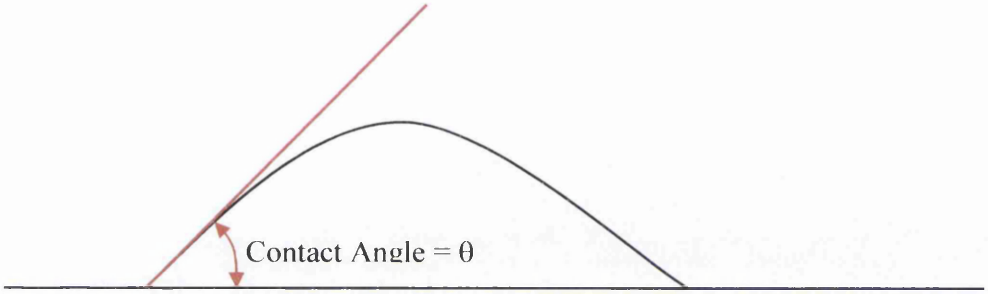


Figure 3.3 : The contact angle of a liquid resting on a solid

$$\gamma_{SA} - \gamma_{SL} = \gamma_{LA}\cos\theta \qquad \text{Equation 3.2}$$

Where,

θ = contact angle

3.2.2 Viscosity measurement

The viscosity was measured using a Contaves Rheomat 120 cone and plate visometer, shown in Figure 3.4. A small quantity of ink is placed between a cone and a flat plate, as shown in Figure 3.5. The cone is then spun at a constant speed and the torque required to maintain the speed is measured. The torque and angular velocity are measured to quantify the viscosity of the ink. This is achieved using Equation 3.1 and 3.2 (38). The shear thinning characteristics of a fluid is determined by measuring the viscosity at several speeds and thus several shear rates.

$$\tau = \frac{3T}{2\pi r^2} \qquad \text{Equation 3.3}$$

$$\dot{\gamma} = \frac{\Omega}{\tan\alpha} \qquad \text{Equation 3.4}$$

Where,

τ is the shear stress
T is Torque
r is the radius of the cone

$\dot{\gamma}$ is the shear rate
Ω is the angular velocity
α is the angle between cone and plate

Figure 3.4 : Contaves Rheomat Viscometer

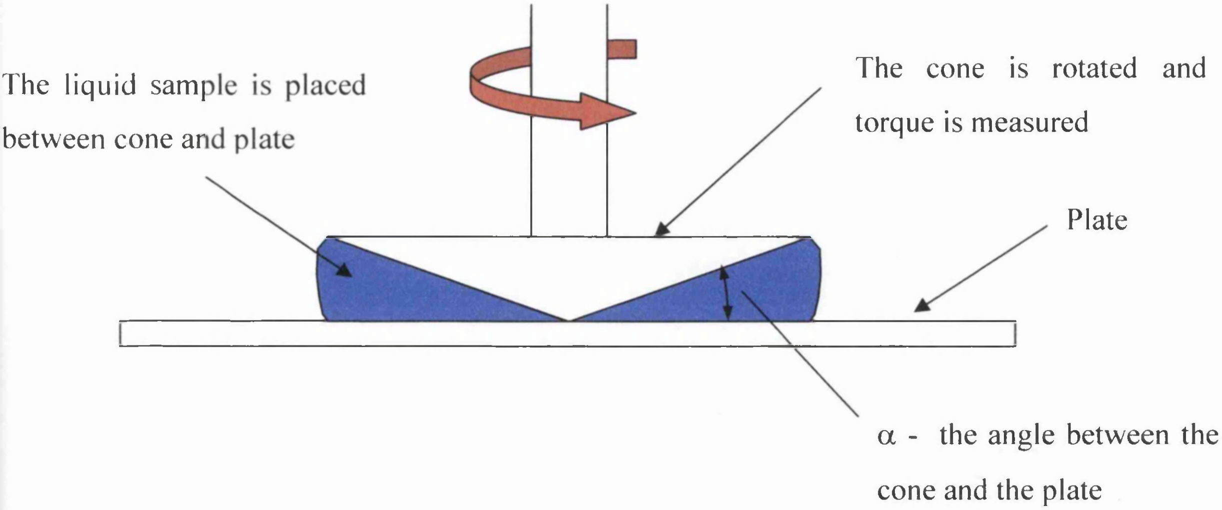


Figure 3.5 : Schematic of a cone and plate viscometer

3.3 Measurement of the printed image

This section describes the image processing techniques and instrumentation used to obtain the required data from the printed image, enabling the measurement of three-dimensional line characteristics. Two methods were used to measure the profile of the lines; image analysis and white light interferometry. Image analysis was used during an initial examination of the lines to split them into classes based on their edge roughness, but it was not possible to measure the three-dimensional characteristics of the lines using image analysis.

3.3.1 Image processing

The image analysis techniques described can be applied to any form of digital image, such as a thermal image or, as in this case used to measure three-dimensional line characteristics with a white light interferometer, a height map. The approaches used to obtain information from the white light interferometer data were synonymous to image processing, but with the distinct difference that the data represented height, as opposed to greyscale value. Thus, a description of image analysis is given as the five steps described were used to develop techniques to measure the three-dimensional profile of lines.

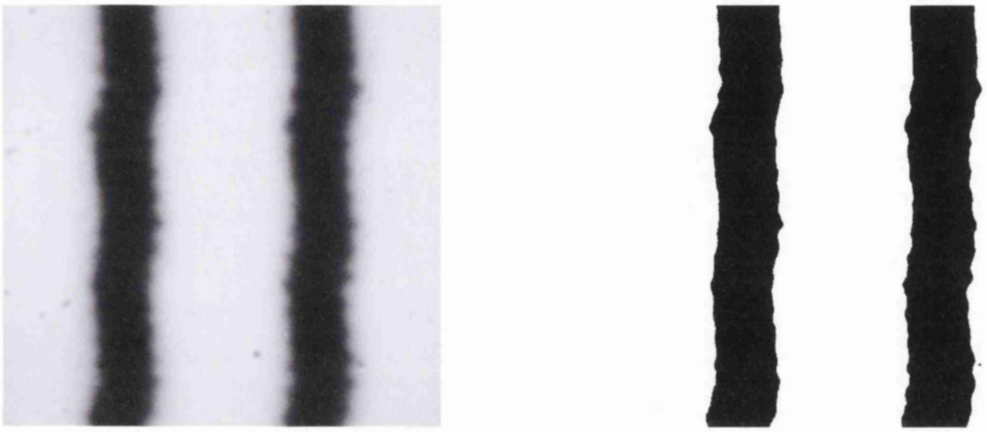
Image processing is the technique used to extract, characterise and interpret pictorial information from the world around us (39). Image processing has many applications, but they can be split into two main groups (40).These are the production of images for closer and more detailed examination by humans or the collection of data for the perception by machines.

There are five steps to image processing and analysis (40): (i) image acquisition; (ii) pre-processing; (iii) segmentation; (iv) detection and description; and (v) interpretation. This study only examines black and white images, therefore colour image processing is not discussed in this section.

Image acquisition is the sensing of the image and representation of it in a digital form. It is often called image capture. A digital camera is used to take the information from the real world and represent it in digital form. The image is split up into an array of squares called pixels, thus discretising the image spatially. Each pixel is given a number between 0 and 225, for standard 8 bit file type, to represent the brightness of the image at the position of the pixel, 0 is black and 255 is white. The brightness range is often called the greyscale.

Pre-processing involves steps used to enhance the image. These include optimisation of the dynamic gain and reduction in noise to improve the quality of the image. The reduction of noise, if required, is normally achieved using filters or averaging techniques.

Segmentation is the separation of the image to highlight the areas of interest. The key aim of segmentation is to separate the area of interest from the background. This is achieved by setting a threshold value of brightness, where every pixel above, or below, the threshold value is detected. This is often called binarisation. An example of detecting a line is shown in Figure 3.6. Figure 3.6(a) shows the original captured image and Figure 3.6(b) shows the segmented image with the line highlighted. Obtaining consistent thresholding is an important part of image processing.



(a) Original image

(b) Segmented image

Figure 3.6 : Example of segmentation

Automated thresholding can be achieved by analysing a histogram of the number of pixels at each greyscale level. For an image of a line the histogram will consist of a curve with 2 peaks, this is called bimodial. One peak for the dark pixels, representing the line, and one peak for the light pixels, representing the substrate, Figure 3.7. These two peaks represent the distribution of pixels making up the substrate and the line. Thresholding techniques try to produce a consistent method of splitting the two peaks and thus the image. It is possible to find either the minimum between the two peaks or the mean point between the maximum of the two peaks. These two methods are shown below.

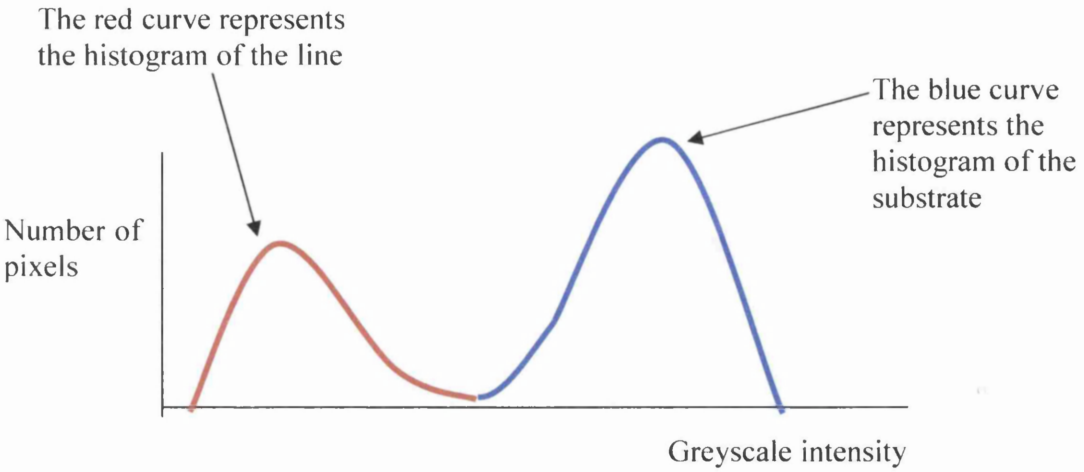


Figure 3.7 : A bimodal greyscale histogram, showing the two peaks representing the line and the substrate

The image can be segmented by finding the minimum of the histogram plot (41). This is shown in Figure 3.1. This has some limitations since the minimum is not always well defined.

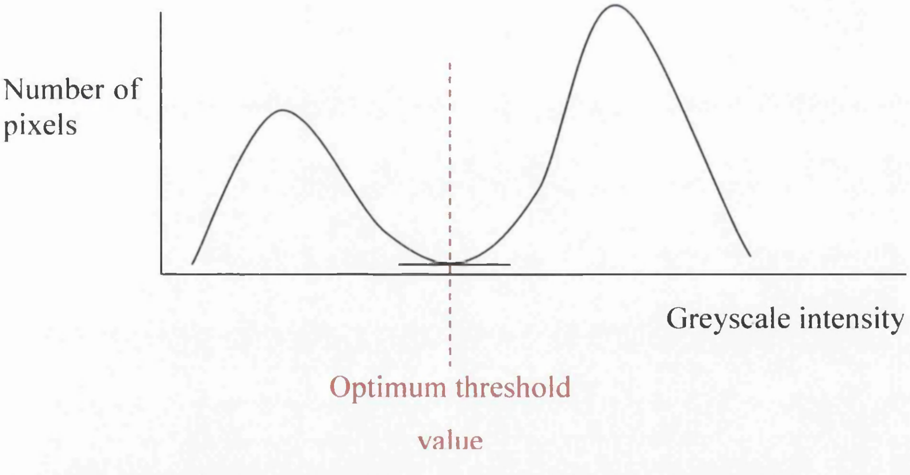


Figure 3.8 : Optimum threshold level using minimum value method

The peaks are often better defined than the minimum and for that reason a more repeatable method of finding the threshold value is finding the mid-point between the two peaks (39, 42). This is shown in Figure 3.9. Previously, this method has been used successfully to examine printed images (42) and was used in this study when analysing lines for characteristic patterns along their length, Section 4.3.

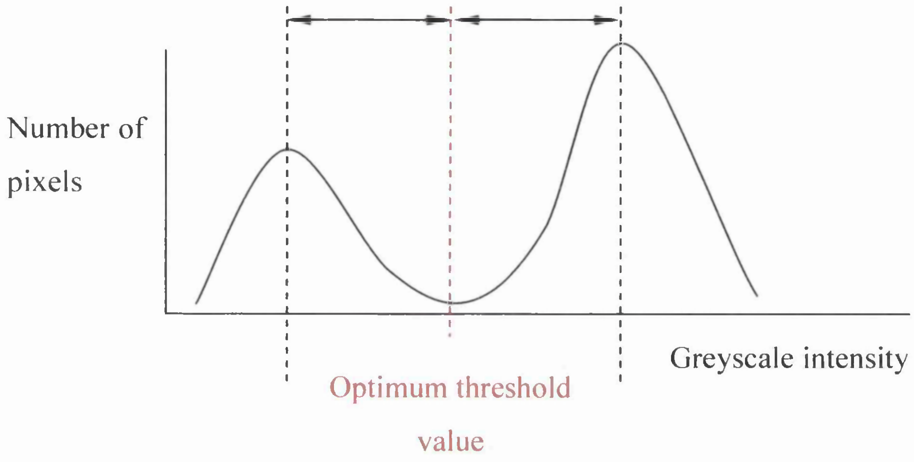


Figure 3.9 : Optimum threshold level using the mid point method

The threshold level affects the measurement of line width. Thus, there is a requirement to understand its effect on the accuracy and precision of the measurement of line width and cross-sectional area. When analysing lines for characteristic patterns along their length, Section 4.3, no quantitative information on line width was extracted for an analysis of the screen printing process parameters. Therefore, a full investigation of the effect of the threshold level on line width was not required. However, setting the threshold level for the three-dimensional data required a more thorough investigation, to quantify the accuracy and precision of setting different threshold levels. This work is described in Section 4.5.

Once the image is segmented, measurements may need to be taken to provide the user with information about the image. For example, the average width of the line in the image in Figure 3.6. Therefore, an interpretation of the raw data is required to gain some information about the system that is being examined.

3.3.2 Image processing instrumentation

A black and white camera and microscope were used to capture magnified images of lines to determine if any patterns existed along the length of the line, Section 4.3. The camera was a Pulnix TM-865. The microscope was a Leica MZ 2125, this had a large range of magnification from 0.8 to 10 times the internal magnification. A xenon light source was used to illuminate the image. The image acquisition system is shown in Figure 3.10.

The spatial calibration was achieved using black circles of known diameters. These are calibrated circles on a glass slide that are placed under the microscope. An image of the circles and their diameters are shown in Appendix A. Calibration is achieved by capturing an image of the circles and finding the diameter of the circle in pixels. As the diameter of the circles is known, in metric units, this information can be used to find the ratio of pixels to µm. By changing the magnification a range of sample lengths and intervals could be obtained. The magnification of the image capture equipment enabled a range of image sizes from an image with a length of about 500µm and a sampling interval of 0.72µm to an image with a length of 6.3mm with an sampling interval of about 9µm.

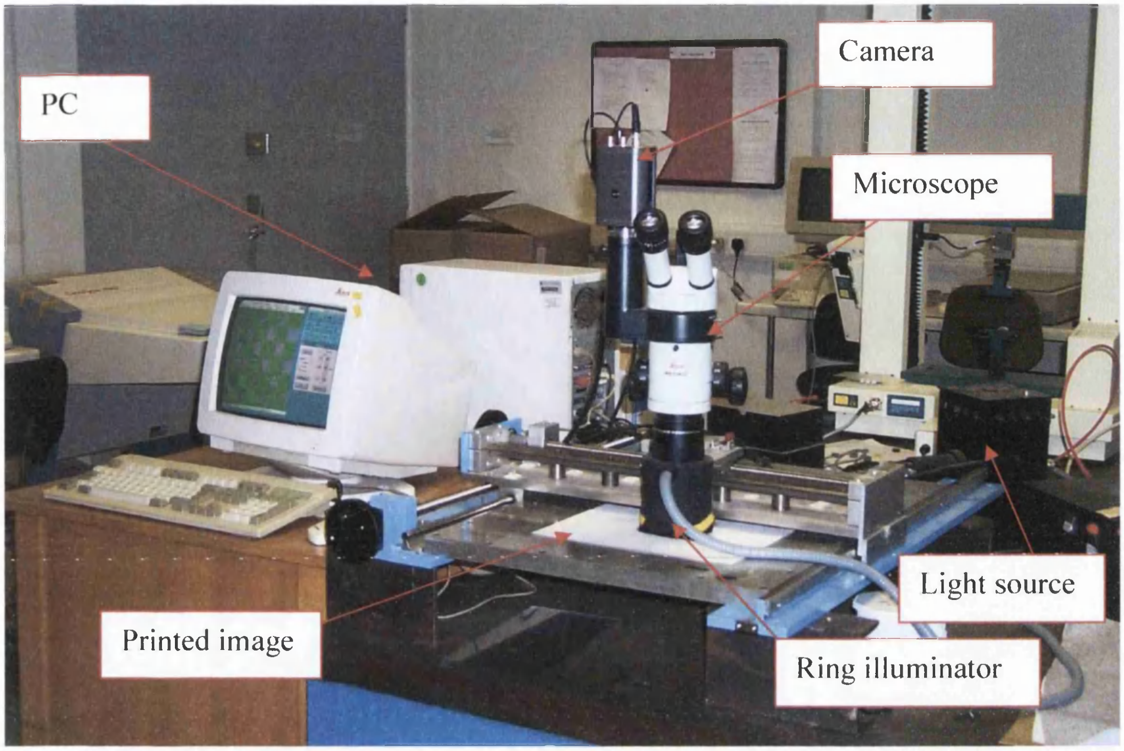


Figure 3.10 : The image analysis system

3.3.3 Choice of instrumentation for three-dimensional measurement

Various methods of measuring the three-dimensional characteristics of the line were considered. Image analysis was investigated to discover if it was possible to extract information on the three-dimensional properties of the ink film from greyscale values.

It was not possible to measure a three-dimensional profile of the line from its optical properties because ink density does not vary linearly with ink film height (43). Ink density is a measure of the darkness of a print and is defined in Section 2.2. A graph showing how ink density varies with ink film height is shown in Figure 3.11. This shows that as ink film height increases the density tends to a plateau. This means that the accuracy of any method that uses optical properties to measure height would decrease as the height increased. The optical properties are also dependent on the ink type, so comparison of different inks would be difficult.

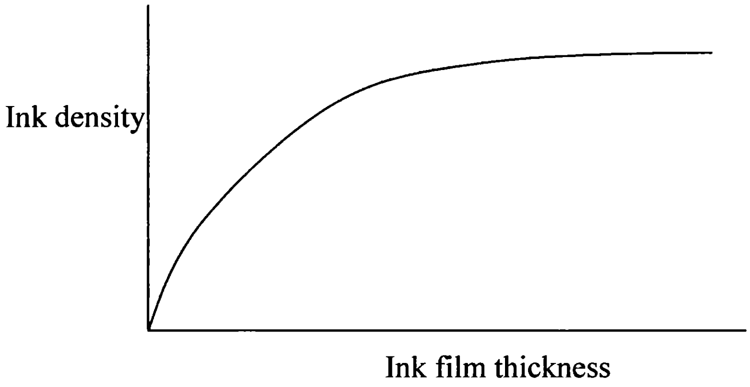


Figure 3.11 : The effect of ink film thickness on ink density (43)

The relationship between greyscale value and ink height, for screen printed lines, was investigated using three lines of known height, measured using a white light interferometer. This would determine if it was possible to establish any information about the three-dimensional properties of a line from the greyscale values. The line heights examined were 12μm, 16μm and 26μm. Greyscale values were obtained using the same lighting conditions and the same ink and substrate were used. Figure 3.12 shows the cross-section of the greyscale values through the three lines. The lines are inverted since a greyscale value of black is 0 and white is 255. The minimum greyscale value for each line is the same, but they are different heights. Thus, using image analysis would make it impossible to distinguish between lines of different height. It would not enable an accurate measurement of the cross-sectional profile, so it would not be possible to calculate the cross-sectional area.

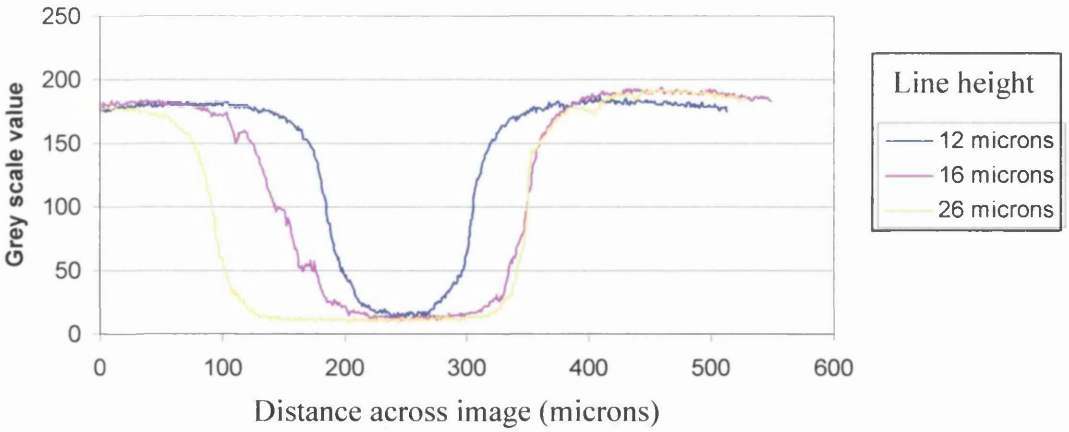


Figure 3.12 : Absolute lightness profile of lines of different height

To measure line height, a tool needs to be used that produces a three-dimensional profile of a surface. It should measure dry ink film thickness so samples can be stored and re-measured if necessary. With wet samples, the line height can change with solvent evaporation and, therefore, become time dependent. By measuring dry, lines there is no time dependency. A non-contact method is best so that the samples are not damaged. This is useful if anomalies occur and the samples need to be re-measured. Three instruments were examined. These are

- Light sectioning microscope. A light sectioning microscope is a device that uses the reflectance of light to measure the relative difference in height of two or more points on a surface of a sample.
- Stylus surface measurer. A stylus measurement device is a contact method. A stylus, attached to a moveable rod, is placed on the sample. The stylus is dragged over the sample. A transducer is used to measure the vertical movement of the stylus. This is used to produce a set of data, which represents the surface profile over a line.
- White light interferometry. White light interferometry is a non-contact method that uses the physics of interference to precisely measure distances.

Using a light sectioning microscope, only one reading can be taken at a time. Therefore, obtaining a profile along the length of a line would be time consuming. It would not be possible to produce a cross-sectional profile of the line, only a measurement of line height. Thus, the cross-sectional area of a line in a given position, and cross-sectional shape could not be measured. It also would not measure line width so image analysis would have to be used as well to measure line width.

If a stylus measurement device was placed perpendicularly to a line then the data produced would represent the cross-section of the line. If this was repeated several times along the length of the line, then the data could be used to examine the variation of the line width, line edge roughness and line height along the length of a line. This would be time-consuming and, since it is contactive, the surface may be easily damaged.

Using white light interferometry, it is possible to build up a three-dimensional profile of a large sample in a short period of time and still maintain a high resolution in the spatial dimensions. Similar techniques to image analysis can be used to segment and measure the image to obtain a measurement of line width, cross-sectional area and height along the length of the line. Thus, it can be used to measure both two- and three-dimensional properties of the line. For this reason, white light interferometry was chosen to measure the printed samples. The next section gives a detailed description of white light interferometry.

3.3.4 White light interferometry

A schematic of an interferometer is shown in Figure 3.13. A beam of light is sent through a beam splitter so that a proportion of the light can be directed to the test surface and a proportion to a reference surface. The beams are reflected off these surfaces and then recombined. The interference caused by the beams travelling different distances is used to measure the height of the test surface (44). This method is called phase-shifting interferometry (PSI) and is limited to very smooth surfaces as errors occur if the difference in surface height measurements are greater than $\lambda/4$. This limits the vertical range of PSI to 160nm.

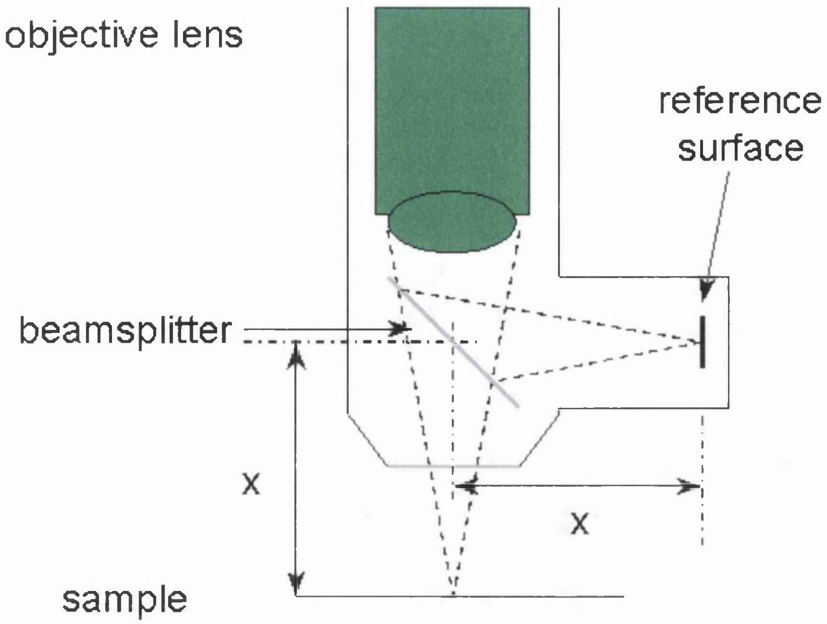


Figure 3.13: Schematic of an interferometer (45)

Vertical scanning interferometry (VSI) is used to find the profiles of rougher surfaces. It can measure peak to trough heights of 500µm. The basic principle of VSI is similar to PSI except the phase shift present in the recombined beam is measured. The light is split and reflected off both a test surface and a reference surface. The light is then recombined and the phase difference between the two waves is monitored. During the measurement, the measurement head moves vertically, controlled by a piezoelectric resistor, monitoring the inference of the combined light. The vertical position of the head is extracted for the peak of the interference signal at each point on the measurement. This is then used to build up the profile of the sample. It is possible to measure the surface profiles with a maximum difference between a peak and a trough of 500µm and resolve the surface profile to sub-micron accuracy. The main advantages are that a large area of the sample can be measured quickly. It is a non-contact and non-destructive method.

Vertical scanning interferometry was chosen as the measurement method for this study since it is a non-contact method that can measure a large sample size, but still measure heights up to 500µm. Screen printing puts down ink film thickness from 2 or 3µm to

30μm or more. A non-contact method is desirable so that samples can be re-measured if anomalies are found in the data. The main advantage of using the white light interferometry is the ability to measure a large area, in a single shot, enabling both line width and cross-sectional area profiles to be extracted from the data. This is considered especially important when examining the continuity of lines.

3.3.5 The WYKO white light interferometer

The WYKO NT-2000 white light interferometer was used to measure the three-dimensional profiles of the line for this study (Figure 3.14). There were three levels of external magnification on the interferometer and three internal. This gave a range of magnification from 2.5x to 100x. The vertical resolution of the WYKO white light interferometer was 3nm. The addressibility, the number of points within each measurement and is normally expressed as the number of pixels in each dimension, of the WYKO is 736 by 480 pixels. The work to optimise the instrument settings is described in Chapter 4.

Figure 3.14 : The WYKO NT-2000 white light interferometer

3.4 Choice of screen printing process parameters

3.4.1 Screen printing process parameters studied

The work in this study aimed to increase the understanding of the effect of screen printing process parameters, as well as develop a repeatable measurement method. The screen printing process parameters were chosen for two reasons. Firstly, screen printing process parameters of known effect were chosen to prove the use of the measurement and analysis techniques developed in Chapter 4. This enabled a comparison of the results obtained in this study to previous data. Secondly, screen printing process parameters known to affect tone gain and ink transfer were examined to increase the understanding of the process. The choice of the screen printing process parameters is discussed within the literature review, Section 2.6. Below is a description of the screen printing process parameters that were investigated in this study.

- **Ink type.** Of the screen printing process parameters, this is one of the most significant on ink transfer and is likely to have an effect on cross-sectional shape. Viscosity and surface tension are the two characteristics of the ink that affect the screen printing process.
- **The screen.** Stencil height and stencil roughness have been shown to affect ink transfer and image quality. These can be used to verify the measurement method used in this study. They may also affect the cross-sectional shape of fine lines.
- **Squeegee angle, type and pressure.** The squeegee angle has not been studied for fine line reproduction, but has been shown to be one of the most significant screen printing process parameters affecting ink transfer. Similarly, the squeegee pressure and type have been shown to influence ink transfer and may have a strong effect on the cross-sectional shape and the quality of the line.
- **Orientation.** Orientation has been shown to affect the line width, but has not been investigated quantitatively.

3.4.2 Process parameters maintained constant throughout the experimental programme

Some screen printing process parameters were kept constant for the experimental programme completed for this study. These are described below.

- The press used was a small format Flieschman screen printing press. This was a flat bed press and is shown in Figure 3.15.
- The substrate used was a glossy PVC sheet. This is non-permeable, so the amount of ink measured is the amount transferred after the solvent had evaporated. This also aided the accurate measurement of the line profile by providing an even, flat reference surface. The Ra value was 0.1μm and the Rz value was 0.5μm.
- An example of the image used is shown in Figure 3.16. This was designed to give a range of line widths at different orientations. The image consists of lines printed at 5 orientations. This allowed an investigation into the effect of line orientation. A range of line widths were printed from 90μm to 340μm.

Figure 3.15 : The screen printing press used for the experiment

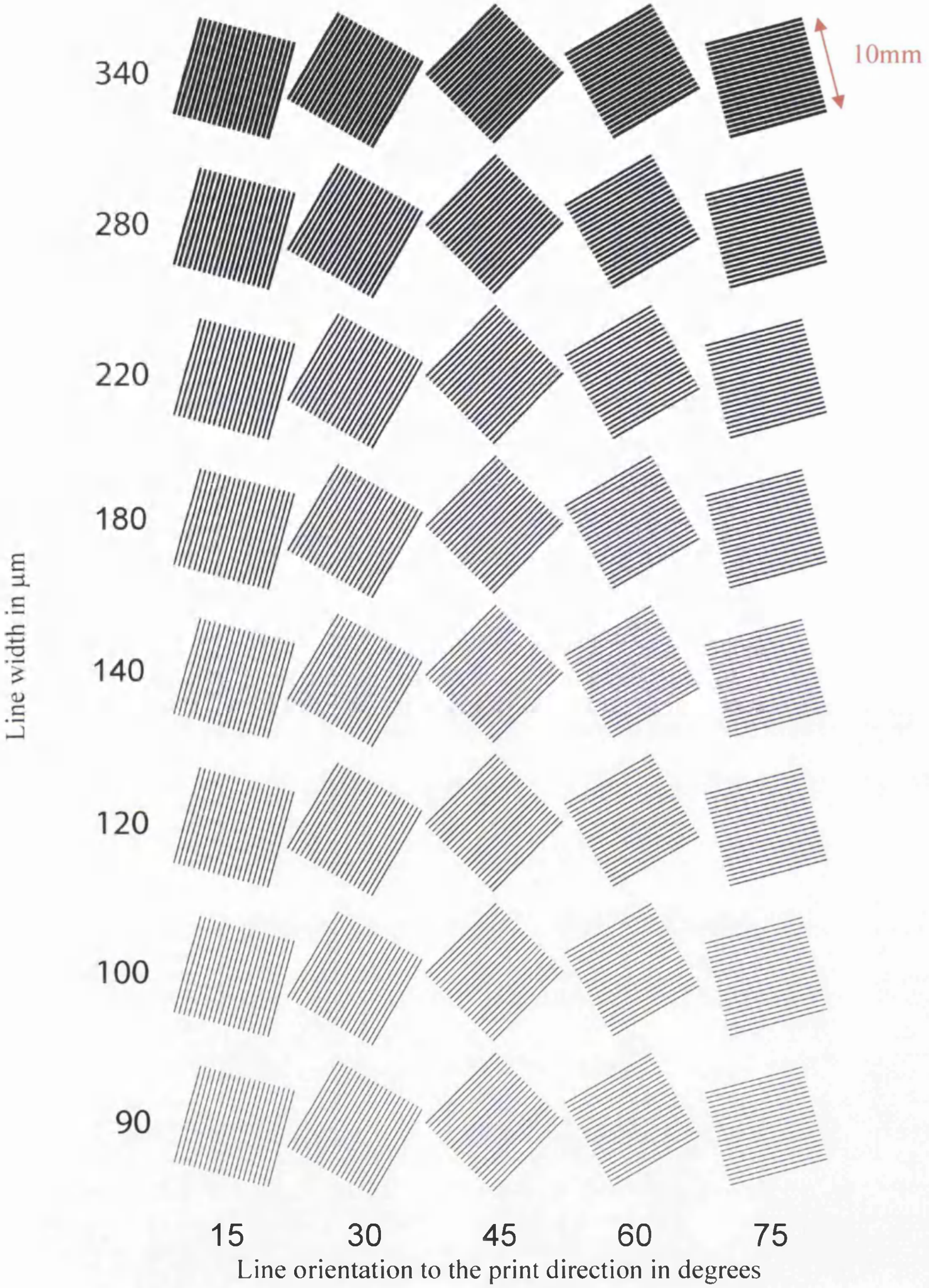


Figure 3.16 : The image used for the investigation into screen printed fine lines. This contained 10mm square patches of lines printed at 8 line widths and 5 orientations.

3.5 Experimental methods

3.5.1 Introduction to experimental methods

This section describes the experimental programme performed to investigate fine line characteristics. This was split into three parts so the influence of specific screen printing process parameters could be studied. These were the squeegee parameters (angle, hardness and pressure), the ink and the screen.

3.5.2 Squeegee parameters

3.5.2.1 Experimental method

The effect of the squeegee angle, hardness and pressure on fine line reproduction was investigated by performing a full factorial experiment. The squeegee angles were taken from the horizontal plane and the pressure values were press settings. The settings used were typical of the ranges used in industrial applications. All the squeegees were backed with a metal plate. This should eliminate the deformation along the height of the squeegee as a source of errors, so the angle set on the press was the same as at the point of printing. To complete the full factorial experiment, 27 combinations needed to be printed. These were completed in 3 sets of 9; one set for each squeegee. In between each set, the screen was cleaned and a new mix of ink was produced. This reduced the chances of ink drying within the screen and partially blocking the mesh, an process known as 'drying-in', and thereby affecting the results. To check for this, the first combination printed in each set was always repeated. The repeated prints could then be analysed to examine whether drying-in occurred. The screen printing process parameters kept constant are shown in Table 3.2.

Table 3.1 : Screen printing process parameters examined in the squeegee experiment

Parameter	Level 1	Level 2	Level 3
Squeegee hardness (Shore A)	65 (soft)	74 (medium)	84 (hard)
Squeegee angle (deg)	70	75	80
Squeegee pressure (bar)	2.5	3.5	4.5

Table 3.2 : Screen printing process parameters kept constant for the squeegee experiment

Screen	120 – 34T
Screen Tension (N/cm)	20
Stencil Rz (μm)	10.1
Stencil Profile (μm)	3.5
Substrate	PVC Gloss
Ink	Sericol Solvent based Mattplast – 20% retarder
Squeegee speed (cm/s)	50

3.5.2.2 Process repeatability for the experiment of squeegee parameters

The squeegee experiment was split into three sets and the same combination of settings was printed at the beginning and end of each set. This allowed the effect of drying in to be evaluated. For the first set there was a small difference between the first and last prints, shown in Figure 3.17. This effect was considered when examining the results. For the last two sets there was a larger difference between the first and last reading, about a 40 percent drop for the last set. The print conditions were the same for these prints, so the difference between them was the time the ink had spent on the mesh. Thus, drying in must have occurred more significantly for the last two sets. For the analysis of interactions the data was kept in full, since it is not possible to examine the interactions without a complete data set.

The data that was least affected by drying-in was used to examine the screen printing process parameters. For the squeegee hardness investigation the first prints from each set were used. For the investigation into the angle and the pressure the prints from the first set only were used.

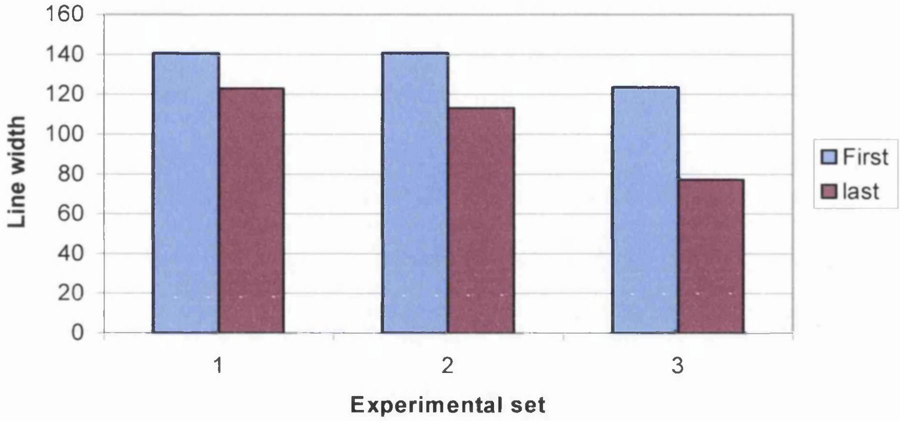


Figure 3.17 : The effect of drying-in through the experimental run

3.5.3 Ink Characteristics

An experiment was designed to examine three UV cured inks. All other screen printing process parameters were kept constant and their values are shown in Table 3.3. The viscosity curves for the inks are typical of shear thinning fluids and are shown in Figure 3.18. The exact shear rate at which screen printing occurs is not known. This makes it difficult to give a value to the viscosity of the inks during the screen printing process. However, it is possible to make a comparison of the inks from the data given and describe the inks as ink 1 having the highest viscosity, then ink 2 and then ink 3 having the lowest viscosity.

Table 3.3 : Screen printing process parameters kept constant for the ink experiment

Parameter	Value
Squeegee hardness	75 Shore A
Squeegee Speed	50 cm/squeegee
Squeegee Pressure	4 Bar (medium)
Mesh	120 – 34
Squeegee Angle	75 Degrees

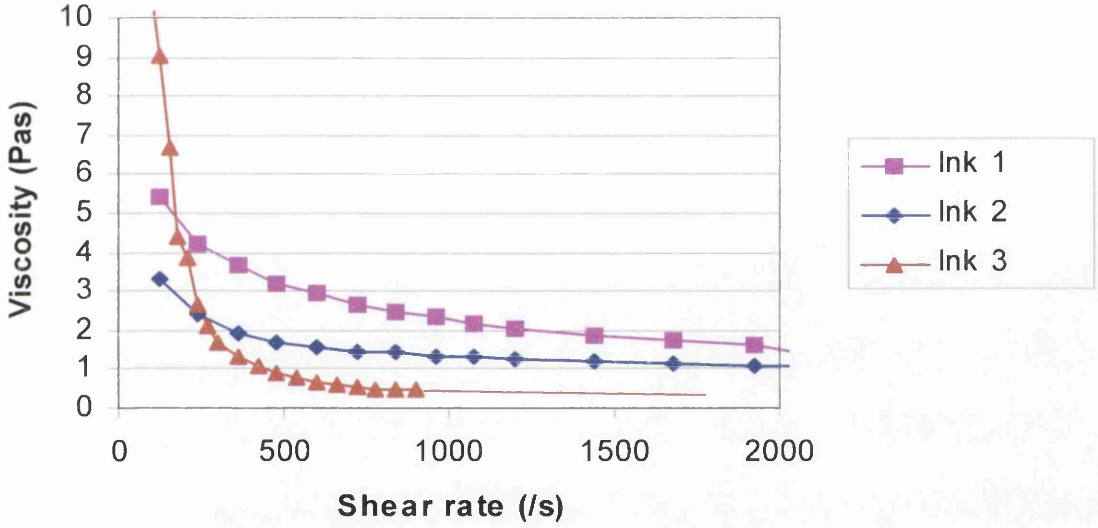


Figure 3.18 : Viscosities of the inks used in study

A Fybrodat dynamic contact angle measuring instrument was used to measure the contact angle of the inks. The contact angle is a measure of how ink clings to and spreads on the substrate. The spreading of the ink is often referred to as the wettability. The lower the contact angle, the more easily the ink wets the substrate. Five measurements, of contact angle, were taken for each ink. These results were averaged and are presented in Figure 3.19, error bars show the spread of the data.

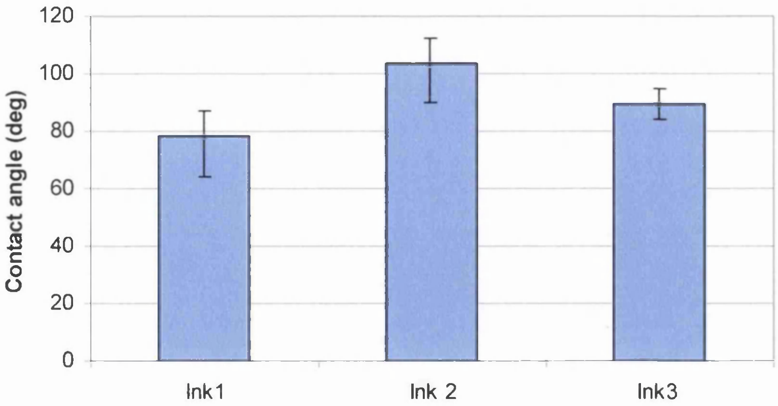


Figure 3.19 : Contact angle of the inks used in this study

3.5.4 Stencil characteristics

The effect of the stencil roughness and screen height on fine lines was investigated. This was carried out using meshes with 90μm and 120μm diameter threads and a variety of stencil thicknesses. An experiment was performed using 10 stencils. The stencils used and their quality characteristics are shown in Table 3.4. The screen printing process parameters kept constant during the experiment are shown in Table 3.5.

Table 3.4 : Stencils used to examine the printed line quality

Mesh	Screen height (μm)	Rz (μm)
120 - 34	4.4	5.5
120 - 34	11.4	3.5
120 - 34	3.1	4.5
120 - 34	7.8	3.0
90 - 40	4.4	6.0
90 - 40	4.2	5.5
90 - 40	3.9	6.5
90 - 40	3.7	5.5
90 - 40	2.8	6.0
90 - 40	3.1	5.5

Table 3.5 : Screen printing process parameters kept constant for the stencil experiment

Ink	Cyan Sericol Ultratone 5% thinner, 10% retarder
Squeegee Angle (deg)	70
Squeegee speed (m/s)	6
Mesh Tension (N/cm)	15 to 17
Squeegee hardness (Shore A)	65
Squeegee pressure (bar)	3.5

3.6 Closure to experimental programme

The experiments undertaken to investigate the influence of screen printing process parameters on fine line reproduction have been described. The screen printing process parameters investigated were the squeegee parameters (speed, type, pressure), the ink, the screen and the orientation of the lines. A white light interferometer was chosen to capture the required three-dimensional information of the printed lines.

A measurement system has been developed to characterise the quality of screen printed fine lines. The steps taken to develop the line measurement methods are described in the next chapter. This measurement system was used to analyse the results from the experiments described in this chapter and the results are presented and discussed in Chapter 5.

Chapter 4

Methods of Analysis for Fine Lines

4.1 Introduction

This chapter describes the steps undertaken to develop techniques to analyse screen printed fine lines. The structure of the technique developed is shown in Figure 4.1. Many considerations were required to arrive at this technique and the development process is outlined in the flow chart in Figure 4.2. The chapter follows this flow to take the reader through the decisions made to develop the measurement method, in doing so, this chapter covers work developing, and determining the errors in measuring the printed lines.

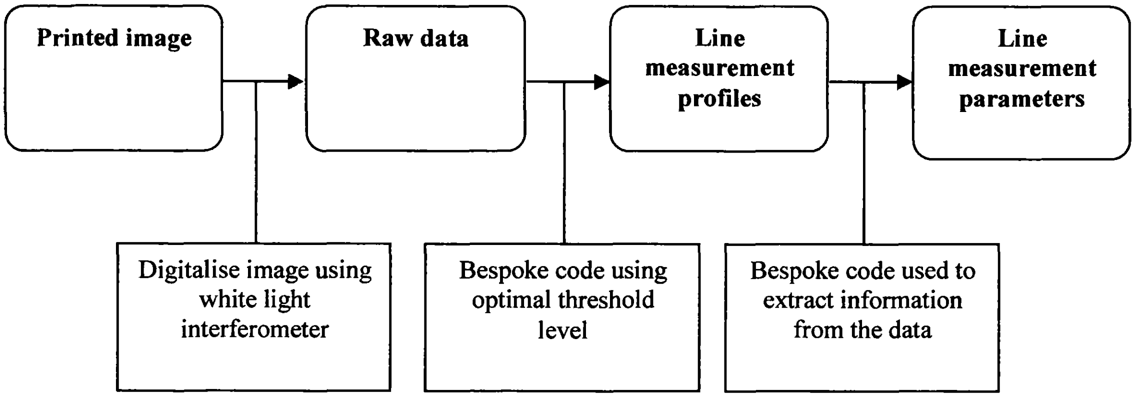


Figure 4.1 : Flow chart showing the system developed to analyse screen printed fine lines

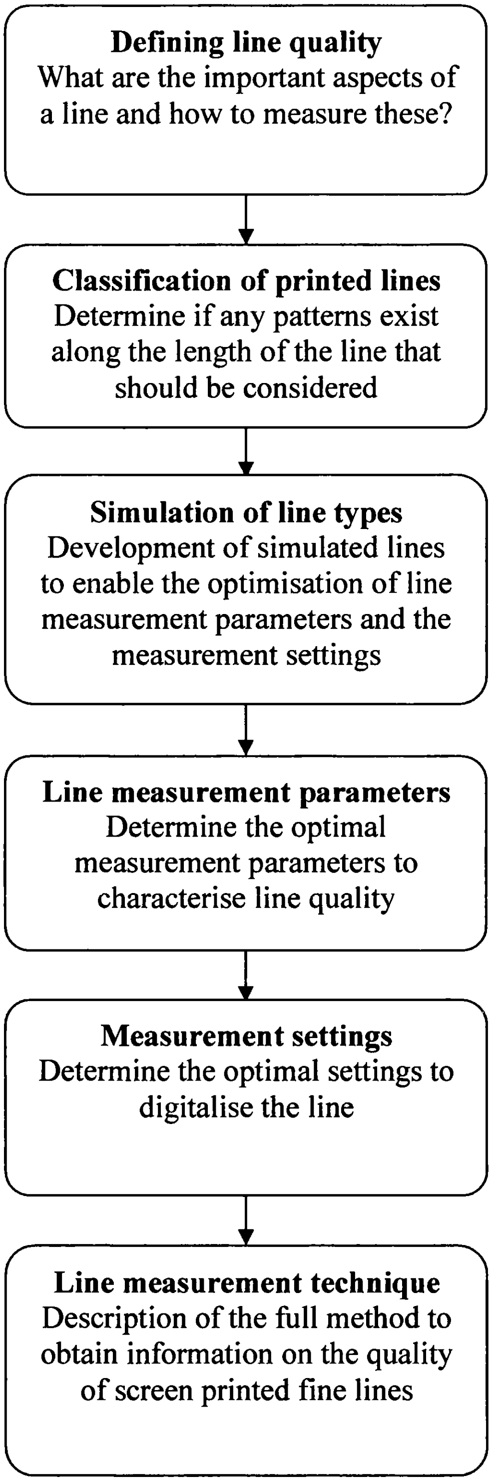


Figure 4.2 : The steps and processes undertaken to develop the line measurement system

4.2 Defining line quality

4.2.1 Introduction to the line quality characteristics

There was a need to establish a method to quantify the quality of a line. This section demonstrates why both the cross-sectional size of the line and its continuity need to be examined. It describes statistical methods that can be used to examine the line width, height and cross-sectional area, as well as how these vary along the length of the line.

4.2.2 Analysis of line cross-sectional size

Line cross-sectional size, within this study, is used as a collective term for the cross-sectional area and the line width, as these have a similar effect on the properties of a line depending on whether the line height is considered uniform across the line width.

Initially, the functionality of lines required investigation to determine the important parameters that characterise the properties of a line. The main function of a printed line in electronics is as a resistor or conductor. For both these functions, the electrical resistance of the line will be important. The resistance R is defined by the equation given below (46).

$$R = \frac{\rho L}{A}$$

Equation 4.1

Where

ρ = resistivity

L = length of resistor

A = cross-sectional area

At present the height of the line is considered to be uniformly distributed across the width and thus the cross-sectional shape of the line is considered to be a rectangle. The height is defined by choice in mesh and is considered to be constant along the length of the line. Therefore, the aspect ratio, defined as the length over width, will define the resistance of the line since all other parameters are assumed constant. This is called the sheet resistance and is defined below (6).

$$R = R_s \frac{L}{w}$$ Equation 4.2

Where,

R_s = sheet resistance

L = length of the resistor

w = width of the resistor

Sheet resistance does not allow width, length and height to be analysed independently. Using the sheet resistance also assumes that the cross-section of the line is a rectangle. This is not a valid assumption for fine lines, as will be shown later, and the effect of this assumption needs to be investigated. Resistance, rather than sheet resistance, needs to be studied to fully analyse the effect of the printing process on the functionality of printed lines.

The aim was to produce a measurement system that examines the effect of the printing processes on the electrical resistance of printed lines. The parameters, in Equation 4.1, that affect the resistance that are affected by the printing process need to be identified. The material properties are set before printing, and are therefore assumed to be fixed. The length of the line is set by the distance between two connectors and can be assumed to be determined before the printing process commences. This means that the cross-sectional area of the line is the parameter that is most affected by the printing process. Thus, the mean cross-sectional area could be used to describe the cross-sectional size of the line. It is though important to relate the cross-sectional size to resistance. Below is a derivation which relates the cross-sectional area to the resistance of the line for a more mathematically correct method to measure the cross-sectional size of the line, rather than just the mean of the cross-sectional area of the line.

A screen printed line does not have a constant cross-sectional area along its length. Therefore, the effect of the variation of the cross-sectional area on resistance was investigated. The line was considered to be made up of many short resistors of equal length. An example is shown in Figure 4.3. A line of length L is considered as three resistors all of length l, but of different cross-sectional areas. The size of each resistor is shown in Table 4.1. The equivalent resistance of resistors placed in series is the addition of the resistances of those resistors (46). Therefore, the line resistance can be calculated by adding the resistances from the three resistors that make it up, Equation 4.3.

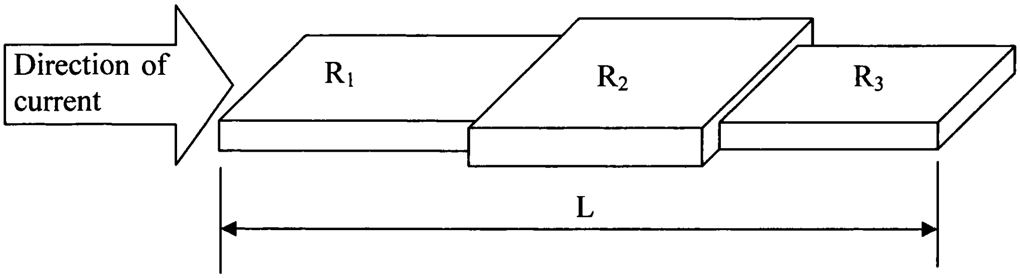


Figure 4.3 : Example of line broken into 3 sections

Table 4.1 : Properties of the resistors

Resistor	length	Cross-sectional area	Resistivity
R_1	l	A_1	ρ
R_2	l	A_2	ρ
R_3	l	A_3	ρ

Total resistance = $R_T = R_1 + R_2 + R_3$ Equation 4.3

If an equivalent area, A_E, is defined as

$$R_T = \rho \frac{L}{A_E} \qquad \text{Equation 4.4}$$

Then, combining Equation 4.3 and Equation 4.4

$$\frac{3}{A_E} = \left(\frac{1}{A_1} + \frac{1}{A_2} + \frac{1}{A_2} \right) \qquad \text{Equation 4.5}$$

This can be extended to cover a line of *n* sections

$$\frac{1}{A_E} = \frac{1}{n} \sum_{\text{i=1 to n}} \frac{1}{A_i} \qquad \text{Equation 4.6}$$

This assumes that there is a perfectly conducting connection between each resistor. Using an equivalent area is mathematically better than using a mean value for the area, although if there are only small changes in cross-sectional area along the length then the mean and equivalent areas will be similar. The differences between the mean and equivalent areas will be examined later in this section.

Assuming that the line has a rectangular cross section is not a good approximation for fine lines, since previous work has shown that there is a curved section at the edges of a cross-sectional profile that is not taken into account by this approximation. Furthermore as the line width decreases, the proportional affect of the curved section will increase. The effect of the curved section needs to be examined and how it affects the area of the line. It would be useful to relate the cross-sectional shape of the line to the width or width and height of the line. This would allow the cross-sectional area of the line to be determined from the measurement of line width.

There are three parameters that can be used to analyse line cross-sectional size. These are

- **Cross-sectional area**. This section has shown that the cross-sectional area of the line is the most relevant parameter to the electrical properties of a printed line. Therefore, for an in-depth analysis this should be measured.
- **Line width**. This only requires 2-D analysis to measure, although it does not give all the information about the line cross-sectional size that may be required. If this method is used then the line height is considered to be uniform across its width.
- **Cross-sectional shape**. As line width decreases, the shape of the cross section is more similar to an inverted parabola, than a rectangle. This should be investigated for fine lines to determine the consequence of assuming line cross-sectional shape is a rectangle.

4.2.3 Analysis of line continuity

The line width is not constant along the length of the line. Methods of measuring this variation on line width are examined in this section. The continuity of the edge of lines affects two parts of line quality, the ability to print lines close together and the minimum line width of a printable line. The advantages and disadvantages of analysing the width and the edge profile will therefore be considered.

Practically, the closer lines can be placed then the smaller the components which are used can be produced. The major limitation on lines being placed close together is the variation of line width along the length.

The variation also has an effect on the minimum line width to be printed. A 10μm variation will have a proportionally smaller effect on a 500μm wide line than on a 100μm wide line. Therefore, to print fine lines this variation needs to be measured. If the variation in the cross-sectional area is large then some cross-sections of the line will be significantly small. This will lead to incorrect electrical properties of the line.

Several techniques were investigated for the analysis of line continuity.

- **Standard deviation.** This is a measure of the spread of a data set. It is defined by

$$\text{Standard deviation} = \sigma = \sqrt{\frac{\sum_{i=1}^{N}(x_a - x_i)^2}{\text{N}}} \qquad \text{Equation 4.7}$$

Where,

N = number of point in data set
x_a = average of data set
x_i = value at point i

- **Skew.** The skew is a measurement of a bias in the data to one side of the mean. A Gaussian distribution has a skew of zero. It is defined as

$$\text{Skew} = \frac{1}{\sigma^3}\sum_{i=1}^{N}(x_a - x_i)^3 \qquad \text{Equation 4.8}$$

- **Fourier analysis.** Fourier analysis is used to analyse repetitive patterns and identify dominant frequencies within a signal. The Fourier transform changes a function from being described in terms of space or time to frequency (47). The Fourier transform pair are the two equations that change a function from the space domain to the frequency domain and vice versa. The Fourier transform pair are

$$G(f) = \int_{-\infty}^{\infty} h(z) EXP\{-i2\pi fz\} dz \qquad \text{Equation 4.9}$$

$$g(z) = \int_{-\infty}^{\infty} H(f) EXP\{i2\pi fz\} df \qquad \text{Equation 4.10}$$

Where

G(f) is the Fourier transform of g(z)
f is the inverse wavelength
z is the spatial co-ordinate

For discretely sample data, the Fourier transform becomes

$$G_n = \sum_{k=0}^{N-1} h_k EXP\left\{\frac{-2\pi i k_n}{N}\right\}$$ Equation 4.11

$$g_k = \frac{1}{N}\sum_{n=0}^{N-1} H_n EXP\left\{\frac{2\pi i k_n}{N}\right\}$$ Equation 4.12

Where,

N = Number of samples

h_k is the matrix of values in the space domain

H_n is the matrix of values in the frequency domain

The discrete Fourier transform breaks the sampled data into sinusoidal waveforms at discrete frequencies, at different phases. When combined, the waveforms added together form the original data. The Fourier transform takes the form of imaginary numbers and the magnitude and phase at each frequency is found by the modulus and argument of the imaginary number at each frequency.

$$\text{Magnitude} = \sqrt{\mathrm{Re}(G)^2 + \mathrm{Im}(G)^2}$$ Equation 4.13

$$\text{Phase} = \frac{\mathrm{Im}(G)}{\mathrm{Re}(G)}$$ Equation 4.14

- **Minimum and maximum size.** These can be used to identify shorts or connections along the line, similar to Webster's defect criteria (24). Solely measuring the average deviation of the line from the mean would not identify severe one off thinning or widening of the lines that would affect the functionality of the line. Thus, it is also important to examine extreme values as well as averaged values.

4.2.4 Summary of the line quality characteristics

The line quality characteristics were the cross-sectional size of the line and the continuity of the line. The cross-sectional area of the line is the parameter that is affected by the printing process that affects line resistance. The continuity of the line width determines how closely lines can be placed together and how thin lines can be printed. It may not be correct to assume that the cross-sectional shape is a rectangle for fine lines. Therefore, the cross-sectional shape should also be studied to determine if a there is relationship between line width and cross-sectional area for fine lines.

Work to determine the optimal parameters to measure line quality is described in Section 4.4. This is described, after an overall analysis of the printed lines to determine any patterns that exist in line discontinuity that may be significant in determining a measurement method.

4.3 Classification of screen printed lines

4.3.1 Investigation of line patterning

The lines printed in the experiment described in Chapter 3 were examined to determine any patterns that exist in edge quality. It was assumed that these would be a representative set of prints to examine line width continuity as many of the most significant process parameters were varied causing a large variation in line quality.

The lines were examined visually and notes taken on their edge quality. Three classes of edge quality were identified. These are described below and examples shown in Figure 4.4 to Figure 4.7.

- **Straight edges**. The edges of the lines show little or no deviation from a straight line. An example of this is shown in Figure 4.4.
- **Rippled edges**. This is a high frequency wavy pattern along the edge of the line creating bad edge definition and a blurred effect for the line edges. An example of this is shown in Figure 4.5.

- **Mesh patterning.** This produces large regularly spaced thinning of the lines. An example of this is shown in Figure 4.6. It was observed that the distance between the thinning of the line was affected by the orientation to the print direction at which the line was printed. Specifically, lines printed at 45^0 to the print direction had a shorter wavelength compared to those printed at 15^0 to the print direction. Representative images, obtained from the experimental programme, are shown in Figure 4.7.

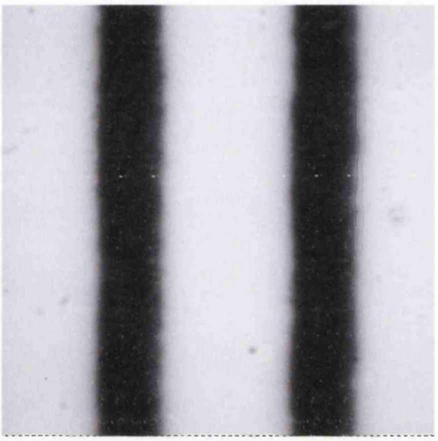


Figure 4.4 : Example of a straight edged line

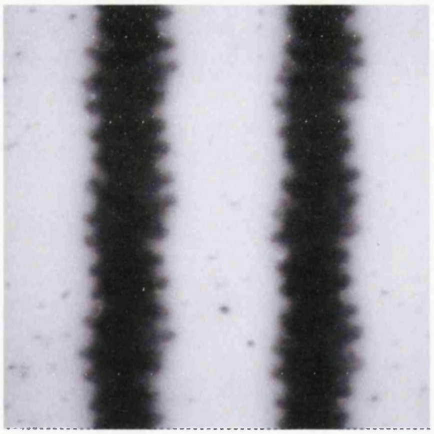


Figure 4.5 : Example of a line with rippled edges

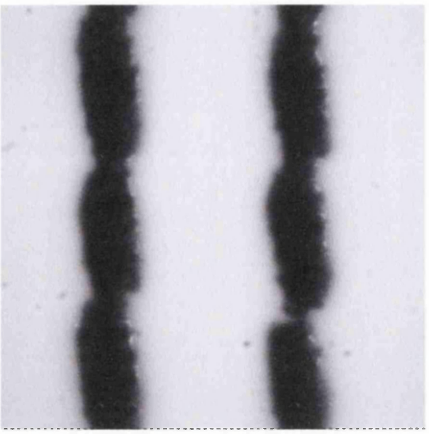
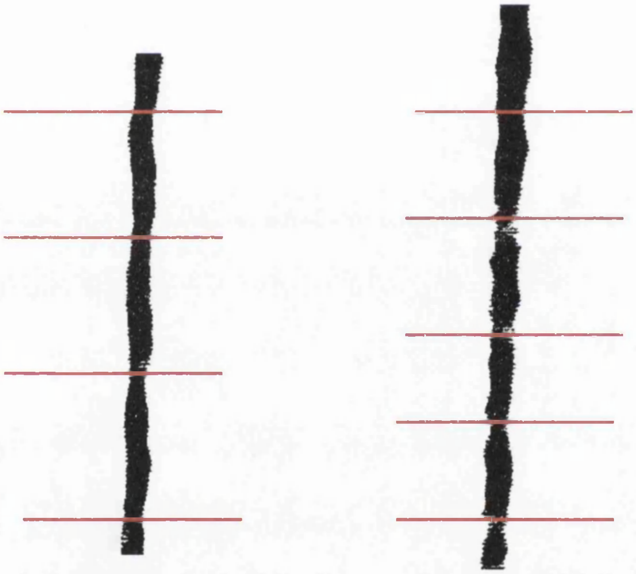


Figure 4.6 : Example of a line with mesh markings



75^0 to the print direction

45^0 to the print direction

Figure 4.7 : Example of mesh marked lines at two orientations to the print direction, they have been binarised to demonstrate the difference in wavelength more clearly

The wavelength of line width pattern is likely to be affected by the mesh count as well as line orientation. Examining these prints will give a good guide to the frequency, but further investigation will be required to find any relationship between mesh count and wavelength of any patterning on the line. The wavelength of the two types of line examined were found using Fourier analysis. The wavelength of the edge rippling was about 70μm. The wavelength of the mesh marking was about 160μm. The amplitude of line width variation ranged from 3-4μm for a smooth line to 20μ to 30μm for a rough edged line. These values have been used as a guide to the fluctuations of the line width data, and the frequencies they occur at, to develop methods to characterise line quality.

4.3.2 Line profile for the measurement of continuity

The variation of the width along the length of the line can be determined by measuring either the width or the edge profile. When considering how closely lines can be placed together, then measuring the edge profile, rather than the width profile would be better. When considering how small a line can be printed, then examining either the cross-sectional area or width profile would be better. Although, it would be advantageous to gain sufficient information from either the edge or width profile to give information on both these cases.

The pattern in the edge profile is either deterministic or random (48). Deterministic refers to a repeated pattern, where the edge profile can be predicted from a sufficiently sized sample. Random data refers to data that follows no pattern and the line width at any point can not be inferred from measuring a sample elsewhere on the line. The effect of the type of data and the phase angle between the two edge profiles has been considered and three scenarios are described below.

- Edge profiles are deterministic and in-phase. For this case, the variation in the width is zero, whatever the variation in the edge profile. Information is lost in measuring width and no information would be given on how close lines can be placed together.
- The edge profiles are deterministic and out of phase. The effect of the phase angle on the standard deviation for two sine waves is shown in Figure 4.8. This shows that deviation in edge profiles, which are between $\pi/4$ and $3\pi/4$ out of phase, would be accentuated by examining the width rather than the edge profile. Thus, trends in the data would be more obvious. In this case, there is a large advantage in measuring the width profile rather than the edge profile.

- The edge profile is random. For this case, the variation in the width is the same as the variation of the edge profile, provided the sample is large enough that it is representative of the whole data.

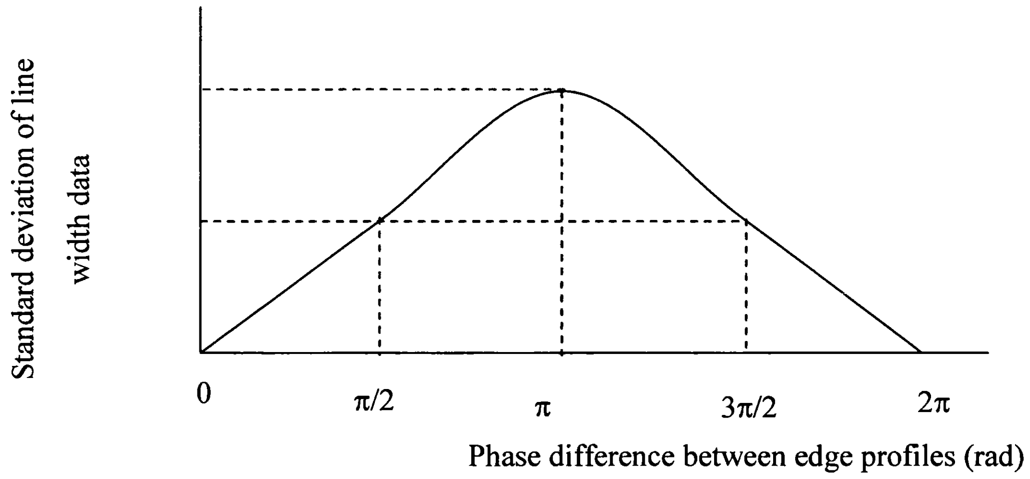


Figure 4.8 : The effect of the phase difference between the two sinusoidal edge profiles on line width standard deviation.

The mesh marking is deterministic. The pattern is repeated along the length of the line and the thinning of the line is similar at every wavelength. The two edge profiles are π radians out of phase, as shown in Figure 4.6. Therefore, by measuring the width, as opposed to the edge profile, any effect will be accentuated and highlighted in the data.

The edge rippling occurs at repeatable wavelength, but the amplitude of rippling is random. Comparing the probability density functions of the width and the edge profiles can reveal this, Figure 4.9. The distribution of the probability is the same for both the edge and the width profiles. Examining the standard deviation of the edge and width profiles also shows this. For this sample, the standard deviation for the width is 9.9μm and 9.4μm for the edge profile. Therefore, the data is random and there is no gain in measuring either the edge or the width profile.

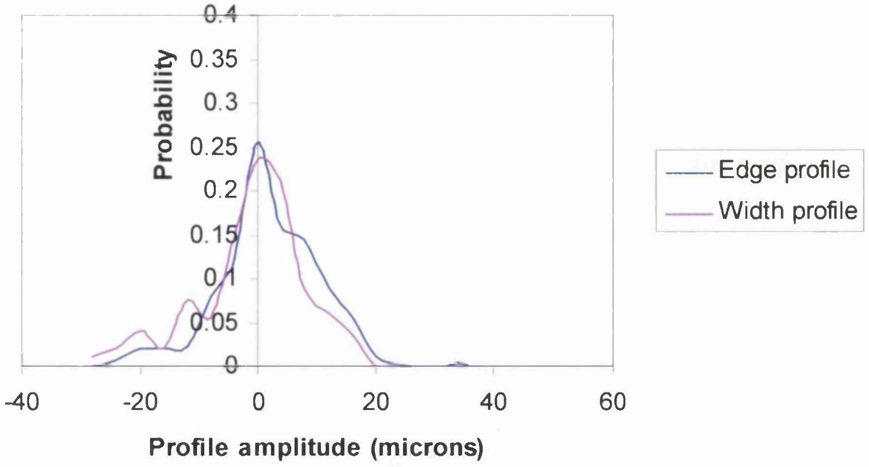


Figure 4.9 : Probability density function for width and edge profiles

For the edge rippling, there is no advantage in measuring either the edge or the width profile. However, there is an advantage to measuring the width profile for the mesh marking, for this reason, the width profile will be measured.

4.3.3 Modelling of line width patterns

Models of line width data were produced based on the patterns shown by the edge rippling and the mesh marking. This enabled the theoretical examination of line cross-sectional size and continuity and, thus, the optimisation of the line measurement parameters. It was shown in Figure 4.7 that mesh marking was affected by the orientation of the line to the print direction. This will be examined further with orientation in Chapter 5. To develop techniques to measure and characterise mesh marked lines they have been modelled at 15^0 to the print direction.

The modelling was achieved by splitting the width profile, along the length of the line, into two components, the maximum line width and a variable component. For edge rippling, the variable component was considered as a sinusoidal function. Equation 4.15 gives the modelled function for edge rippling.

$$w(y) = \left(w_{max} - \frac{B}{2}\right) + \frac{B}{2}\sin(2\pi f y) \qquad \text{Equation 4.15}$$

Where,

w – line width

y – position along the length of the line

B – peak to peak variation along the length of the line

f – frequency

w_{max} – maximum line width

Adjoining rectangles at a slight angle to each other can represent the shape of the mesh marking at 15^0 to the print direction. Figure 4.10 shows how rectangles can be placed to form a pattern similar to that shown in Figure 4.6. The width profile of such a line would consist of trapeziums, as shown in Figure 4.11. The mesh marking was modelled using repetitions of the ideal trapezium shown in Figure 4.12, with a peak to peak amplitude of B and a wavelength of T.

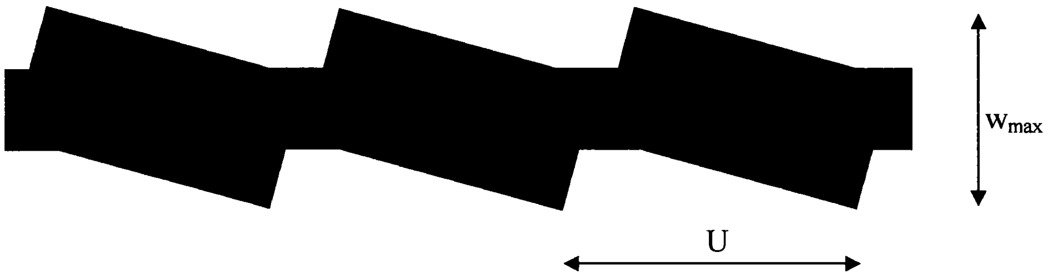


Figure 4.10 : Shape of mesh marking

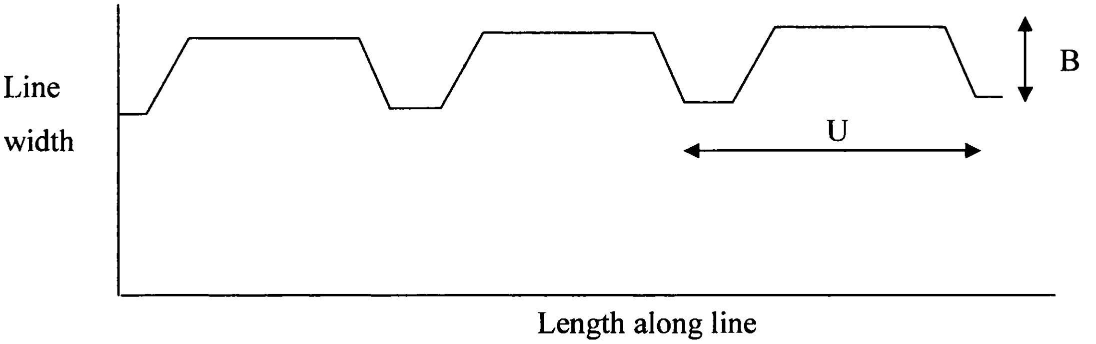


Figure 4.11 : Width profile of mesh marking

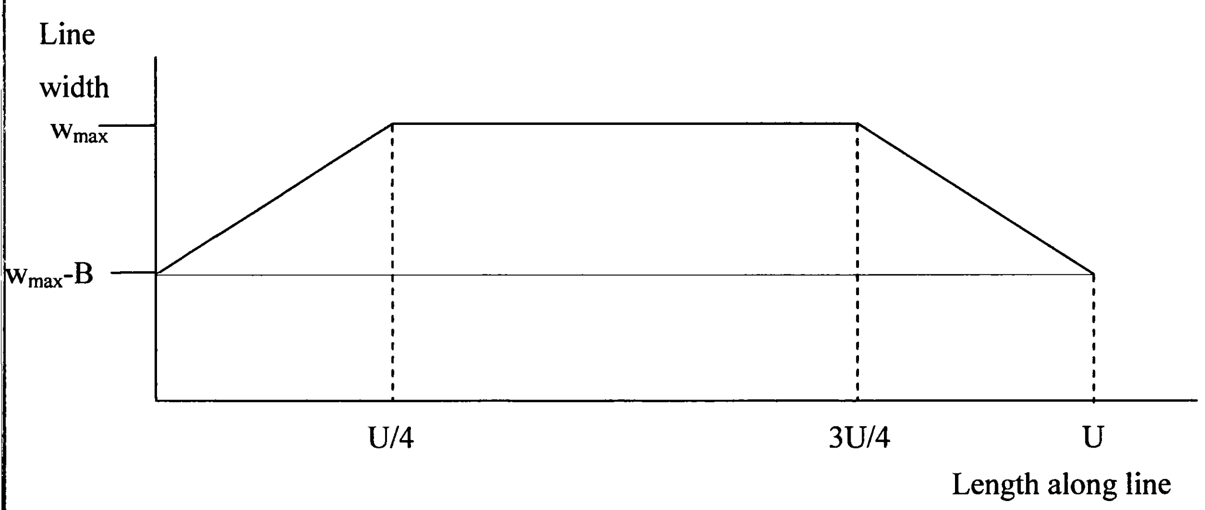


Figure 4.12 : Ideal trapezium used to simulate mesh marking width profile

4.4 Line measurement parameters

The line measurement parameters are the parameters used to describe the quality characteristics of the line enabling a quantitative study of the how screen printing process parameters affect the quality of the printed lines.

4.4.1 Measurement of line size

As discussed previously in Section 4.2, two methods were considered to measure the line width and cross-sectional area. These were the equivalent area or the mean area. The methods have been considered theoretically to show the mathematical differences between the two calculations. A sine curve was used to represent the variable component of the line size data and an offset was added to model the mean size of the line. The variation within the data was compared with the mean for the two methods.

Figure 4.13 shows the comparison between the two methods. On the horizontal, axis the amplitude of variation divided by the mean was plotted. This is a comparison of the deviation compared to the actual size of the line, expressed as a percentage. The percentage difference between the mean and equivalent area was plotted along the vertical axis. For a small variation, the difference between the mean and the equivalent area is small. This is demonstrated by relating the percentage variation to line width. For an amplitude of variation of 20% of the mean, the difference between the mean and equivalent area is only about 2%. This equates to a standard deviation of 14µm in a 100µm wide line and a standard deviation of 28µm in a 200µm wide line.

Lines of practical interest have small variations of line width or cross-sectional area along their length, as large variations are detrimental to the quality of the line. If the line width or cross-sectional area changed by 25% along its length, then, this would have a significant effect on the electrical and functional properties of a line. At this level of variation, the difference between the equivalent and mean area is less than 4%. Therefore, for lines of practical interest there is little difference between the equivalent and mean cross-sectional area or width.

It, therefore, becomes apparent that what is required is a representative value for the line size. It has been determined that the difference between the mean and the equivalent size is small for lines of practical interest. Using the mean value is easier to understand than an equivalent area. It is easier to interpret the mean value, as it is linearly related to the variations along the length of the line, and therefore gives a clearer representation of the cross-sectional size of the line. Therefore, this study will use the mean rather than the equivalent area.

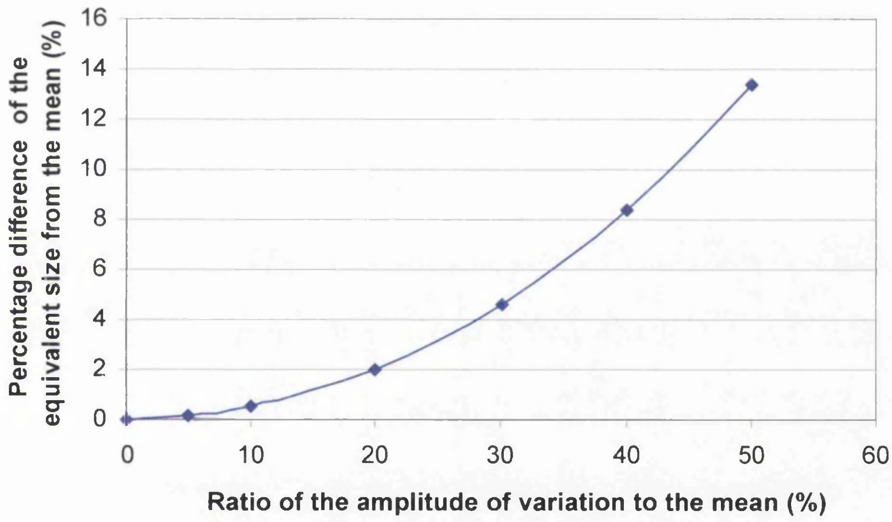


Figure 4.13 : Difference between mean and equivalent width

4.4.2 Line continuity

Measuring line continuity in the frequency domain was considered since it could provide information on the frequency and amplitude of the patterning and thus enable the distinction between mesh marking and edge rippling. There was, though, a problem with leakage and aliasing since the data was discretely sampled. Using the Fourier transform would only allow the accurate prediction of the dominant frequencies within the sample and not the amplitude at the dominant frequencies (49). Leakage will occur if there is not a whole number of oscillations in the sample length. Small changes in the mesh marking frequency, caused by mesh tension, would affect the results. Thus, lines printed using different screens and tensions would have different amounts of leakage and it would be impossible to compare them.

The standard deviation of the width was used to measure line continuity. Standard deviation is a statically proven method for measuring the spread of a data set. Although, it does not distinguish between mesh marking and edge rippling, how this can be achieved is investigated in Section 4.4.3.

4.4.3 Distinguishing between line classes

Examining the continuity of the line width using standard deviation alone determines whether a line has good or poor edge quality, but does not determine why a line has poor edge quality. More information could be obtained if a method existed that distinguished whether the poor edge quality of a line was due to edge rippling or mesh marking. The two classes are probably produced due to different mechanisms, therefore, distinguishing between them would determine, not just that the line was poorly printed, but why. Two methods were considered, these were skew and filtering.

Skew is a measurement of any bias of the probability density function (p.d.f.) to one side of the mean. For a perfectly random signal then the skew is zero. Therefore the skew for the edge rippling will be zero, as edge rippling is random, this is shown in Section 4.3.3. The probability density function (p.d.f.) of a trapezium shaped waveform, and the mesh marking, is biased since there are more points above the mean than below. Figure 4.14 shows the p.d.f. of the width profile of a line with mesh marking.

Edge rippling has no bias in the data set, but the mesh marking does, therefore, it would be possible to distinguish between these line classes by measuring the skew of the line width or cross-sectional area profile. The skewness is not capable of measuring the amount of mesh marking, only that it exists. This is because as the amplitude increases the distribution remains the same, just over a larger range, therefore the skew remains the same.

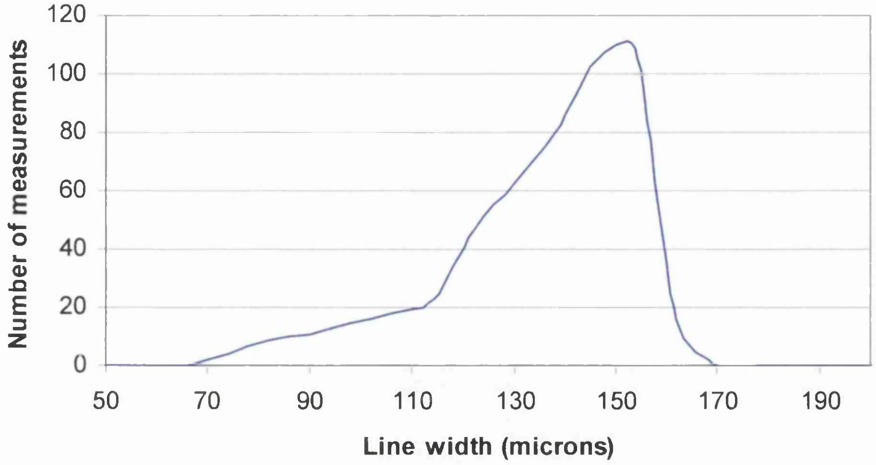
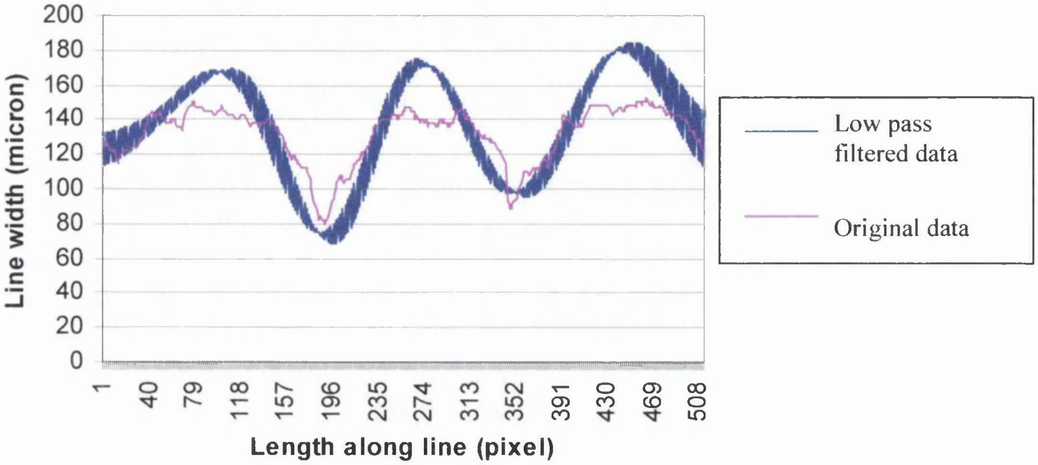


Figure 4.14 : The probability density function of a line with mesh marking

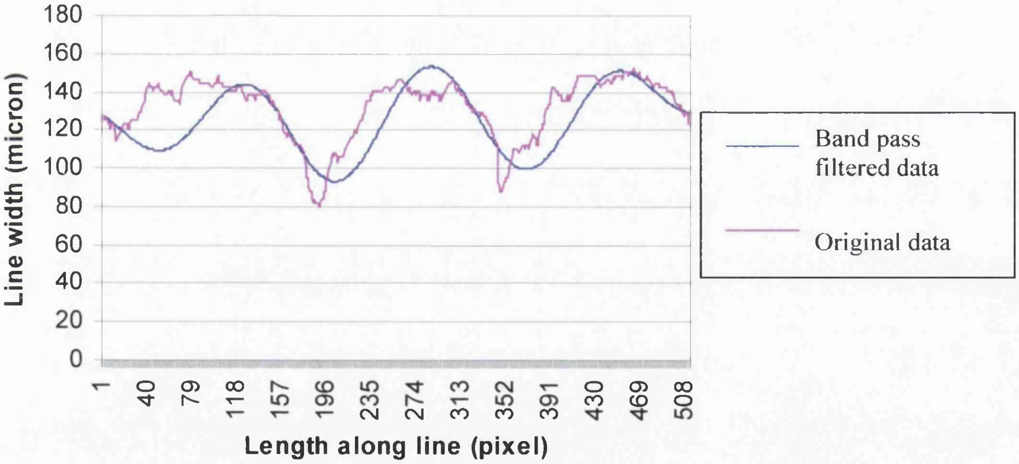
Filtering to can be used to separate the components of the line width data at the two frequencies of the edge rippling and the mesh marking. This is because the frequency of the mesh marking is significantly lower than that of the edge rippling.

Separating components of different frequencies using filtering is the recommended method for analysing different frequencies in surface texture analysis (51). An analogy can be drawn between the line width data and a surface profile. The mesh marking is considered as the shape of the signal and the rippling as the roughness. These can be separated by a low-pass filter with the cut off frequency set between the frequencies of the patterns. A program taken from 'Numerical Recipes in Basic' (52) was used for the Fast Fourier Transform filtering and incorporated into a macro written by the author.

The problem of using a low pass filter is that noise can be produced from the very low frequencies in the sample. Filtering out the low frequencies as well as the high frequencies reduces this. Thus, only the required frequency is examined. This type of filter is called a band pass. Figure 4.15 shows the use of a low pass and band pass filter on some line width data of a mesh marked line.



(a) Low pass filter



(b) Band pass filter

Figure 4.15 : The reduction in noise using a band pass instead of a low pass filter

The method employed by this study to distinguish between edge rippling and mesh marking had the following steps.

1. The line width profile was band pass filtered so that only the components of the frequencies close to the mesh marking frequency were passed.
2. The standard deviation of the filtered and unfiltered data was found and compared.
3. The amount of mesh marking was determined by difference between the standard deviation of the filtered and unfiltered data. If the standard deviation of the filtered and unfiltered data were similar then the lack of continuity in line width would be caused by mesh marking. If the standard deviation of the filtered and unfiltered data were different then edge rippling would be the reason for the lack in continuity.

A limitation of using a band pass filter is that the frequency of the mesh marking must be estimated to complete the analysis. This should be possible from knowledge of the system. If the estimated range is too large then several band passes may be required to be sure of a full examination.

4.4.4 Line cross-sectional shape

The cross-sectional shape was investigated so that the relationship between line cross-sectional area and line width for fine lines could be understood. This would establish if a more accurate method of determining line cross-sectional area from line width, other than assuming a rectangular cross-section, could be developed.

4.4.4.1 Correlating line cross-sectional area and line width

The cross-sectional shape of lines has been defined previously by assuming line height is uniform across width of the line. This is not the case, as a curved section must always exist at the edge of the line, as is shown in Figure 4.16. Many lines were examined and it was found that, for very fine lines, the cross-sectional shape resembled an inverted parabola. For wider lines, the centre of the cross-section is flat, but the line still retains a curved section at the edges. If the line width is large then the cross-sectional shape is close to the uniform ideal. Examples of line cross-sectional shape are shown in Figure 4.17. For fine lines, the effect of the curved section is more significant on the total area and the assumption of the uniform distribution is not accurate. Therefore, it is important to consider other methods of characterising the cross-sectional shape of the cross-section of a line.

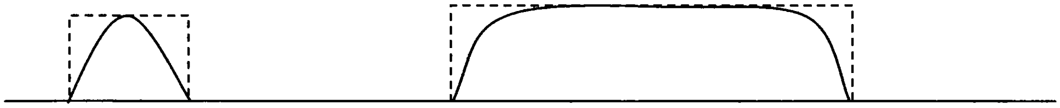
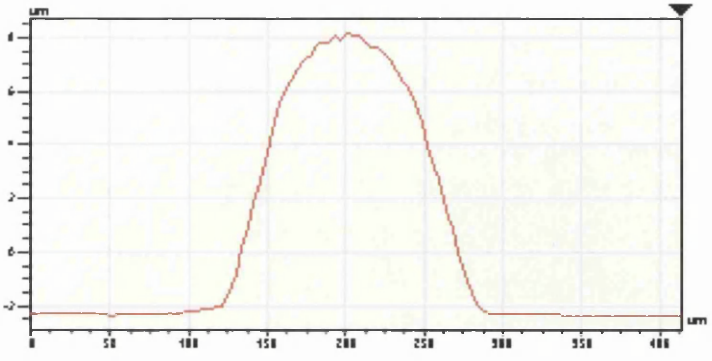


Figure 4.16 : Comparison of a line cross-section to a uniform distribution of the line height along the width



(a) Example of a curved cross-section

(b) Example of a cross section with curved and flat parts

Figure 4.17 : Examples of line cross-sections

To characterise the cross-sectional size of the line, the actual area was related to the area of a rectangle with the same height and width. To compare these, the area of the cross-section was divided by the multiple of the height and the width of the line. This parameter was called the rectangular index and denoted by RI.

$$\text{Rectangular Index} = \text{RI} = \frac{\text{line cross-sectional area}}{\text{line height} \times \text{line width}} \qquad \text{Equation 4.16}$$

This is a new parameter derived specifically to investigate the relationship between the cross-sectional area and line width.

4.4.5 Modelling line cross-sectional shape

Modelling the cross-sectional shape would enable a further understanding of the relationship between line cross-sectional area and line width for fine lines. Two methods were considered to model the line cross-sectional shape; using Fourier series fitting and splitting the cross-section into basic shapes. These methods are described fully in the Appendix B.

Splitting the line cross-section into shapes was used, in this study, to model the line cross-sectional shape of the line, rather than by the alternative method of applying Fourier analysis. Splitting the curve up into shapes only requires one number to define the shape of the cross-section. Thus, it is easier to make comparisons between lines since there is only one descriptor. Although, splitting the curve up into shapes is only possible if it is assumed that the line cross-section is made up of a flat section and a curved section. How this was achieved is described below.

The area of the line cross-section can be modelled in two parts, Figure 4.18 and Figure 4.19. The curved section can be represented as a quadratic function or cubic. The flat section can be represented as a uniform distribution. Further details about how this method was used to model the cross-sectional shape of the line is given in Appendix B.

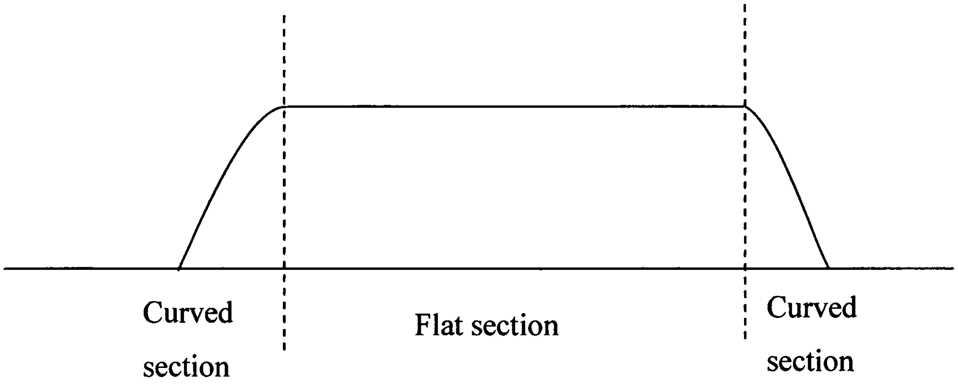
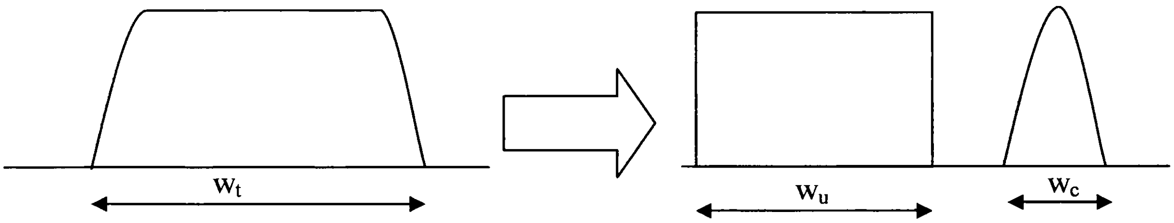


Figure 4.18 : Flat and curved sections of a line



Where,

w_t is the total width of the line

w_u is the width of the line with a uniform height

w_c is the width of the curved section of the line

Figure 4.19 : Representation of a line split into a curved and a flat section

It can be shown, Appendix B, that for a line with a curved section only the cross-sectional area would be:

$$\text{Cross-sectional area} = \frac{2Hw}{3} \qquad \text{Equation 4.17}$$

Where H – line height

w – line width

Therefore,

$$\text{Rectangular index} = \text{RI} = \frac{\text{Line cross - sectional area}}{\text{Width x Height}} \qquad \text{Equation 4.18}$$

$$= \frac{2Hw}{3} \bullet \frac{1}{Hw}$$

$$= \frac{2}{3} \approx 0.667$$

The analysis of a line with a curved and flat section was also considered and is described in Appendix B. The length of the curved section is denoted by w_c and the length of the flat section is denoted by w_u, as shown in Figure 4.19.

$$\text{Rectangular index} = \frac{\left(w_u + \frac{2w_c}{3}\right)}{w_t} \qquad \text{Equation 4.19}$$

Since $w_t = w_u + w_c$

Therefore,

$$RI = 1 - \frac{w_c}{3w_t} \qquad \text{Equation 4.20}$$

From this modelling an understanding of the value of the rectangular index for different line shapes can be inferred. If w_c is large compared with w_u, then RI will be two-thirds. If w_u is large compared with w_c then RI will be 1. These results are summarised in Table 4.2. Therefore, if the curved section is assumed to be an inverted parabola then the error in the cross-sectional area can be as much as 33% compared to the area of a uniform distribution.

Table 4.2 : The effect of changing height and width on modelled area

If $w_u >> w_c$ then $RI = 1$
If $w_u = w_c$ then $RI = 0.83$
If $w_c >> w_u$ then $RI = 0.67$

It would be advantageous to find a way to estimate RI from the measurement of line width. This may involve examining line cross-sectional shape. To examine shape w_c and w_u need to be measured, these parameters are defined in Figure 4.19. To do this a measurement from a detailed cross-section of the line could be taken. A tolerance from the maximum height could be set, above which the line is considered to be flat. This would define the size of w_u. This will give accurate results since the length of the flat section is calculated for each cross-section. Thus, four points on the line cross-section need to be known. These are the start, the width, and the two points between which the line can be considered to be flat Figure 4.20. Again this requires more detailed information to be known about the cross-section of the line.

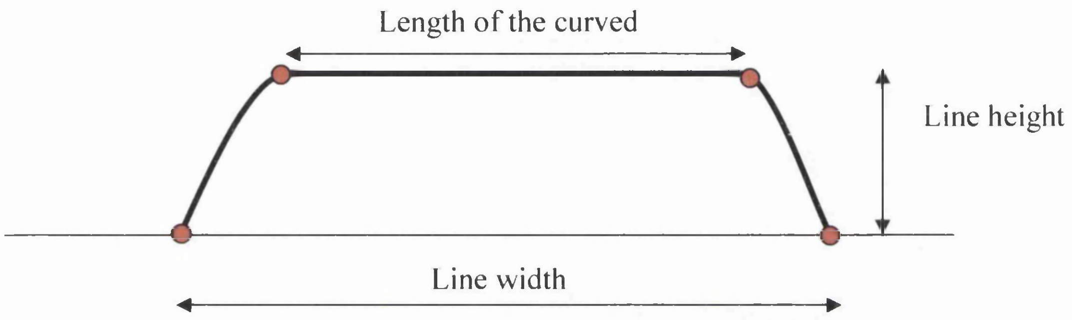


Figure 4.20, Points, shown in red, required to define the length of the flat section and line width to enable a direct measurement of line shape characteristics. The line measurement parameters found from this data are also shown.

It is hard to objectively define the two points between which the line is considered flat. Therefore, another objective definition of w_c was considered, using the parameter rectangular index. Equation 4.20 shows the relationship between the rectangular index the width of the curved section, w_c, and the total width, w_t. This relationship can be used to define w_c as shown in Equation 4.21.

$$w_c = 3w_t(1 - RI) \qquad \text{Equation 4.21}$$

Thus, w_c is not user dependent, since it is an objective measurement of w_c, and will give the correct w_c for a given line width and rectangular index (RI). A limitation exists due to assuming the shape of the curved section was a parabola and the minimum value of RI was two-thirds. If RI is calculated at less than two-thirds, w_c will be calculated to be greater than the total width of the line. If this is the case w_c should be considered as being equal to the total width.

4.4.6 Summary of line measurement parameters

The table below summaries the line measurement parameters.

Table 4.3 : Summary of line measurement parameters

Line characteristic evaluated	**Line measurement parameter**
Three-dimensional line size	Mean of the line cross-sectional area
Two-dimensional line size	Mean of the line width
Line continuity	Standard deviation of the line width
Line cross-section shape	Rectangular index $= \frac{\text{line cross - sectional area}}{\text{line height} \times \text{line width}}$

4.5 Optimisation of measurement settings

4.5.1 Introduction to measurement settings

It is important to reduce measurement errors, by finding the optimal measurement settings, to increase the sensitivity of the measurement system. It is, also, important to quantify measurement errors so that the significance of trends within the results can be understood. The settings to ensure and accurate representation of the line have been established and, in doing so, it was possible to determine the measurement uncertainty of the line measurement parameters. The measure settings were the evaluation length, the sampling interval, the threshold level and the substrate level.

4.5.2 Evaluation length

The evaluation length was optimised by simulating, using the models described in section 4.4.2, the effect of incomplete oscillations within the measurement length on the mean and standard deviation. The number of points along the length of the line was set to 500. The units used along the length represent the pixels that an image is made up from. The units used across the width represent microns. Initially the resolution across the width is set to 3 decimal places. This is equivalent to 1000th of a micron.

The simulated values were compared to theoretically calculated values for a complete oscillation. The theoretically calculated values of the parameters are shown in Table 4.4. The mean and the standard deviation value are independent of the frequency. The theoretical value for the standard deviation is therefore directly proportional to the magnitude of the sine wave. The theoretical value of the mean is linearly related to the magnitude.

Table 4.4 : Ideal values for the probability parameters for the simulated lines

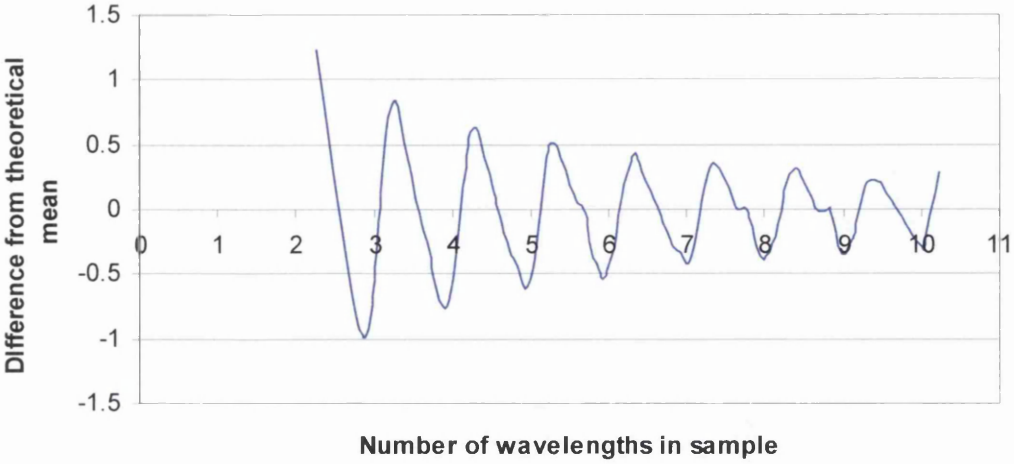
	Mean	Standard deviation
Edge rippling (sine curve)	$\left(w_{max} - \frac{B}{2}\right)$	$\frac{1}{\sqrt{2}} \times \frac{B}{2}$
Mesh Marking (trapezium curve)	$\left(w_{max} - \frac{B}{4}\right)$	0.323B

Where,

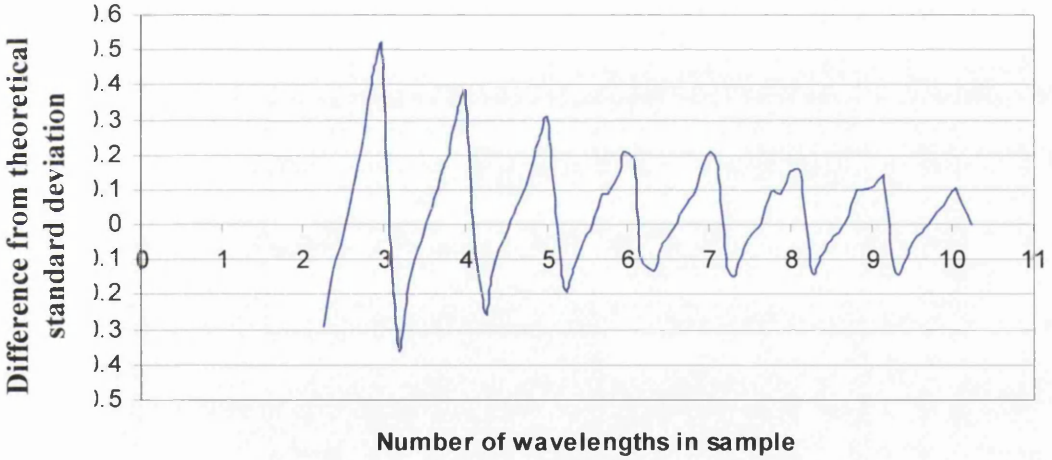
B = peak to peak amplitude of signal

w_{max} = maximum width

If the sample length is not a multiple of the wavelength, since an incomplete oscillation exists, the results will differ from the theoretical value. The largest error will occur if half an incomplete oscillation exists in the data set (49). The error from not measuring a multiple of a complete wavelength reduces as the number of wavelengths within the sample increases, since the proportion of the incomplete wavelength decreases, i.e the error will be larger if only 3 wavelengths are measured compared with 20. The mesh marked patterning has a lower frequency, thus larger wavelength, than the edge rippling. Thus, analysis was considered for the mesh marking as the error will always be higher for this than the edge rippling. Both the trapezium and the sine models were examined, since the sine wave represents the filtered data and also requires evaluation.



(a) Mean value

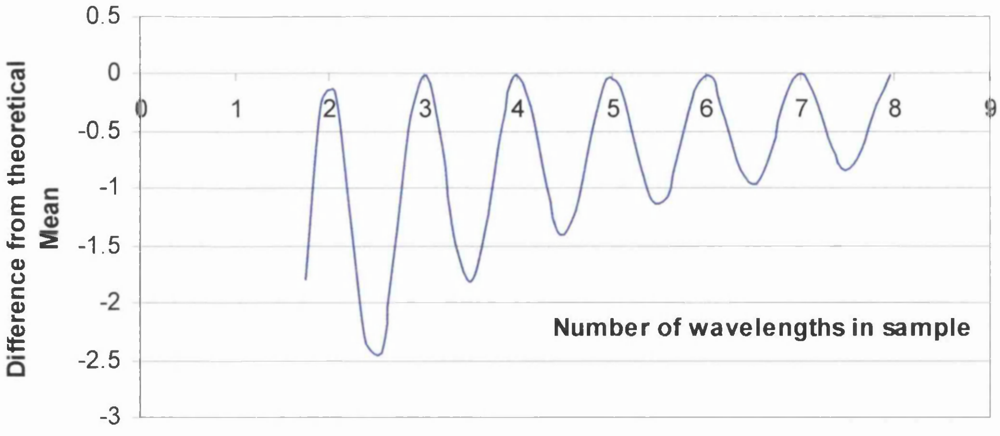


(b) Standard deviation

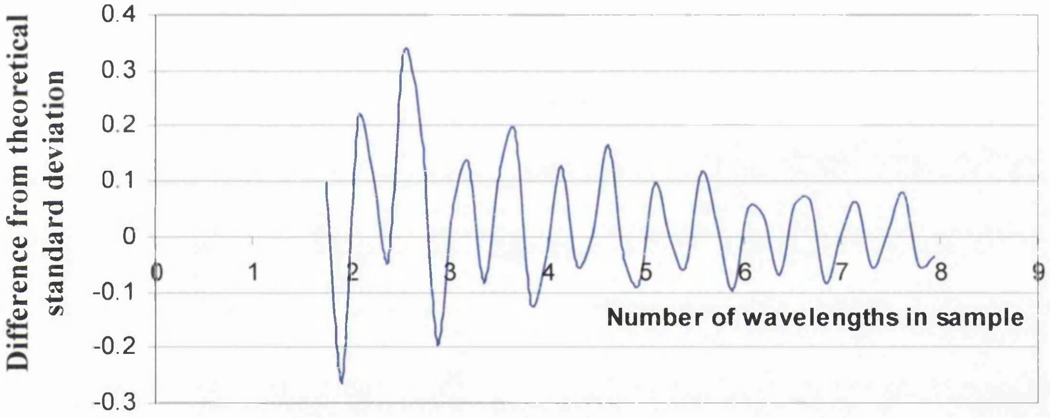
Figure 4.21 : The effect of increasing the sample length on measurement error for the trapezium model

Figure 4.21 (a) and (b) show that if more than three oscillations are examined then the error in the mean is less than 1 unit and the error in the standard deviation is less than 0.4 units. This relates to an accuracy of plus or minus 1μm for the mean. This is below the sampling interval required and used by the study. The range of the standard deviation from straight edge lines to bad lines is from about 4 to 20μm. An accuracy of 0.4μm is low compared with this range.

If a filter was used on a line width data the output data would form a sine curve. Therefore, a sine curve is required to be examined in the same way as the trapezium model in Section 4.3. This was achieved in a similar way to examining the trapezium pattern. Figure 4.22 shows the effect of increasing the number of wavelengths measured in a sample on the mean and the standard deviation value. This shows that for a sample length of at least 3 oscillations with a magnitude of 20 then the mean will not be affected by more than 1.8 units and the standard deviation value by 0.2 units.



(a) Mean



(b) Standard deviation

Figure 4.22 : The effect of increasing the sample length on measurement error for filter data, a sine curve

4.5.3 Sampling interval

To accurately measure features, such as edge rippling, the sampling interval must be small enough to represent patterns in the line width. The sampling theorem states the sampling rate must be at least twice the highest frequency in the sampled data (49). The mesh rippling wavelength was found to be about 70μm along the length of the line. Therefore, the sampling interval along the length of the line must be less than 30μm.

The sampling interval across the width also required consideration. The sampling interval across the width can be considered as the sensitivity of the measurement method to deviations in line width. The magnitude of the rippling was shown in Section 4.3 to be from 5 μm to 20 μm. Therefore the sensitivity, or sampling interval, across the width should be less than 2.5μm.

4.5.4 Threshold level

The effect of threshold level on the precision and accuracy of measuring the 3 dimensional characteristics of a line was investigated. This enabled the optimisation of the threshold level as well as the precision and accuracy of the measurements of line width and cross-sectional area to be determined.

4.5.4.1 Limitations associated with setting the threshold level

Investigation of the threshold level is required to find its optimum setting. The factors that affect the threshold level are described below, followed by a discussion of the steps taken to evaluate and eliminate any limitations.

- **Flatness of Substrate.** If there is a height difference from one side to the other then anomalies may occur in the results. If there is a difference, as shown in Figure 4.23, where height does not drop below the threshold value, then the program may not pick up on the end of the line. In this case, the line will be calculated to be much wider than it is.
- **Substrate roughness.** The threshold hold level cannot be smaller than the R_t of the substrate. R_t is the difference between the maximum peak and trough of the surface roughness profile (44). If the threshold is below this level then the program may pick up on an irregularity in the substrate rather than the line. This is shown in Figure 4.24. The substrate can be considered as the noise level of the signal.

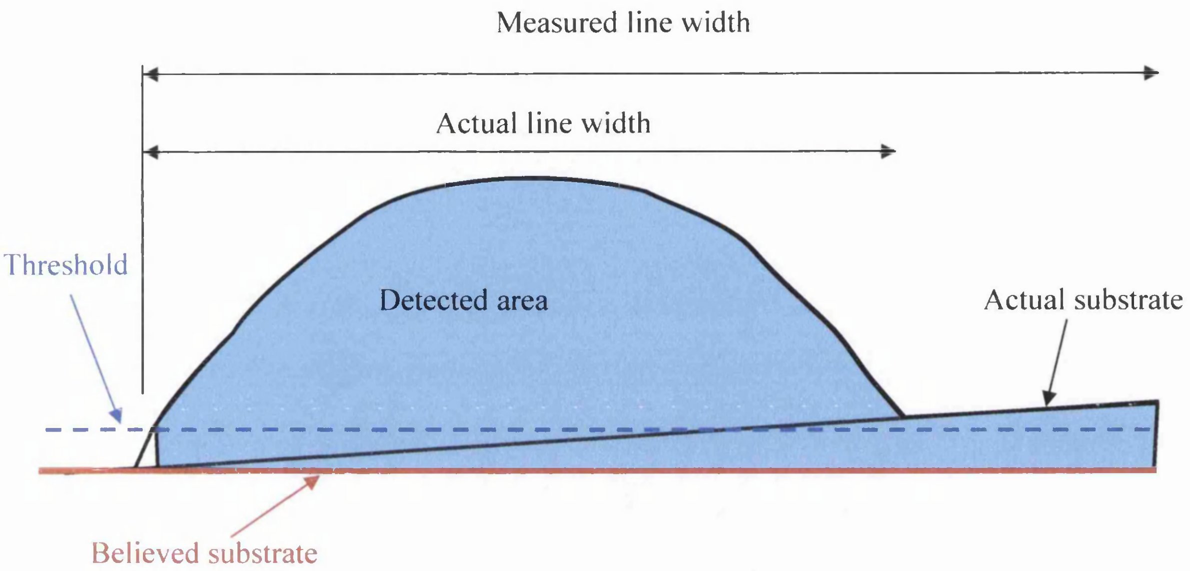


Figure 4.23 : Line width and cross-sectional area measured too large due to the substrate not being horizontal when the printed image is digitalised

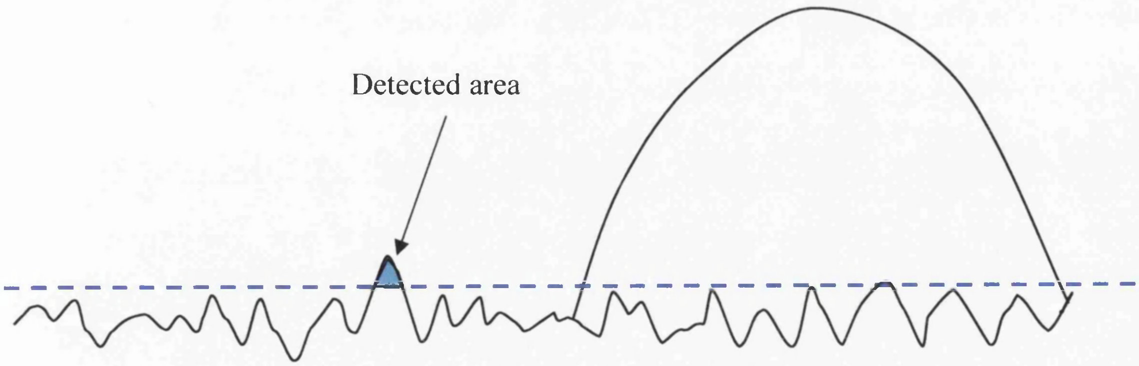


Figure 4.24 : Incorrect measurement of the line due to the threshold level set too low

4.5.4.2 Optimisation of threshold level

Two investigations were completed to investigate the optimum threshold level. Firstly, single cross-sections were examined, to determine how the accuracy and precision was affected by threshold level. This was carried out for single cross-sections as it allows the threshold level to be set lower than for the whole measurement area, since tilt or anomalies on the surface do not affect it as much. A second investigation was carried out to find the minimum threshold level that could be set over the whole measurement area. This enabled the optimum threshold to be set and an evaluation of the accuracy and precision of the measurement at that threshold level to be found.

Two parameters limited the threshold value, namely, the substrate roughness and the tilt. If the threshold value was set to zero then the measured value of line width would be the actual value of line width. This is not possible, in practice, since the substrate is not perfectly smooth and it is impossible to consistently record the samples on a white light interferometer with zero tilt. There are two errors that exist as a consequence of setting the threshold above zero. The complete line width is not being measured, thus there will be a part of the cross-section that is not measured. This will give an offset error. This offset error is unlikely to be the same for each cross-section, therefore there will be a random error. The offset error can be measured and adjusted for.

There are two types of error associated with the measurement method; the accuracy and the precision. The accuracy is how far the mean value is from the correct value. Precision is the variation or spread of the data (18). For this case, the error described above as offset is the accuracy of the measurement tool. The error described as random error is the precision of the tool.

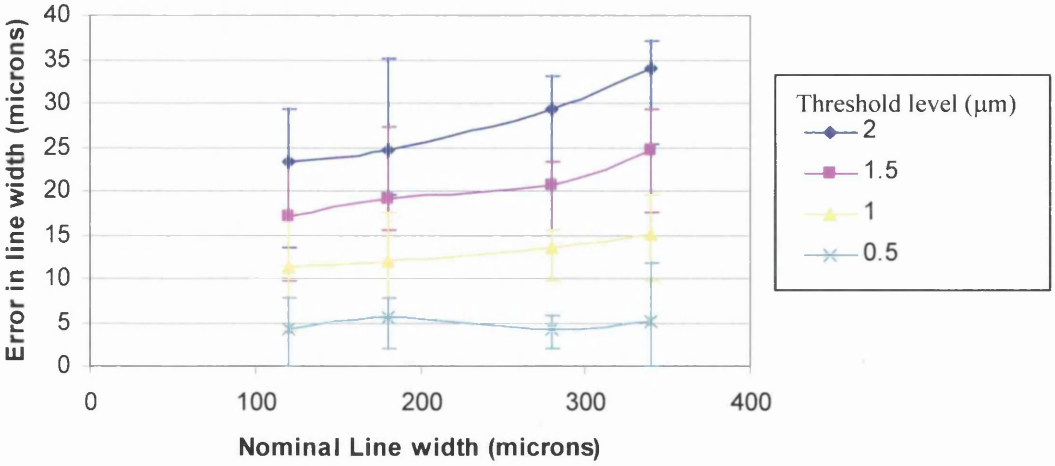
The error on line width and cross-sectional area was studied for different threshold levels. For the investigation into the accuracy and precision of the three-dimensional tool, single cross-sections were examined. An example of the data used is shown in Figure 4.25. A cross-section of a line was examined to determine the line width and area measured at different threshold levels. This was then compared to the actual line width. In this way, the measured width and area can be compared to the actual width and area of exactly the same cross-section. The effect of the substrate and tilt were greatly reduced by measuring a single cross section with a profile that extends only a few microns either side of the edge of the line. This enables the threshold level to be set lower than for the whole measurement area, since tilt or anomalies on the surface do not affect it as much.

Figure 4.25 : A cross section of a line

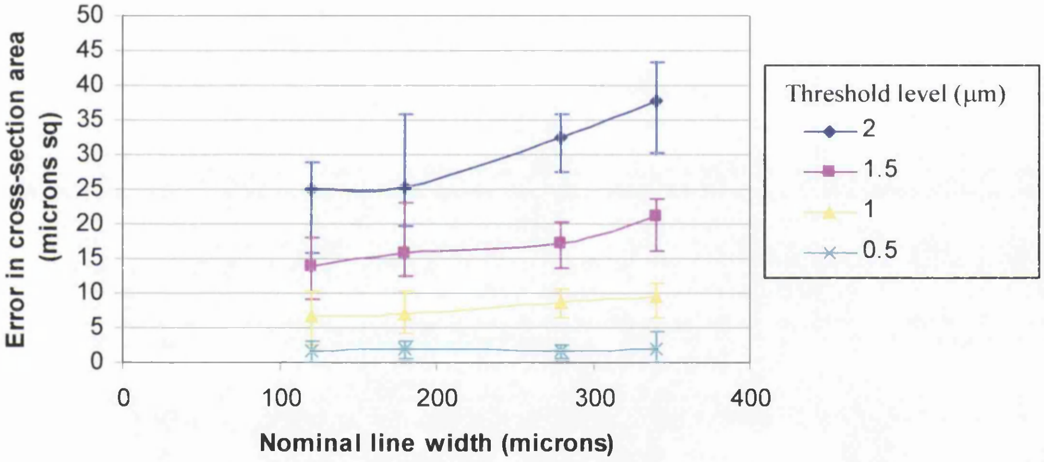
A set of lines at 120μm, 180μm, 280μm and 340μm nominal line width were examined. Lines of different width were used to determine whether line width influenced the accuracy and precision of the measurement of line width and cross-sectional area. The cross-section used was an average over a 300μm length of the sample. 5 samples were examined for each line width studied, making a total of 20 samples. The height varied from 4μm to 8μm.

Firstly, the actual line width, for each cross-section, had to be determined Therefore, the most accurate method of repeatably determining the line width was required. This was achieved by determining the lowest possible threshold level at which no anomalies in the data were seen. By using single cross-sections it was possible to set a lower threshold than could be set for analysing a full data set, although the threshold level could not be 0 as there will always be a small amount of tilt and roughness on the substrate. At a threshold value of 0.1μm some of the recorded line widths produced anomalies. The lowest threshold level at which no errors occurred was 0.25μm. For this reason, the threshold for the actual line width and area measurement was chosen to be 0.25μm. Threshold levels of 0.5μm, 1μm, 1.5μm and 2μm were then used to investigate the effect of changing the threshold on line width and cross-sectional area.

The accuracy and precision of the measurement system was examined using the mean and standard deviation value of the error from actual line width. Figure 4.26 shows how the mean errors in width and area vary with the line width and reveals how the trends are similar for both area and width. For the low threshold values, the error was hardly affected by width. The increase in line width error, using a threshold of 1μm, from a 120μm line to a 340μm line was only about 4μm. For higher levels of threshold, the mean error in width and area was affected by the line width. For low threshold values, it was found that width has little effect on the area but, for higher threshold values the line width has a significant effect.



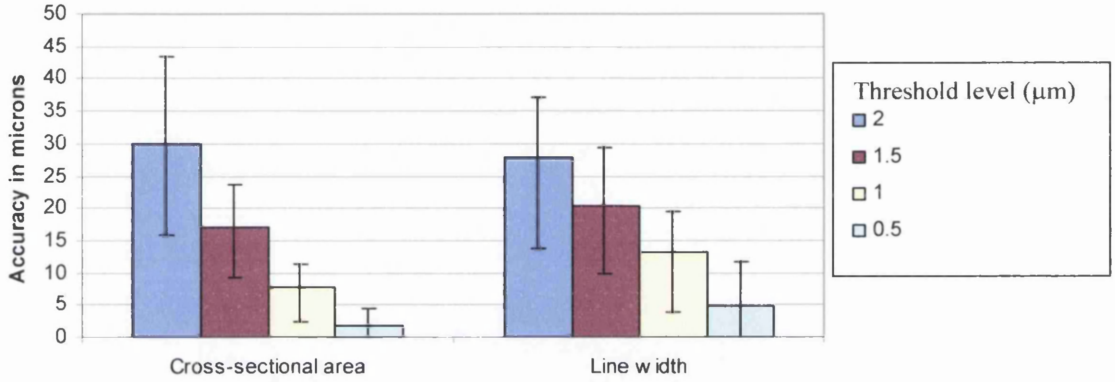
(a) Line width



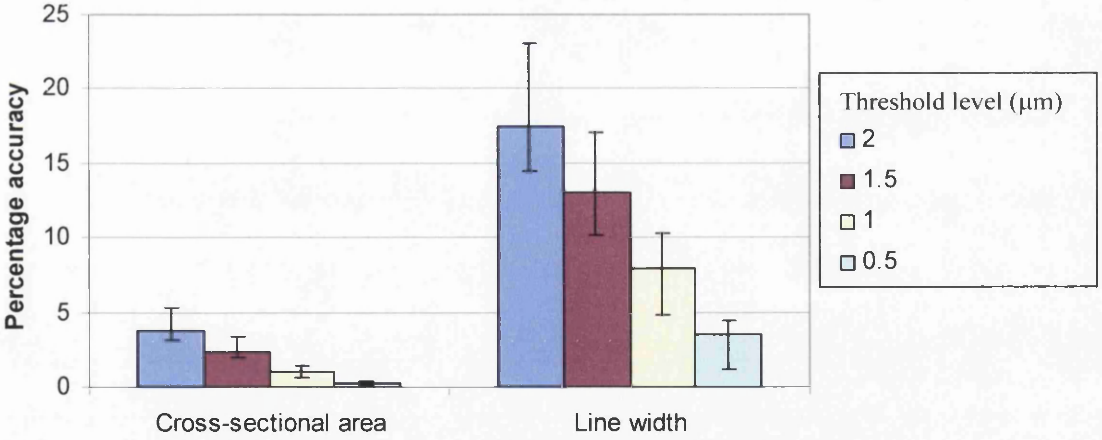
(b) Cross-sectional area

Figure 4.26 : The influence of threshold level on the accuracy of the measurement of line width and cross-sectional area

Figure 4.26 (a) and (b) show that the mean error increases as the threshold level increases. To show the effect of the threshold level more clearly, the results for the width and the cross-sectional area at each threshold level were averaged. The comparison of the error in the width and the cross-sectional area is shown in Figure 4.27. The absolute errors of width and cross-sectional area are similar, but the area of a cross-section is much larger than the width. Therefore, the percentage error in the width is much greater then the percentage error in the area. The results are shown for the percentage error for the width and area for 180μm lines in Figure 4.27 (b). The absolute error is comparatively unaffected by line width, so the percentage error is dependent on line width, therefore it would be misleading to average all the results at each threshold.



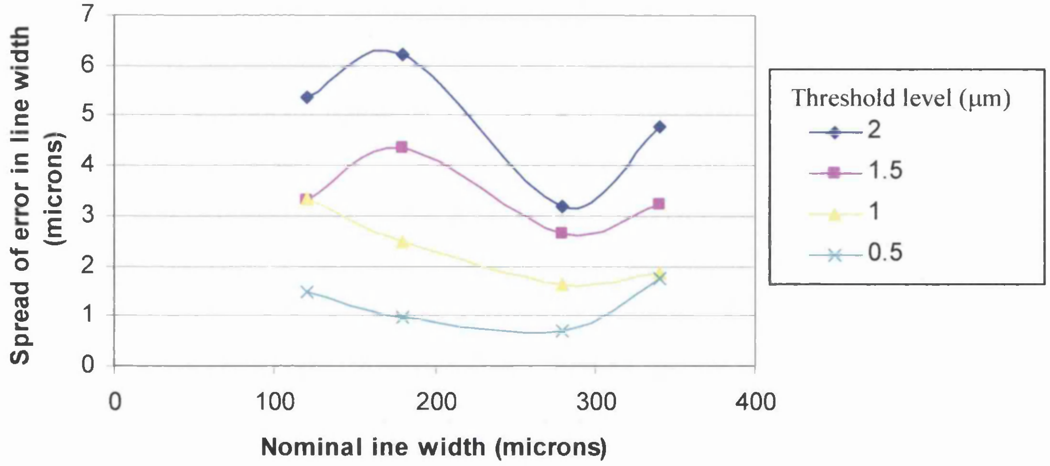
(a) Accuracy



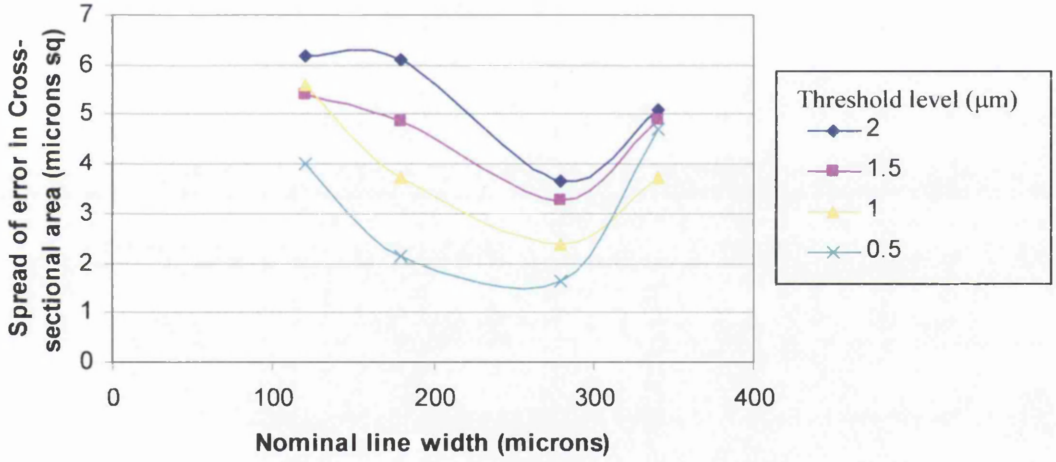
(b) Percentage accuracy for the 180μm line

Figure 4.27 : The accuracy of the measurement of line width and cross-sectional area at different threshold levels

The error bars in Figure 4.26 show that the random error in the width and cross-sectional area is not affected by line width. This is shown more clearly in Figure 4.28, a plot of the standard deviation of the spread obtained at each line width and threshold level. The precision of the measurement of line width can be considered to be constant for all line widths for a given threshold level. Thus, to study the random error, all results can be considered together, Figure 4.29. The precision is linearly affected by threshold level, an increase in threshold value causes an increase in the random error of the area. The width and the area are compared using a percentage error for the 180μm lines, this is shown in Figure 4.29. This shows that the error for the area was negligible. The error in the width for narrow lines is significant at high threshold levels.

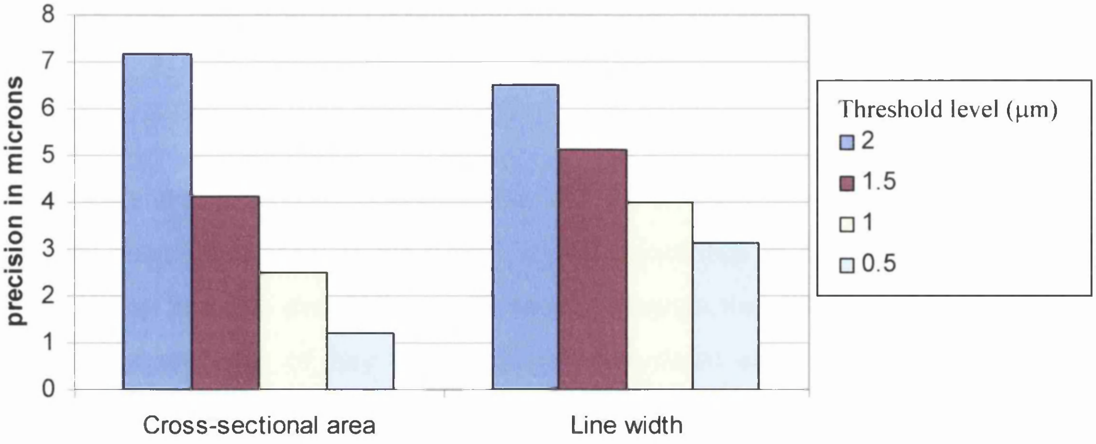


(a) Line width

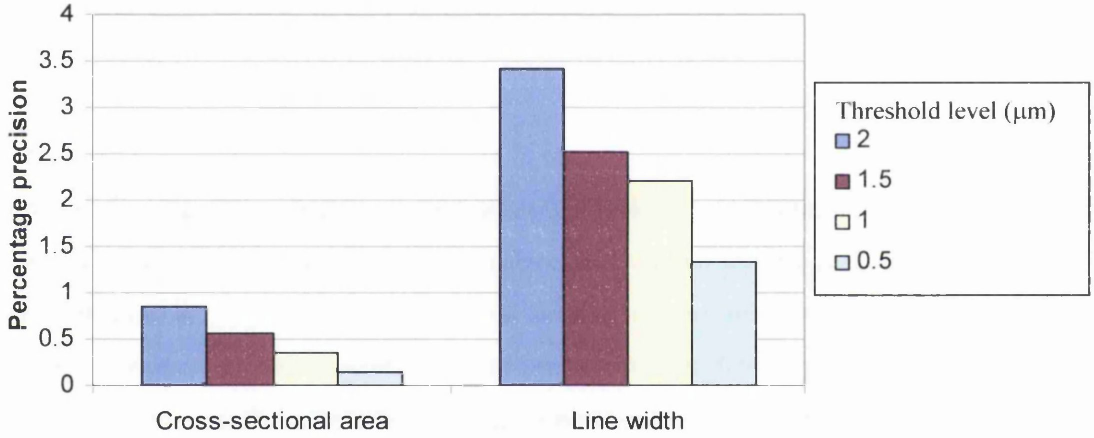


(b) Cross-sectional area

Figure 4.28 : The effect of line width on the precision of the measurement of line width and cross-sectional area at different threshold levels



(a) Overall precision



(b) Percentage precision for the 180μm line

Figure 4.29 : The precision of the measurement of line width and cross-sectional at different threshold levels

In ideal circumstances then it would be possible to use the lowest value of the threshold to reduce errors. This is not possible due to the roughness of the substrate and the tilt while measuring. Tilt can be reduced and accounted for, but it would be impossible to completely remove its effect. The techniques for measuring and accounting for tilt are described in Section 4.6.4. The threshold level to be chosen is dependent on the roughness of the substrate. The same substrate was used throughout this study and it was smooth, equivalent to a low noise level, to enable a low threshold level and thus more accurate results.

There is a trade off between accuracy and precision, and the errors which are introduced by measuring the substrate as part of the line. The work described in this section has shown that the lowest possible threshold should be set to ensure the best accuracy and precision of the measurement of line width and cross-sectional area. Therefore, the limiting factor is the roughness of the substrate, as this will determine how low the threshold can be set. To ensure the substrate was not included in the measurement of the line width the threshold level was set to twice R_t, where R_t is the maximum peak to trough value of the surface profile data. R_t for the substrate used was found to be 0.5μm, therefore the threshold level was set to 1μm.

4.5.5 Substrate level

Two methods of finding the substrate datum were considered. A histogram plot was considered in a similar way to image analysis, as described in Section 3.3.2. The heights were put into 256 bins and plotted as a histogram. From this, the threshold level can be found from the minimum value or a substrate level found from the first peak. This system would not take into account the tilt of the sample, which is hard to keep at sub-micron level over the 1mm length of the sample. A method to determine the substrate datum, which accounts for the tilt in the sample is described below.

Inaccuracies caused by the substrate not being horizontal when it was recorded needed to be overcome. To do this, great care was taken recording the samples to ensure they were as level as possible. To measure the flatness of the substrate, the substrate height was calculated at each side of the sample. The positions of substrate height measurement are shown in Figure 4.30. For line 1, the substrate height 1 was used and, for line 2, substrate height 2 was used. The substrate height values were checked to be within two micron of each other. This ensured the all the profiles measured were flat and errors were reduced at the measurement stage, thus negating any requirement for more complicated post processing to achieve a reliable substrate datum. Nearly all the samples were measured within this tolerance first time. Those that were not were re-measured. If a lower tolerance had been set, many samples would have to be re-measured. This tolerance was found to give accurate results on all the samples examined in Chapter 5.

The substrate level closest to each was used, as shown in Figure 4.30. The substrate height for line 1 was used a analyse line 1 and the substrate height for line 2 was used to analyse line 2.

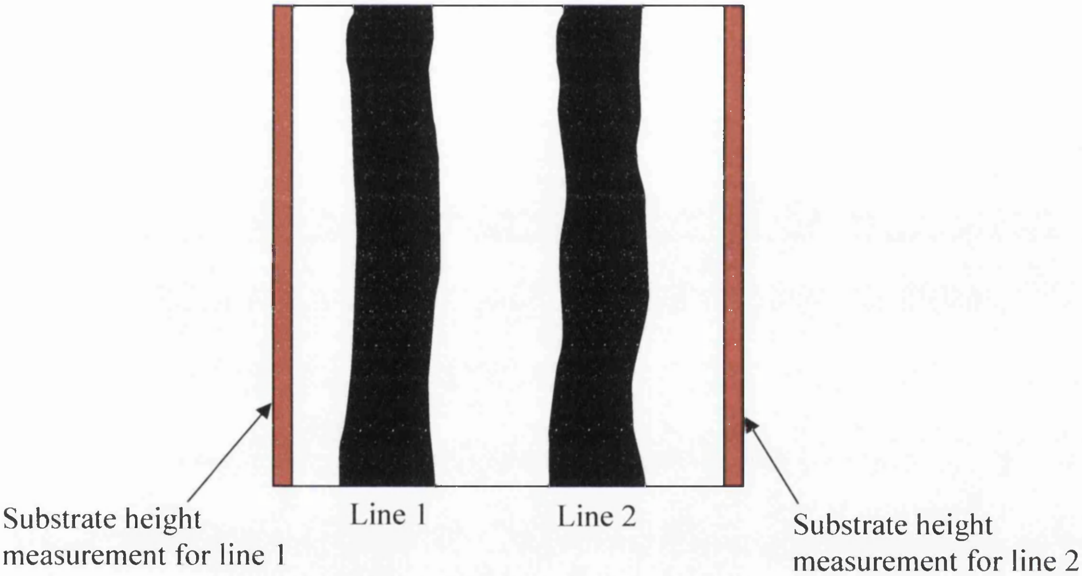


Figure 4.30 : Substrate height measurement. The figure illustrates where, within the data set, the measurement of the substrate height was made.

4.5.6 Summary of measurement settings

In this section the settings required to ensure the results are representative of the printed lines have been detailed. This is summarised in Table 4.5.

Table 4.5 : Summary of measurement settings

Measurement setting	**Value**
Evaluation length	At least 3 mesh marking wave lengths
Sampling interval along the length of the line	30μm
Sampling interval across the width of the line	2.5μm
Threshold level	1μm above the substrate

4.6 Description of measurement technique

This section takes all the information from this chapter and fully describes the method used to extract relevant measurement parameters from the printed lines. It describes the settings used on the instrumentation to ensure the correct sampling interval and sample length. The method used to segment the three-dimensional data to objectively measure the profiles for line width, line cross-sectional area and line height is described.

The WYKO surface profiler, described in Chapter 3, was used to obtain a three-dimensional profile of screen printed lines. It was shown in Section 4.4.6 that the sampling interval had to be less than 2.5μm across the width of the line. To ensure this, the magnification of the interferometer was set to 5. This meant the resolution across the width was 1.95μm per pixel and 1.67μm per pixel along the length. The sampling interval along the length of the line did not have to be this small and it was set to every other pixel, thus a sampling interval of 3.34μm was used along the length of the line. The addressability, ability to store a number of discrete points (53), of the WYKO interferometer was 736 by 480. This meant the evaluation length was 1229μm. This was more than three mesh marking wavelengths for all the lines printed in this study. It would have been possible to go to a higher resolution, by changing the magnification, but this was not necessary as the sampling interval across the width was less than 2.5μm and a higher magnification would have reduced the evaluation length to contain less that three mesh marking wavelengths. Within the measured area, it was possible to record two lines and this was called the measurement area, as shown in Figure 4.31.

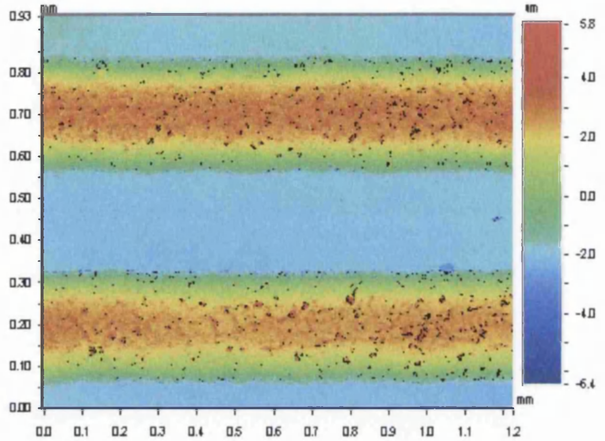


Figure 4.31 : Example of a measurement area used to digitalise the printed lines. Two lines side by side were captured within each measurement area.

The surface profile was exported in ASCII format to allow post-processing using bespoke code written by the author. A macro was written, by the author, in Microsoft Excel to analyse the data in a similar method as an image processor detects and segments an image; except the data represents actual distance measurements. Thus, the threshold value is not a greyscale value, but a height of the ink film above the substrate. The threshold level chosen was 1μm, as described in Section 4.6. Using this threshold level meant the precision for the line width was 2.5μm, and, 4μm for the cross-sectional area. The programme analysed both lines within the measurement area. The values of width and area were adjusted for the offset error shown in section 4.6. This was 13μm for line width and 8μm^2 for cross-sectional area. The substrate levels at each side of the image were checked to ensure that they were within 2μm, this ensured that the sample was flat when the data was recorded.

The macro exported the profile, mean, standard deviation, maximum and minimum for:-

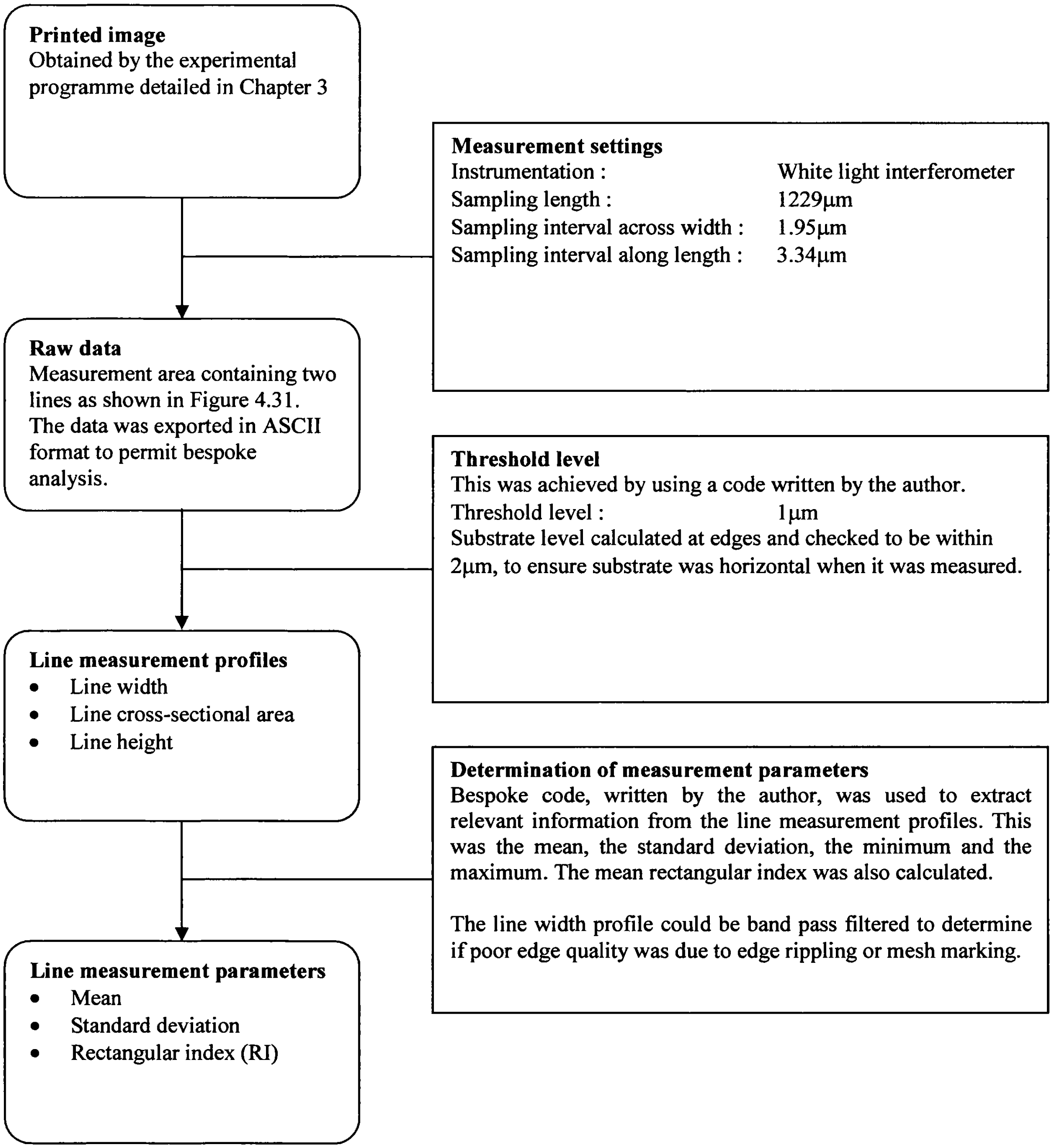
- Line width – End of line minus the start of the line
- Cross-sectional area - Numerical integration of the height data within the line width.
- Line height – Largest value of line height within the line width
- RI – comparison of the actual area with that of a uniform height across the width

The profiles could also be examined using a FFT band pass filter. This removed the high frequency signal of the edge rippling and could be analysed as described in Section 4.4.3 to distinguish between the classes of edge defect.

The uncertainty in the measurement method is summarised in Table 4.6 and the steps taken in determining the line measurement parameters are summarised in Figure 4.32.

Table 4.6 : Measurement uncertainty for the measurement method

Line measurement parameter	Measurement uncertainty
Line width	±2.5μm
Cross-sectional area	±4μm^2



Printed image
Obtained by the experimental programme detailed in Chapter 3

Measurement settings

Instrumentation :	White light interferometer
Sampling length :	1229μm
Sampling interval across width :	1.95μm
Sampling interval along length :	3.34μm

Raw data
Measurement area containing two lines as shown in Figure 4.31. The data was exported in ASCII format to permit bespoke analysis.

Threshold level
This was achieved by using a code written by the author.
Threshold level : 1μm
Substrate level calculated at edges and checked to be within 2μm, to ensure substrate was horizontal when it was measured.

Line measurement profiles
- Line width
- Line cross-sectional area
- Line height

Determination of measurement parameters
Bespoke code, written by the author, was used to extract relevant information from the line measurement profiles. This was the mean, the standard deviation, the minimum and the maximum. The mean rectangular index was also calculated.

The line width profile could be band pass filtered to determine if poor edge quality was due to edge rippling or mesh marking.

Line measurement parameters
- Mean
- Standard deviation
- Rectangular index (RI)

Figure 4.32, Flow chart showing the steps of the fine line measurement system. This shows how the line measurement parameters were obtained from the printed image

4.7 Closure for the development of line measurement methods

Within this section the development of the measurement system has been described. The functionality of lines was examined and it was shown that the area was the parameter that was affected by the screen printing process that determined the resistance of the line. To produce an effective measurement system, both cross-sectional size and the continuity of lines requires measurement. The size directly affects the properties of the line. The continuity affects how close lines can be placed together and the minimum line width.

The optimal techniques to measure the line cross-sectional size and continuity were the mean and standard deviation. The sample length and sampling interval were also examined theoretically. The optimum threshold level was determined and the accuracy and precision were measured. This Chapter concluded by bringing all the work in this chapter together and describing the measurement technique developed from this work. The work showed that a single measurement area would be representative of the line provided the line was repeatable along its length. This method can, therefore, be used to measure the process repeatability by measuring several measurement areas. This was carried out and described at the beginning of the next chapter. From this the total sample length that would be representative of the line, taking into account the process variability, was determined.

Chapter 5

Investigation of fine line screen printing

5.1 Introduction to the investigation into fine line printing

The previous Chapter has described the development of analytical and statistical techniques to characterise the quality of screen printed fine lines. These techniques were used to analyse the experimental programme described in Chapter 3 and the results are presented and discussed in this Chapter. This Chapter begins with a summary of the experiment undertaken to investigate fine line printing. The repeatability of the screen printing process was first examined and from this the required sample length was determined. The effect of the line orientation was investigated and followed by the process parameters. Relationships were established between process parameters and line size, continuity and cross-sectional shape. A correlation between line width and cross sectional area was investigated.

5.2 Summary of experimental method

An experiment was performed to investigate the influence of process parameters on fine line reproduction. A full description of the experiment is given in Section 3.5, a summary of the main details is given here. The printing press, image and the substrate type were maintained constant for all of the experiment. The image was chosen so that the orientation of the lines to the print and the mesh could be investigated.

The experiment was split into 3 parts so that specific parameters could be concentrated on. These were an investigation of the effect of squeegee parameters, the ink type and the screen on fine line reproduction. For the squeegee parameters, a full factorial experiment was undertaken examining squeegee pressure, angle and hardness. Three levels were used for each parameter, thus a total of 36 combinations of settings were investigated. This allowed the investigation of the interactions between these parameters. Three inks were investigated and their viscosities and contact angles were characterised. For the investigation into the effect of the screen on fine line reproduction, 10 stencils were examined of differing profile (stencil thickness) and roughness. Thus, the total number of screen printing process parameter conditions to be investigated was 49.

5.3 Measurement of results

The techniques described in Chapter 4 were used to measure the printed images obtained from the experiment detailed in Chapter 3. The aim of the work was to investigate, not just, the screen printing process parameters, but also the orientation of the line to the print direction and the repeatability of screen printing. The printed image contained 10x10mm sized patches of lines printed at different line widths and orientations, as shown in Figure 3.16. The measurement method described in Chapter 4 uses a white light interferometer to measure an area approximately 1mm^2. For each of the printed conditions, line width and orientation, more than one measurement area was measured. The number of measurements obtained is described below.

The investigation into screen printing process repeatability and the uncertainty of the results was achieved by measuring 5 measurement areas for each of the 49 printed conditions and at 4 line widths (90µm, 120µm, 180µm and 280µm). It was only possible to retrieve useable results from the 340μm wide line for prints from the investigation into the ink properties and for 6 of the trials investigating the screen. This was because in many cases the 340μm wide lines had spread and adjacent lines had joined, thus no data could be retrieved. Thus a total of over 200 conditions were investigated and over 1000 measurements were made.

The investigation of the orientation was achieved by measuring five orientations, (15, 30, 45, 60 and 75 degrees) at 3 line widths (90μm, 180μm and 280μm). This was achieved for all 49 of the screen printing process parameter combinations printed. Thus, a total of 735 conditions were measured. An average of 3 measurements was used at each condition, therefore a total of over 2200 measurements were made.

The screen printing process parameters were investigated using an average of the results used to investigate the process repeatability. Therefore a total of over 3200 measurements were made.

5.4 Process repeatability and uncertainty within data

The work described in this section aimed to further the understanding of the ability of screen printing to reproduce fine lines and to determine the uncertainty within the data set. This work ensured the correct number of samples was taken so that the results were representative of the whole line and that the significance of any trends found within the data could be determined. Placing error bars on all the plots of the results would lead to cluttered results and, therefore, a lack of clarity of the trends. Therefore, the uncertainty of the complete data set has been characterised so that it is not necessary to evaluate the scatter for each individual result.

The difference between the maximum and minimum values of the line measurement parameters measured from five measurement areas was used to evaluate the capability of the screen printing process to repeatability produce fine lines. This was named the spread of the data and is defined in Equation 5.1.

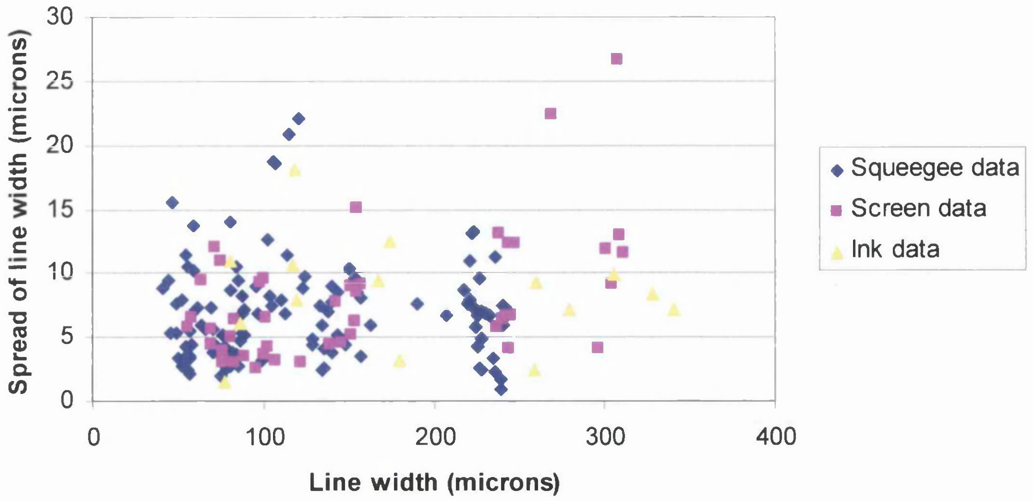
$$\text{Spread} = \begin{array}{l}\text{Maximum of the 5 line}\\ \text{measurement parameters}\end{array} - \begin{array}{l}\text{Minimum of the 5 line}\\ \text{measurement parameters}\end{array} \qquad \text{Equation 5.1}$$

Where, the line measurement parameter is either the line width, line cross-sectional area or line width standard deviation.

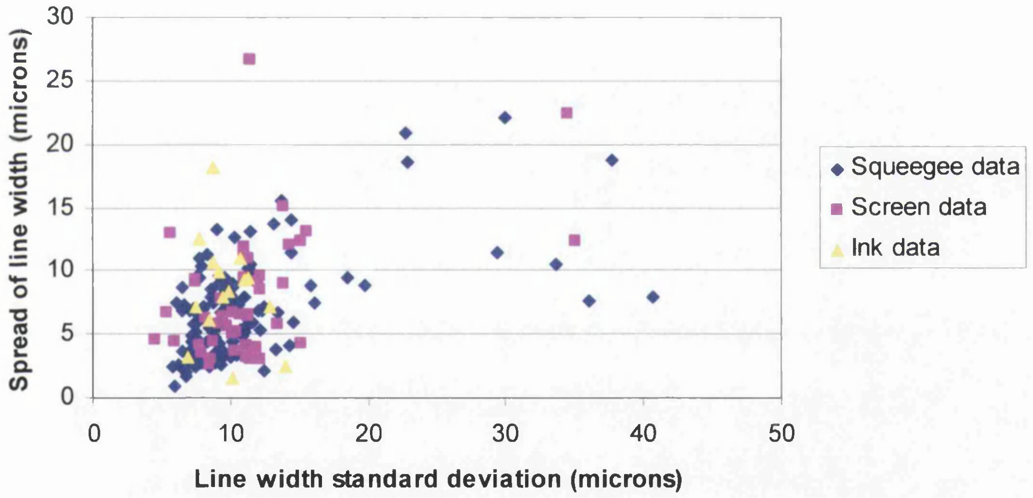
Chapter 4 described the measurement system and the measurement error was determined. Provided the variation over the length of the line is deterministic, i.e. repeatable over a large scale, then difference between the line measurement parameters obtained from two measurement areas would be within the measurement error. Therefore, any difference between the line measurement parameters would be due to the process not being repeatable along the length of a line. Thus, by investigating the spread of the data (Equation 5.1) then it is possible to assess the repeatability of the screen printing process to reproduce fine lines.

5.4.1 Line width and cross-sectional area

Figure 5.1 and Figure 5.2 show the spread for the line width and the cross-sectional area respectively. The results are split into the three parts; the squeegee parameters; the ink; and the screen. The spread of the line width data is plotted against line width, Figure 5.1 (a), and line width standard deviation, Figure 5.1 (b). The spread is similar for all line widths and is less than 10–15μm for nearly all trials performed. No strong relationship was found between the spread of the line width data and line width standard deviation. Although lines with a high standard deviation value had a large spread, lines with a low standard deviation showed a range of spreads. It was concluded that the process variability was about ±7μm for the line width. The measurement error was ± 2μm, this is equivalent to the sampling interval. Thus there can be considered a variation over the print of at least ±5μm. Therefore, it is necessary to take a large sample of readings to ensure a statistically correct result. The number of measurements required is determined in Section 5.3.4.



(a) Spread of line width data compared to line width



(b) Spread of the line width data compared to line continuity

Figure 5.1 : Spread of line width data

The spread of the cross-sectional area was examined by plotting the percentage spread against line width. The percentage spread was used as it was not possible to compare individual lines together because of the large variations in the area of lines with different widths and different printing conditions. For most of the trials the spread was less than 20%. This is significantly larger than the estimated measurement error of less than 1 percent. This suggests a large variation in the cross-sectional area along the length and reinforces the requirement to obtain a large number of readings to obtain a statistically valid result.

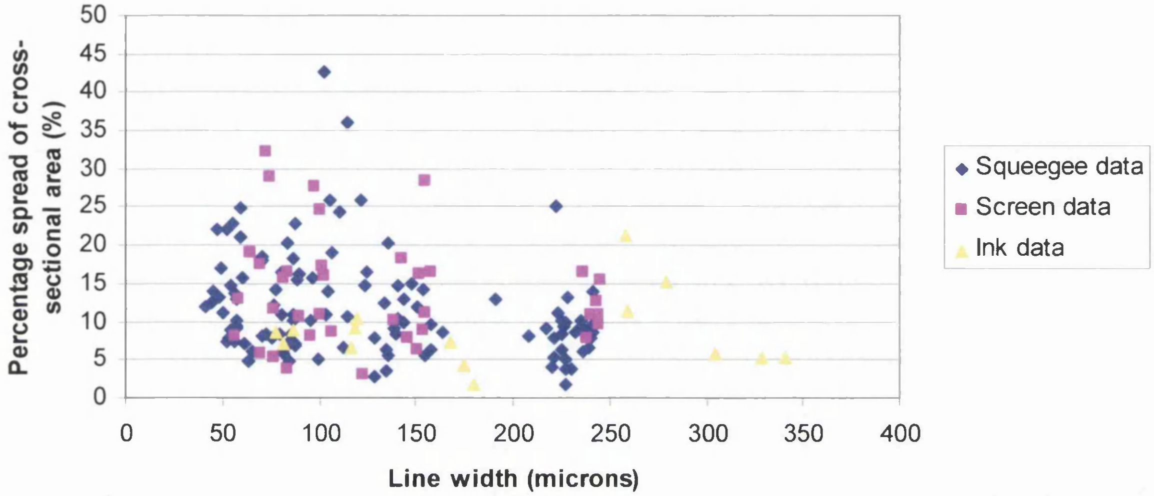


Figure 5.2 : Spread of the cross-sectional area data

5.4.2 Line width standard deviation

Figure 5.3 shows that the process variability increases with line width standard deviation. For lines with an standard deviation of 20μm, considered to have rough edges, the spread of the line width standard deviation varies from about 10μm to 20μm. For the majority of lines, and those considered as high quality lines with a low standard deviation, the spread of line width standard deviation was much lower. Most of the smooth edged lines had a spread of less than 5μm, although some had a spread up to 7μm. Rough edged lines had a spread of up to 15μm or more. Thus, the uncertainty in the data for line width standard deviation was about ±3μm for smooth lines and ±8μm to 10 μm for rough edged lines.

Figure 5.3 shows that as the edge quality of the line reduces the process becomes less repeatable. This means the mesh marking is not a perfectly repeatable pattern and to quantify line quality a large sample is required from several parts of the line.

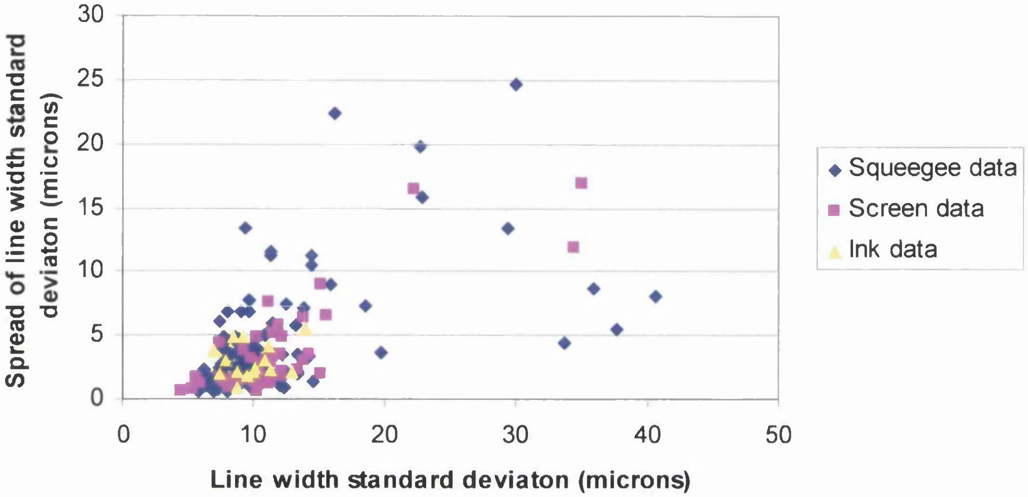


Figure 5.3 : Spread of line continuity Data

5.4.3 Repeatability and sample length

It was important to ensure that sufficient measurements are obtained such that the results are representative of the whole line. An estimate of the population mean and variance (variance is the square of the standard deviation) has to be established from a sample mean and variance. Population refers to parameters associated with the complete line. This is achieved by finding the standard deviation of the sample means (54). If the population is assumed normally distributed then Equation 5.1 can be used to find the standard deviation of the sample means. This is called the standard error to distinguish it from the standard deviation of the population.

$$\sigma_{\bar{x}} = \frac{\sigma_{pop}}{\sqrt{N}}$$ Equation 5.2

Where,

$\sigma_{\bar{x}}$ is the standard deviation of the sample means (standard error)

σ_{pop} is the population standard deviation

N is the number of samples

Equation 5.2 shows that the standard error of the sample means is directly related to the standard deviation of the population. Therefore, smooth lines will have a have smaller sample mean standard error than rough lines for the same sample size. This study wishes to characterise both rough and smooth lines, therefore the limiting factor on sample size, to ensure a small error for the sample means, will be the rough lines. It is, therefore, necessary to examine rough edged lines as opposed to smooth to ensure a sufficient sample size.

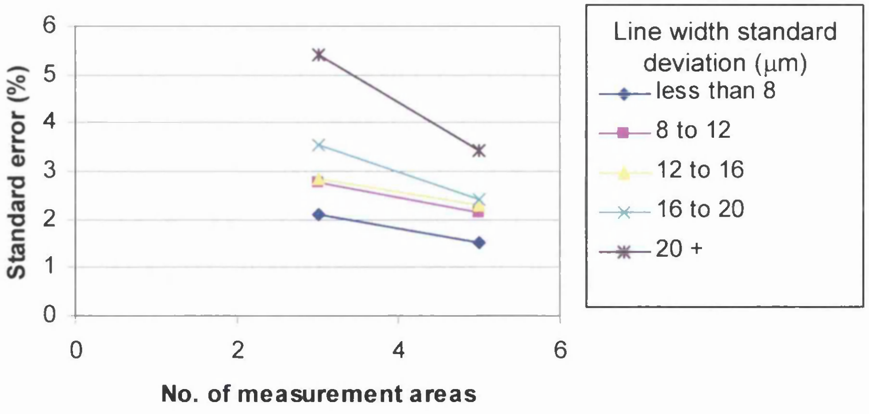
Figure 4.7 in Section 4.3.3 shows that the population for rippled edged lines was normally distributed. In section 4.4.4, though, it was shown that the mesh marked lines were not normally distributed, but had a skewed distribution. Thus, it is not possible to assume that the population of the rough edged lines is normally distributed and these are the lines which will determine the required sample size. It can, though, be assumed that the mean and standard deviation of the sample means of the line width or cross-sectional area are normally distributed, as variations due to the sampling will be random. Thus, the standard error can be found for measuring either 3 or 5 measurement areas, as described in Section 5.3.

The standard error was found for every trial performed for this experiment and for each line width, as for the investigation into process repeatability, i.e. over 1000 conditions. To plot each result would lead to confusing presentation, so the results were split by line width standard deviation. This method of splitting the data was chosen as the standard deviation of the population has an effect on the number of samples required to be taken.

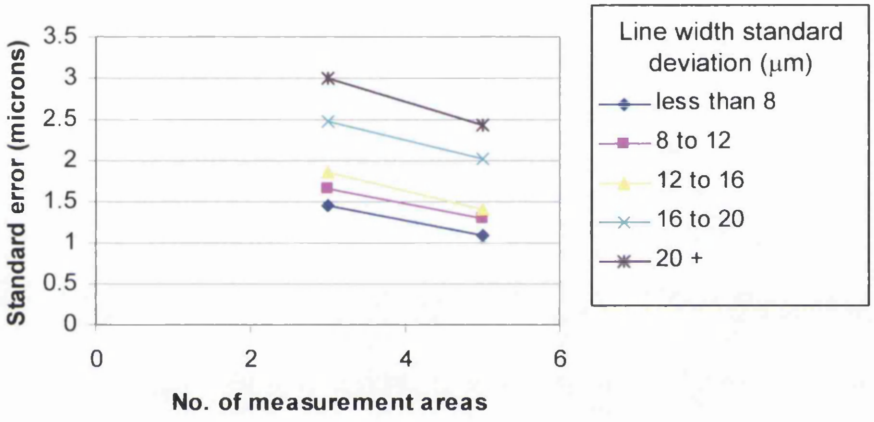
This enabled a comparison of lines of different edge roughness. The results were separated into lines with a standard deviation of less than 8μm, 8μm to 12μm, 12μm to 16μm, 16μm to 20μm and more than 20μm.

Figure 5.4 shows the standard error, for taking 3 and 5 measurement areas, in the sample means for the cross-sectional area and the width, as well as the standard error in the width standard deviation. The decrease in error from 3 to 5 measurement areas for the cross-sectional area was 1 to 2 percent, for the line width it was 0.5μm and for line width standard deviation it was 0.5 to 1μm. Generally, the rougher edge lines had a larger standard error than the smoother edge lines. For the line width and line width standard deviation the change in error is less than the measurement error determined in Chapter 4. The change for the cross-sectional area is small compared with the overall error in the cross-sectional area. Therefore, the change in error form 3 to 5 measurement areas is not significant and 3 samples would give an accurate representation of the line. Although, when results were analysed extra confidence in the results was obtained by using the average of the 5 samples.

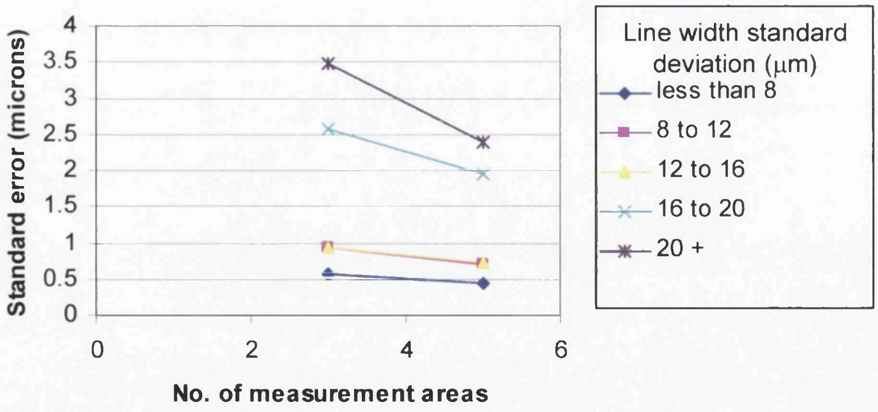
Using the standard error it is possible to examine the confidence limits for sample means. As the sample means are normally distributed there is a 95.4% chance that the sample means are within two standard errors of the population mean (54). For a sample of five measurement areas, twice the cross-sectional area standard error was about 8%, for the line width this was about 5μm and for the standard deviation this was about 2μm for smooth lines and 5 for the rough lines. This ties in well with estimation of the process variability from the previous section examining the spread of the data.



(a) cross-sectional area



(b) line width



(c) line width standard deviation

Figure 5.4 : The effect of the number of measurement areas on the standard error of the line measurement parameters

5.4.4 Discussion of process repeatability

A detailed investigation of the repeatability of screen printed fine lines has been presented. No study has achieved such detail to determine the repeatability of screen printing to produce fine lines. Calculating the difference of the line quality parameters on five 1cm^2 measurement areas achieved this.

The repeatability is a major factor in fine line screen printing. For this reason it was necessary to take a large number of samples for this study to ensure a representative value of the measurement parameters were obtained. Other studies into fine line screen printing have not judged the size of the sample required to obtain repeatable results and, thus, have not obtained such a large number of samples. The large sample size in this study has enabled the repeatable measurement of poor quality lines as well as good. This will enable a good comparison between line quality and lead to the understanding required to obtain good line edge quality and repeatability.

The repeatability of the screen printing reproduction of fine lines is related to the standard deviation of line width, and thus the continuity of the line. Straight edged lines are more repeatable than rough edged lines and poor edge quality resulted in poor repeatability of the fine lines.

Good repeatability can be ensured by obtaining good line edge quality, since straight edged lines are more repeatable than rough edged lines. It is, therefore, important to understand why poor edge quality occurs and how to achieve straight edged lines. It is possible to obtain straight edged and repeatable lines at all the line widths examined by this study. The effect of the parameter effects on line edge quality is required to be investigated to show how to achieve straight edged and repeatable lines. This work is described in the rest of the chapter.

5.4.5 Summary of the process repeatability and uncertainty of the data

This section investigated the repeatability of the screen printing process and determined the sample size required to ensured the results were representative of the lines measured. Straight edged lines were shown to be more repeatable than lines with poor edge quality, thus the required sample length was smaller for straight edged lines. It was shown that 3 measurement areas were required for the results to be representative of the lines measured, but an average of 5 was used for this study to ensure further confidence in the results.

The uncertainty within the data was established so that, when the results were analysed, the significance of trends in the data could be determined. This was achieved using the complete data so that it was not necessary to evaluate the scatter for each individual result, as placing error bars on all the plots of the results would be lead to cluttered results and, therefore, a lack of clarity of the trends. The uncertainty of the data is summarised in Table 5.1.

Table 5.1 : The uncertainty within the data for the line measurement parameters

Line measurement Parameter	**Uncertainty within data**
Line width	±5μm
Line cross-sectional area	±10%
Line width standard deviation (smooth lines)	±3μm
Line width standard deviation (rough edged lines)	±8 to 10μm

5.5 The effect of changing the line orientation on line reproduction

5.5.1 Introduction

The effect of the orientation to the print direction, and the effect of the orientation to the mesh, was investigated. Measurements were obtained at 5 orientations, for three line widths, for all the screen printing process parameter combinations printed. Therefore, it was possible to investigate the effect of the orientation, the interaction between orientation and process parameters and the 3 way interaction between line width, orientation and process parameters.

This section concentrates on the orientation, although a description of the more obvious screen printing process parameter trends are described to help the interpretation of the results. These trends are shown more clearly and discussed fully in Sections 5.6, 5.7 and 5.8 where the process parameters are concentrated on.

5.5.2 Experimental method

For the investigation into the orientation, all the screen and all the ink prints were examined. The squeegee parameters were examined using the averaging technique, described in Section 3.5.1, to minimise the effect of drying in. For each print, three line widths were measured, these were 90μm, 180μm and 280μm. This enabled any interactions between the line width and orientation to be determined.

Five line orientations were investigated (Figure 5.5), whose orientation relative to the print direction, for lines (a) to (e), were 15^0 to 75^0 in steps of 15^0. Thus, to analyse print direction, the study examined five different orientations. When examining orientation relative to the mesh, the lines are grouped into three angles.

- Lines (a) and (e) are at 15^0 to the mesh
- Lines (b) and (d) are at 30^0 to the mesh
- Line (c) is at 15^0 to the mesh

This assumes that there is no distortion of the mesh, and thus change in orientation between lines and the mesh, during printing. This is because the mesh is held together by the stencil so the stencil is likely to distort with the mesh, maintaining the same angle. Any distortion will be small compared with the 15^0 change from one line orientation to the next.

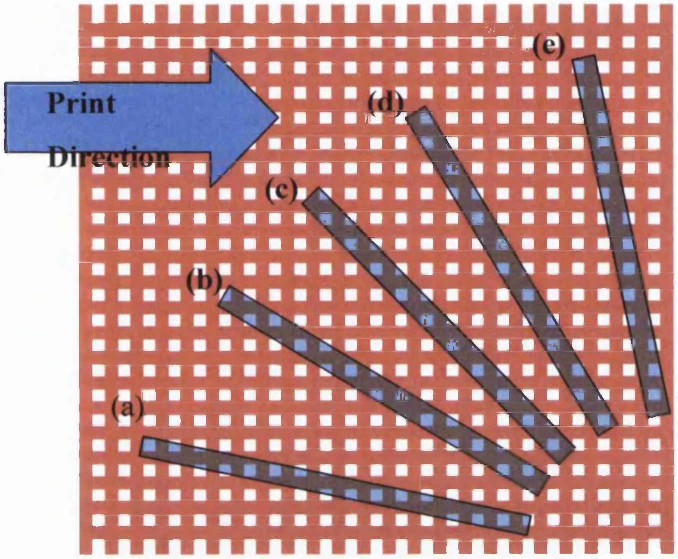


Figure 5.5 : Orientation of the lines examined by this study

5.5.3 Interpretation of orientation results

Due to the placement of the lines on the screen and the fact that there are five different line orientations relative to the print direction, but only three relative to the mesh the reading of the graphs require some explanation for clarity.

There are two fundamental curve shapes that can be produced by the analysis of the lines placed in the orientation of this study. These are found if

1. The effect of the print direction is dominant and the effect of the mesh is considered negligible on the parameter investigated
2. The effect of the mesh is dominant and the effect of the print direction is considered negligible on the parameter investigated

There is also a need to consider the possibility that both the mesh and the print direction have an effect on the parameter investigated.

Below the shapes of curves formed by these effects are described. This assumes that the effect of orientation is linear. This assumption has been made since previous studies into ink transfer have shown that parameter effects are linear (13). It also assumes that the effect of changing the line orientation relative to the mesh and the effect of changing the line orientation relative to the print direction occur independently and that there is no interaction between them.

The shape of the curve expected, if the effect of the print direction is dominant on the parameter investigated, is a straight line increasing or decreasing from one orientation to the next, i.e. each line orientation has a greater or lesser value for the parameter investigated than the one before. Most importantly lines at orientation of 15^0 and 75^0 have a different value of the parameter investigated.

The shape of the curve expected if the mesh is dominant is shown in Figure 5.6. This would produce a parabola, or inverted parabola, with a minimum, or maximum, at 45 degrees to the print direction. The important aspect to note, is that the values at 15 and 75 degrees to the print direction would be similar, as these orientation are the same relative to the mesh direction, and different to the value at 45 degrees to the print direction.

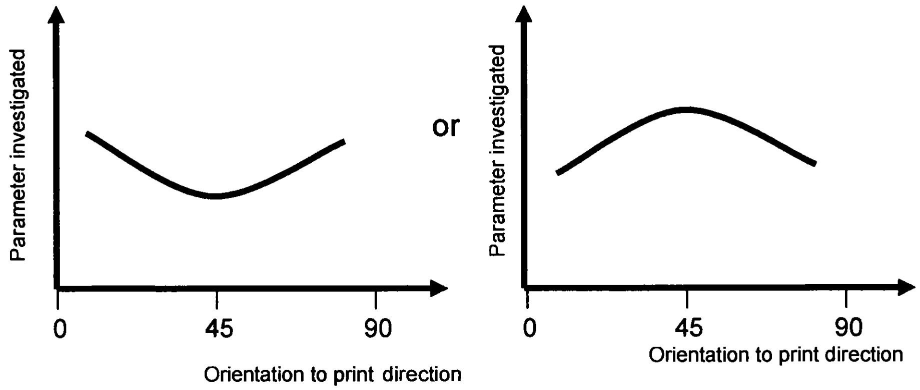


Figure 5.6 : Expected curve shapes if effect of orientation to the mesh is dominant

It is also important to consider if both the mesh and the print direction affect the parameter investigated. The expected curve would be an addition of the effect of both the mesh and the print direction, thus tilting the curve as shown in Figure 5.7.

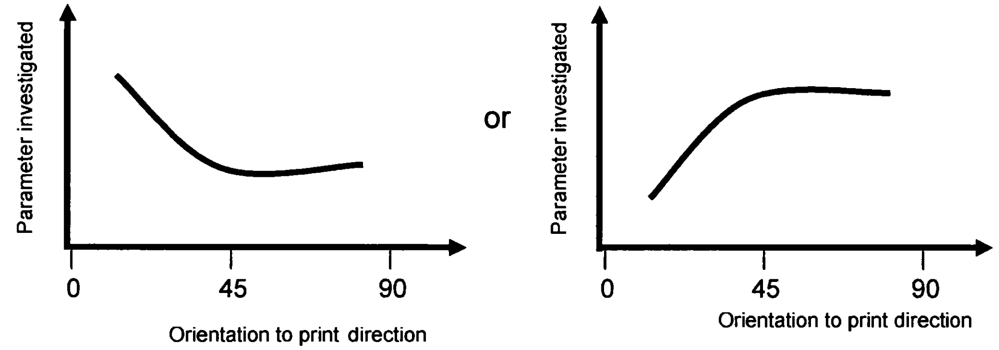


Figure 5.7 : Expected curve shapes if both orientation to the mesh and print direction are significant

5.5.4 The effect of orientation on line width and cross-sectional area

The results are presented for the three line widths investigated for the effect of orientation on line width and line cross-sectional area. It was shown, in Section 5.4, that a change in line width of ± 5µm would be a significant result. The line width results, Figures 5.8 to 5.12, are shown for each screen printing process parameter investigated for each line width measured. Presenting the data in this way enables the investigation into the interaction between line width, screen printing process parameters and orientation.

Figure 5.8 shows the effect of the orientation on line width for the three line widths investigated for changing the ink type. For each line width investigated the width increased linearly from 15 to 75 degrees to the print direction. For the 90µm wide lines the increase was about 7 to 12µm and about 20 to 25µm for the 280µm wide lines. There seems to be slight interaction between orientation and ink type for the 180µm wide lines.

The increase in line width was different for ink types. Ink 2 increased by about 5µm, but inks 1 and 3 increased by about 10 to 15µm. The results suggest that a small interaction exists between line width and orientation, with wider lines being affected more, by a change in orientation, than narrow lines. If the change in width is considered as a percentage, then the increase in width from 15 to 75 degrees to the print direction is about 10%.

There is an interaction between the ink type and the line width. The 90µm wide lines printed using ink 1 were wider lines than using inks 2 and 3. The 180µm and 280µm wide lines printed with ink 3 were wider that those printed with inks 1 and 2. This phenomenon is described and discussed in more detail in Section 5.5.

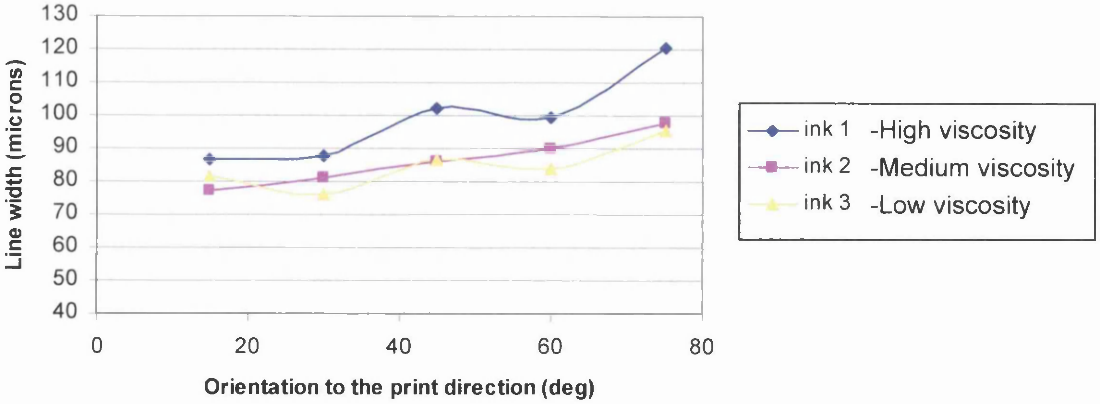
Figure 5.9 shows the effect of the orientation on line width for the three line widths investigated for changing the screen height. There is a general trend in the results of a linear increase in line width from 15 to 75 degrees to the print direction. The effect of orientation on line width for the results from the screen experiment are much smaller than the results from the ink experiment. For the 90µm wide lines an increase of about 5µm to 8µm was found. For the 180 µm wide lines an increase of about 5µm to 10 µm was found and an increase of a bout 5µm to 15µm found for the 280µm wide lines.

An interaction appears to exist between the screen and the orientation for the size of the increase of line width. For lines printed using screens with a profile of 4.3µm there was no significant increase in line width. Whereas, for other screens, profile of 7.8µm, the increase is about 7µm for the 90µm width line to 15µm for the 280µm wide lines. The error in the measurement of line width was about ±5µm, therefore, the interaction is small. It could be considered that there is an effect on all screens, but for some of the screens the effect is so small it has not been found using this measurement method, as the increase could be less than 5µm. The screen profile does not appear to affect the line width.

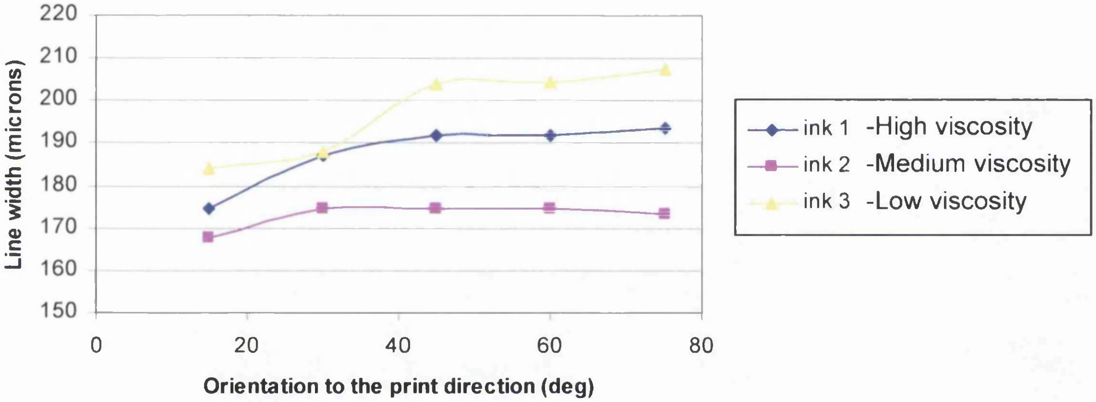
Figures 5.10 to 5.12 show the effect of orientation on line width for the squeegee hardness, angle and pressure respectively. A general trend exists for the results of a linear increase from 15 to 75 degrees to the print direction. The squeegee hardness results show an increase of line width of about 15 to 20μm for the three line widths investigated. The squeegee angle results show an increase of about 20μm for the 90μm and 180μm wide lines, but about 15μm for the 280μm wide lines. The squeegee pressure results show an increase of 15 to 20μm for the 90μm and 280μm wide lines and 5 to 8 μm for the 180μm wide lines. No significant interaction was found between the squeegee parameters and the orientation.

The process parameters did have an effect on line width. The soft and medium squeegees produced lines of about the same width, but the hard squeegee produced thinner lines. The squeegee angle had a large effect on line width, with angles closer to the horizontal producing wider lines. The squeegee pressure showed an interaction with line width. The 3.5 and 4.5 bar lines had similar line width. At 90μm lines the lines printed with a pressure of 2.5 printed lines of similar width to the 3.5 and 4.5 bar lines. For 180μm lines the lines printed at 2.5 bar had a less line width by about 5 to 10μm than those at 3.5 and 4.5bar and at 280μm the line width was less by about 15 to 25μm. The process parameter effects are discussed further in Section 5.5.

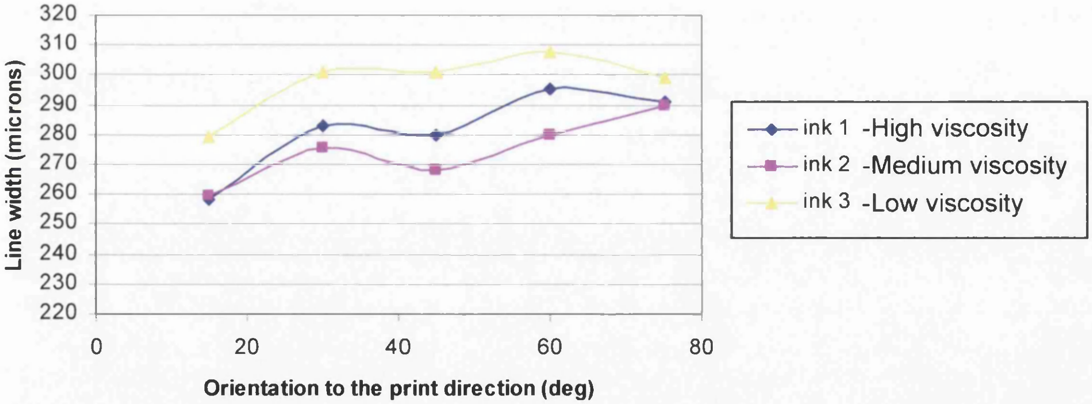
The line width was affected by the orientation relative to the print direction for all the lines printed, but the line width was not affected by the orientation to the mesh. There was evidence of an interaction between orientation and line width. For several cases, the increase from the parallel to perpendicular to the print direction increased as line width increased.



(a) 90μm wide lines

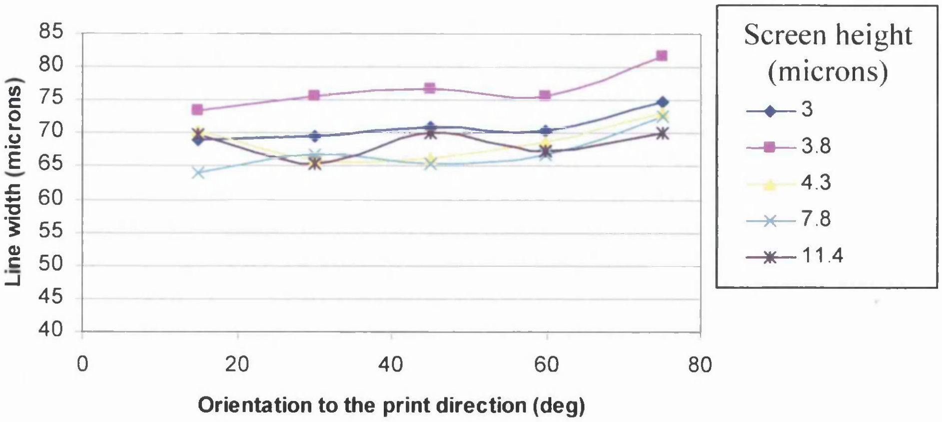


(b) 180μm wide lines

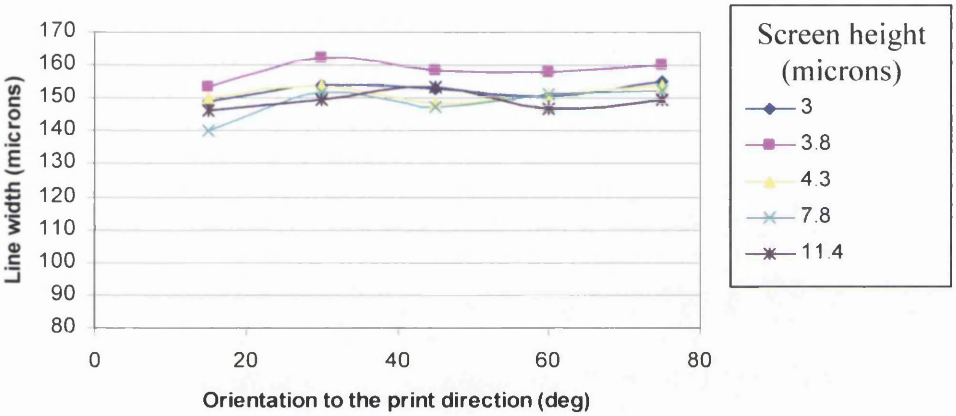


(b) 280μm wide lines

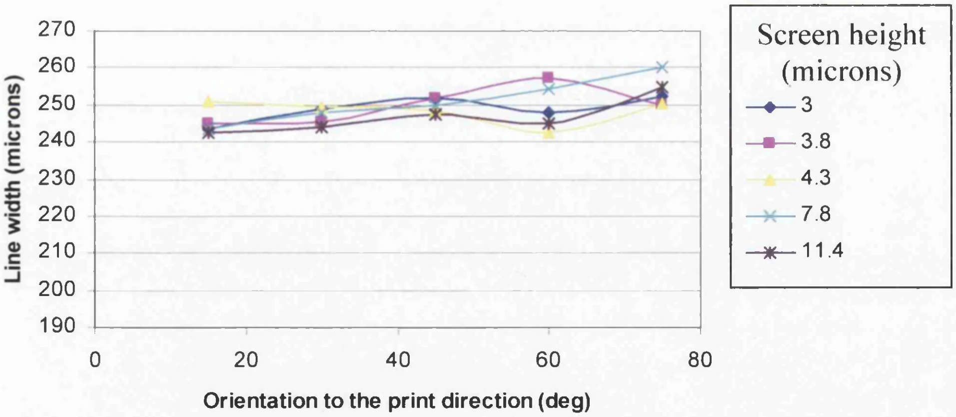
Figure 5.8 : The effect of the orientation on line width and the interaction with the ink



(a) 90µm wide lines

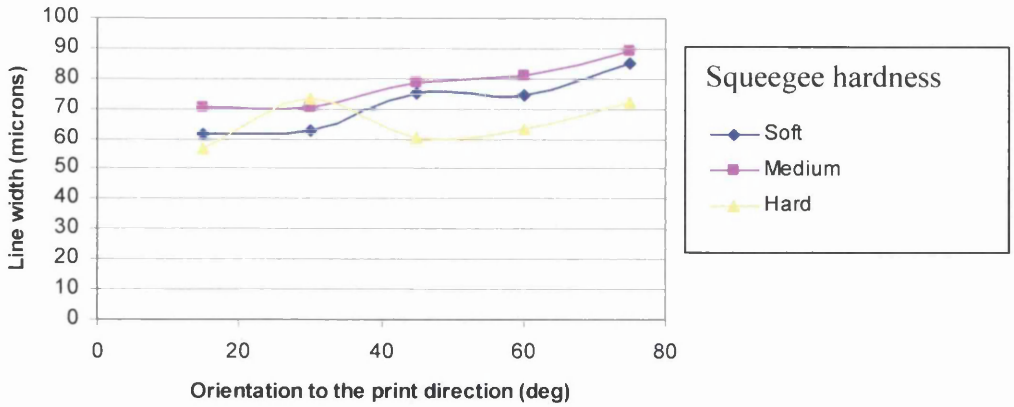


(b) 180µm wide lines

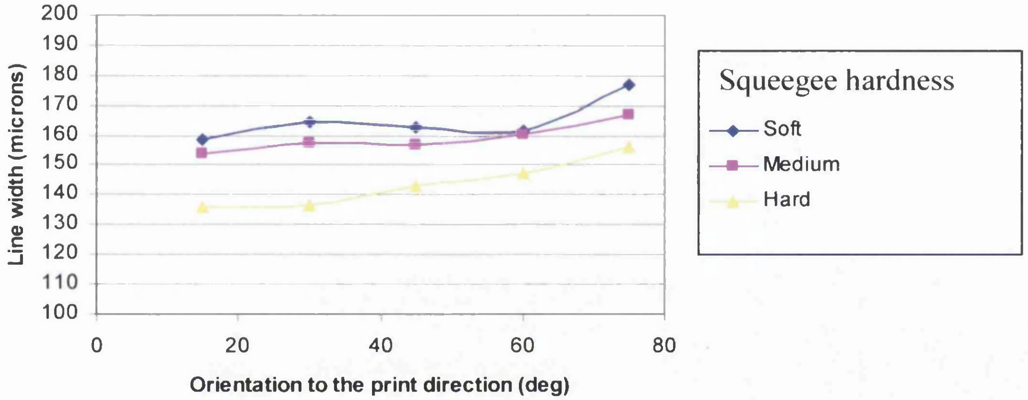


(b) 280µm wide lines

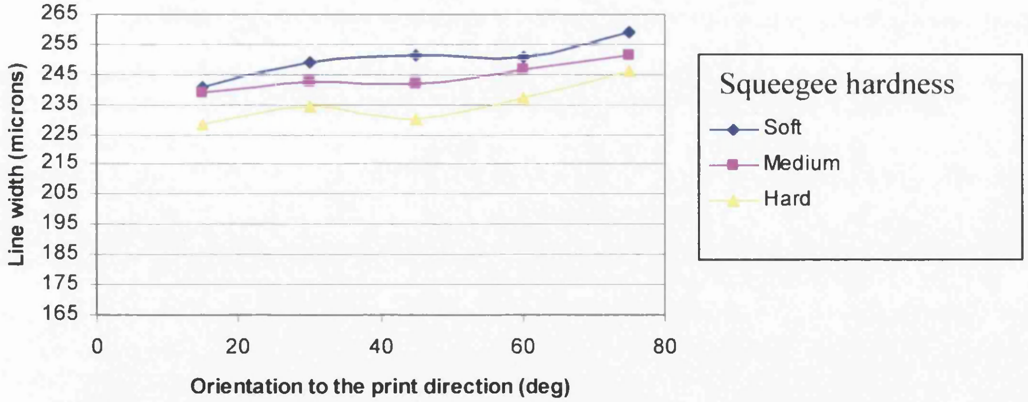
Figure 5.9 : The effect of the orientation on line width and the interaction with the screen height



(a) 90μm wide lines

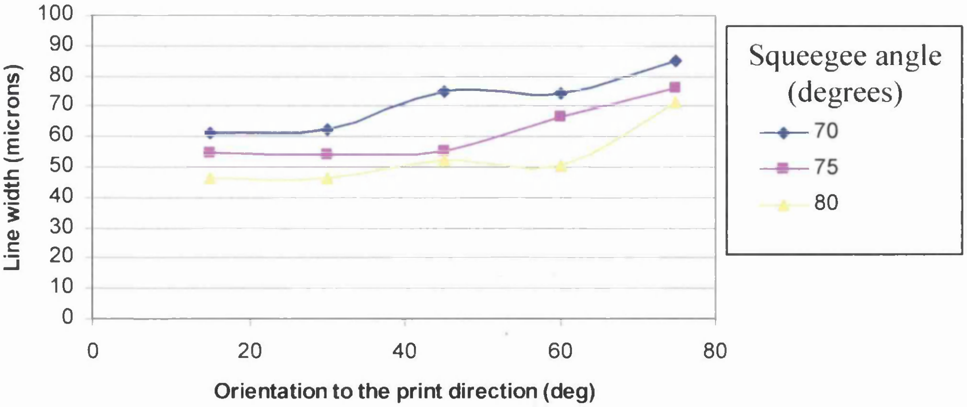


(b) 180μm wide lines

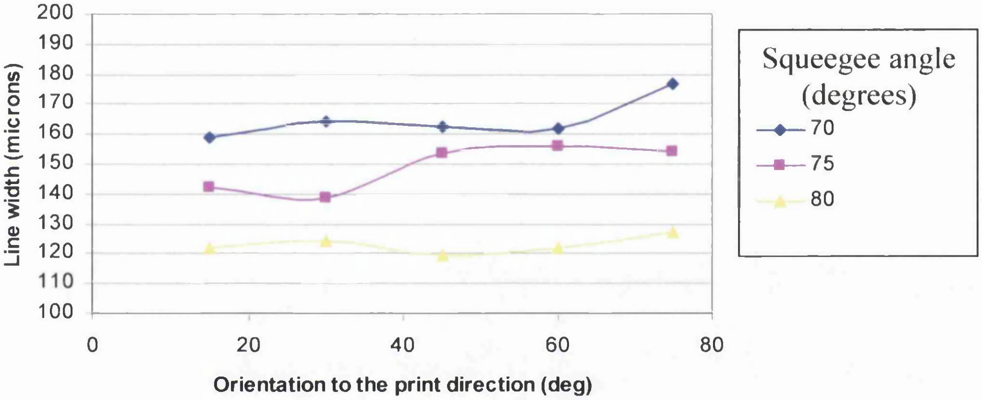


(b) 280μm wide lines

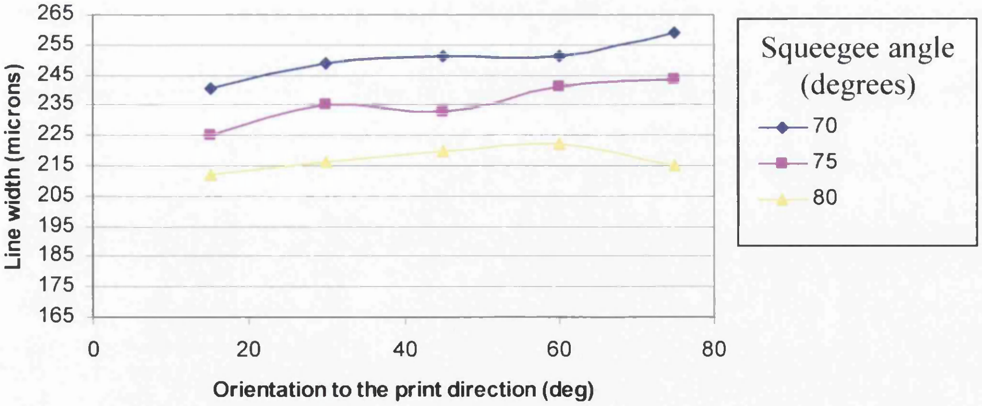
Figure 5.10 : The effect of the orientation on line width and the interaction with the squeegee hardness



(a) 90µm wide lines

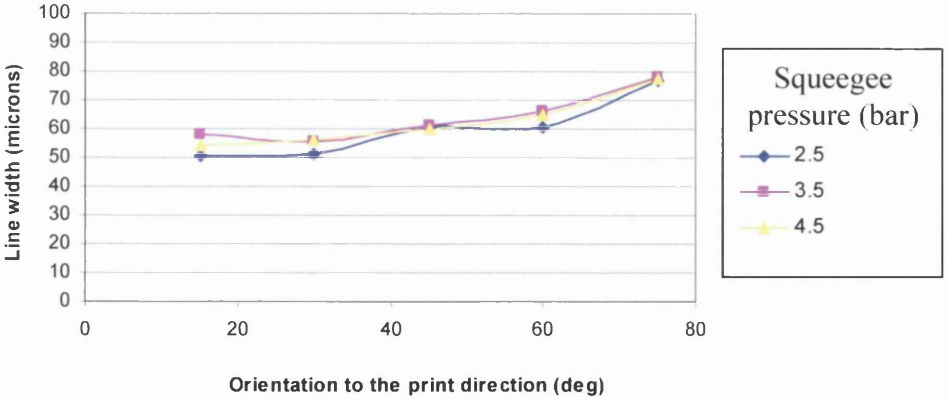


(b) 180µm wide lines

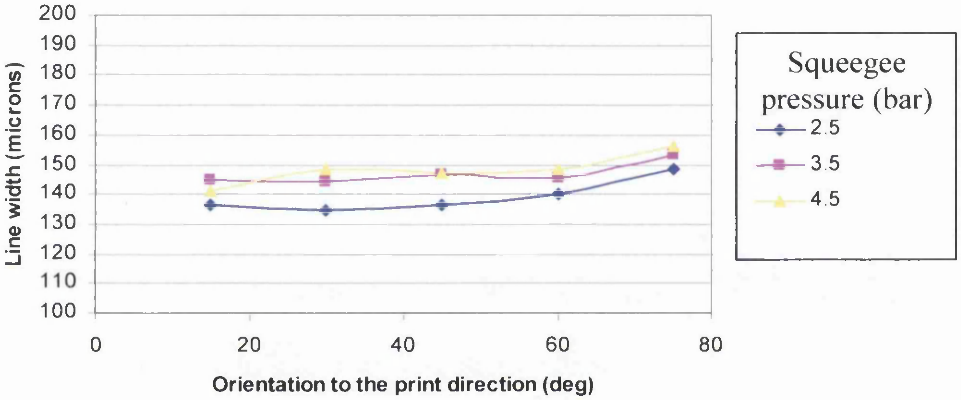


(b) 280µm wide lines

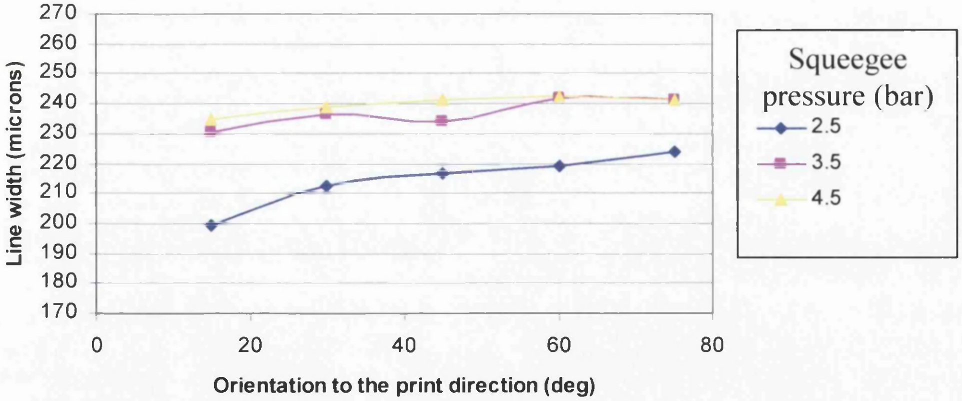
Figure 5.11 : The effect of the orientation on line width and the interaction with the squeegee angle



(a) 90μm wide lines



(b) 180μm wide lines



(b) 280μm wide lines

Figure 5.12 : The effect of the orientation on line width and the interaction with the squeegee pressure

The effect of the orientation on cross-sectional area is shown in Figures 5.13 to 5.17. These are laid out in a similar manner to the line width results, split into the screen printing process parameters investigated. Section 5.5 showed a difference of ±10% would constitute a significant result.

Figure 5.13 shows the effect of the orientation on cross-sectional area for the three line widths investigated for changing the ink type. For the 90µm wide lines there was a slight decrease, of about 10% from 15 to 75 degrees from the print direction. For the 180µm and 280µm no significant change occurred from 15 to 75 degrees to the print direction. There was no interaction between the ink type and orientation for cross-sectional area. There was a slight interaction between line width and orientation on cross-sectional area.

There is also an interaction between the ink type and line width. For the 90µm wide lines all inks printed similar cross-sectional areas. For the 180µm and 280µm wide lines more ink was deposited for inks 1 and 3 as with ink 2. This is discussed further in Section 5.5

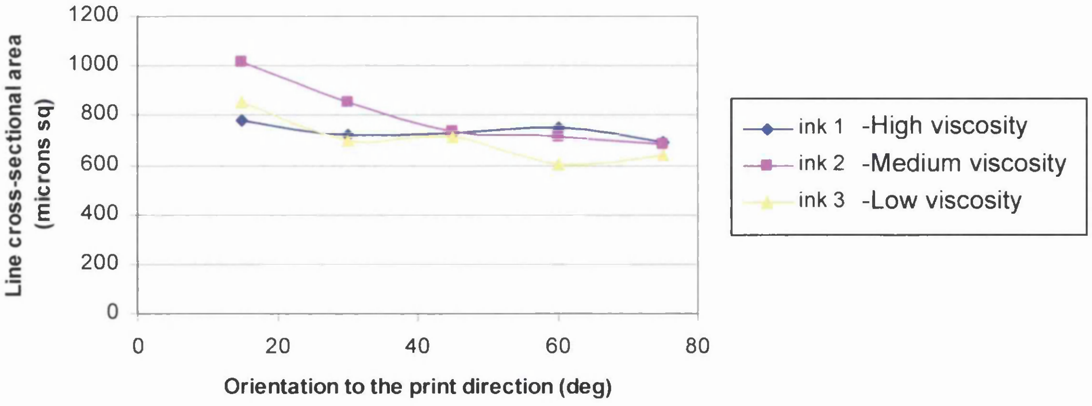
Figure 5.14 shows the effect of the orientation on cross-sectional area for the three line widths investigated for changing the screen height. This shows that the orientation had no significant effect on cross-sectional area for these results and there was no interaction between the screen and orientation. The screens with profiles ranging from 3µm to 7.8µm had similar ink transfer, but more ink was transferred through the screen with a profile of 11.4µm. There may also be trends for the rest of the screens, but it is hard to pick out with the data presented as in Figure 5.14. The effect of the screen on cross-sectional area is described and discussed further in Section 5.5

Figures 5.15 to 5.17 show the effect of orientation on cross-sectional area for the squeegee hardness, angle and pressure respectively. For each of these parameters the same trend existed. For the 90µm wide lines there was a slight increase from 15 to 75 degrees from the print direction. For the 180µm and 280µm there was a slight decrease from 15 to 75 degrees from the print direction. For each case the change from 15 to 75 degrees was about 10 to 15%, thus the results are only just significant. There was no interaction between the squeegee parameters and orientation for cross-sectional area. There was a slight interaction between line width and orientation on cross-sectional area. It appears from the results that at low line widths cross-sectional area increases from parallel to perpendicular to the print direction, but decreases for wider lines.

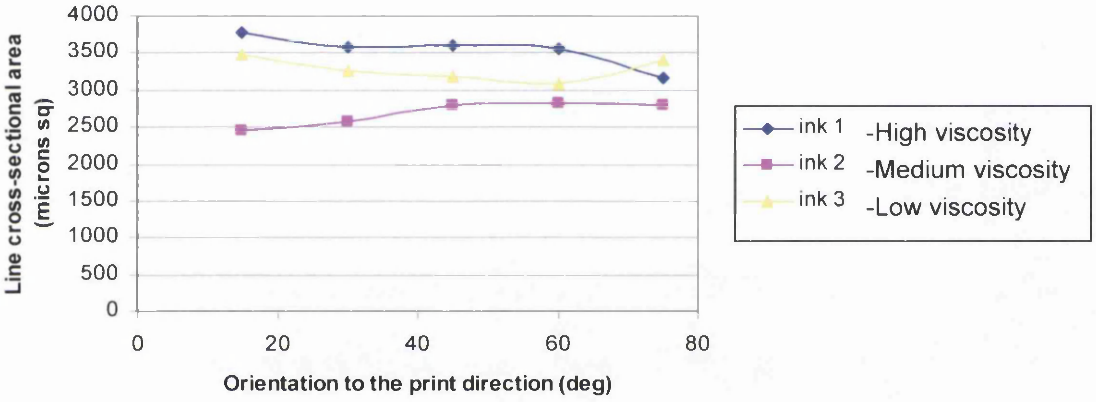
The effect of the process parameters was similar to those on line width. The squeegee pressure had the same interaction as exhibited with the line width. The effect of the process parameters on cross-sectional area are presented in detail in Section 5.5.

Orientation has an effect on line width, with lines printed perpendicular to the print direction wider than those printed parallel to the print direction. This difference varied from less than 5μm to 20μm. There was evidence that the orientation had a larger effect on wider lines, although this was not always the case.

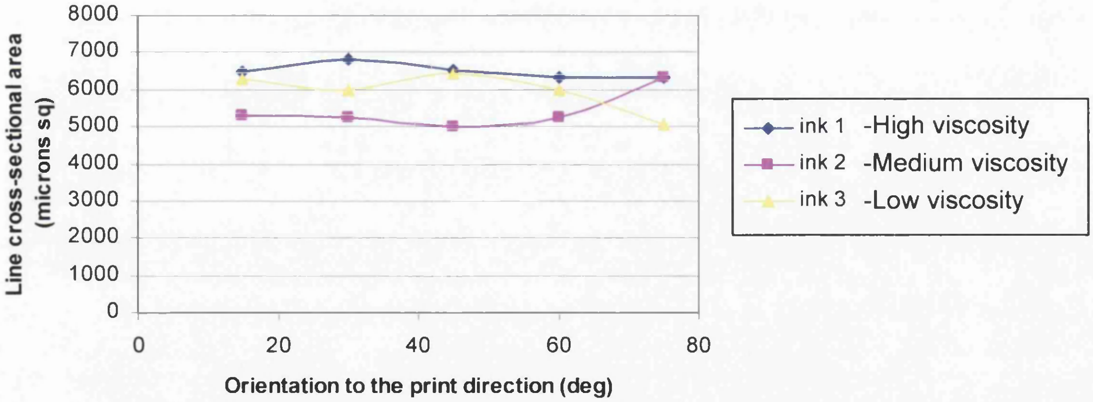
There was a barely significant decrease in cross-sectional area, or no change, from 15 to 75 degrees to the print direction for the majority of the printing conditions, the exception was the 90μm wide lines printed for the squeegee experiment. This showed the importance in measuring the three dimensional properties of the line, since although the line width increases slightly the actual area decreases.



(a) 90μm wide lines

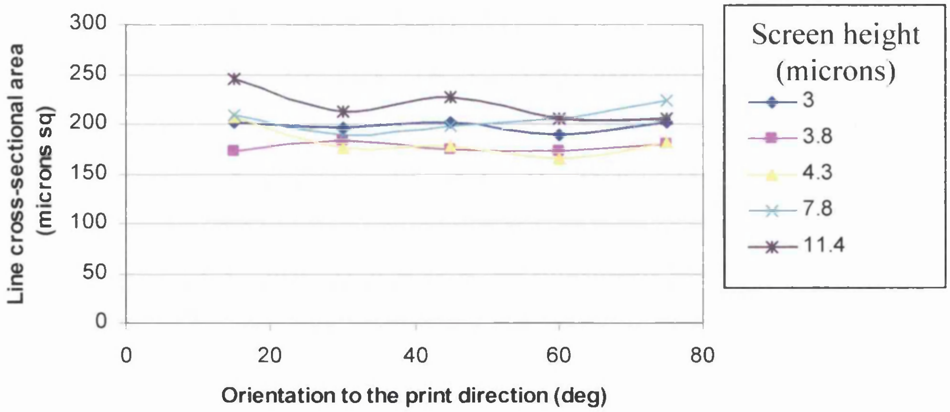


(b) 180μm wide lines

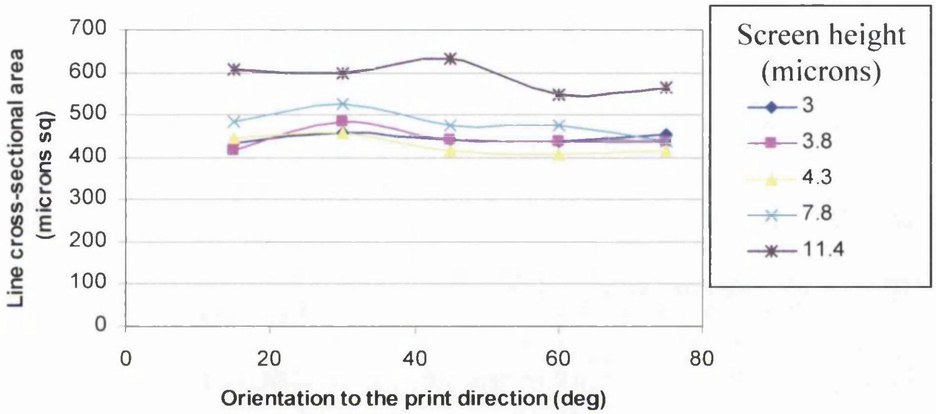


(b) 280μm wide lines

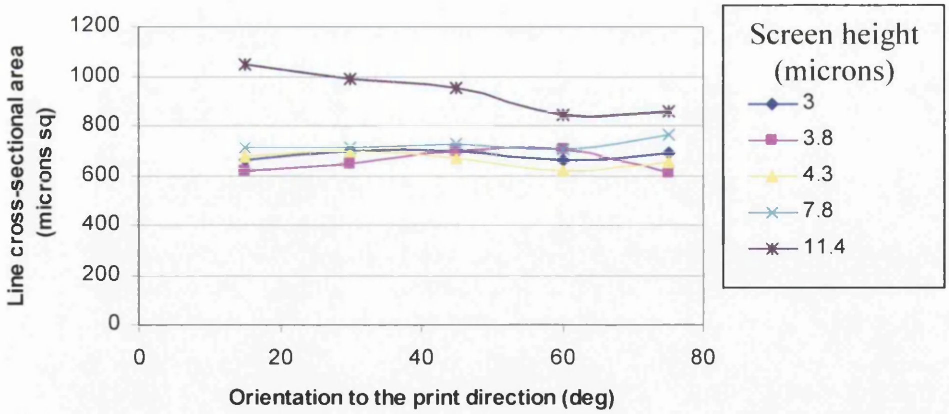
Figure 5.13 : The effect of the orientation on cross-sectional area and the interaction with the ink type



(a) 90μm wide lines

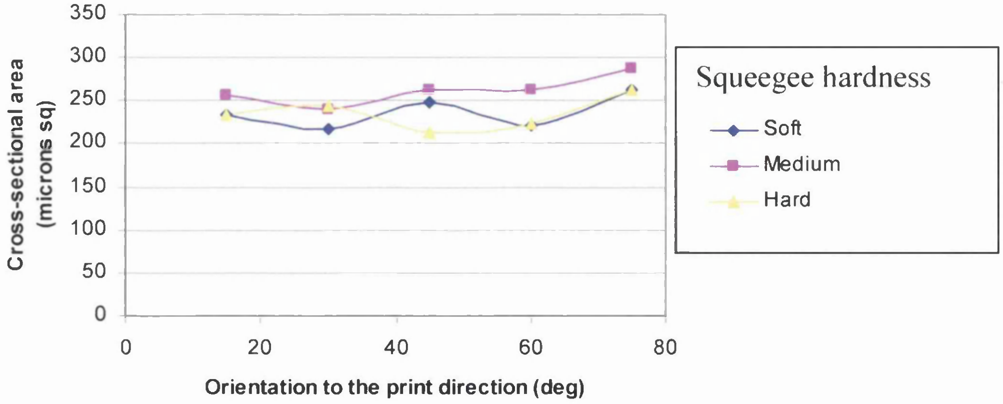


(b) 180μm wide lines

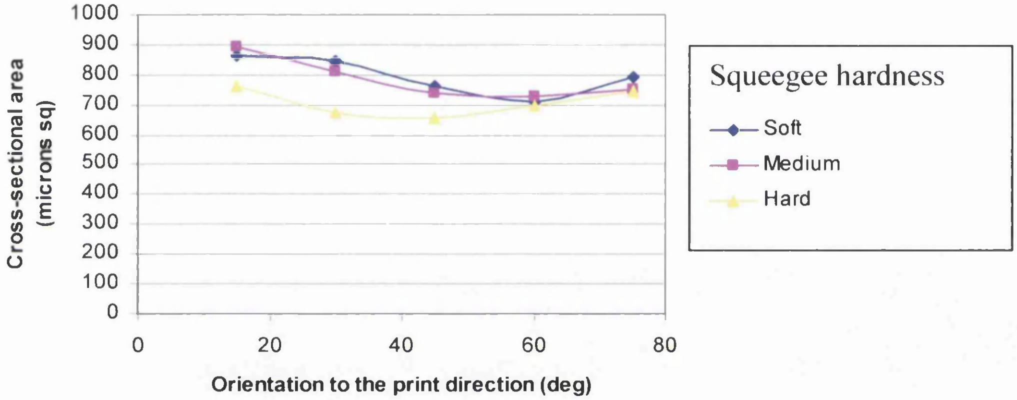


(b) 280μm wide lines

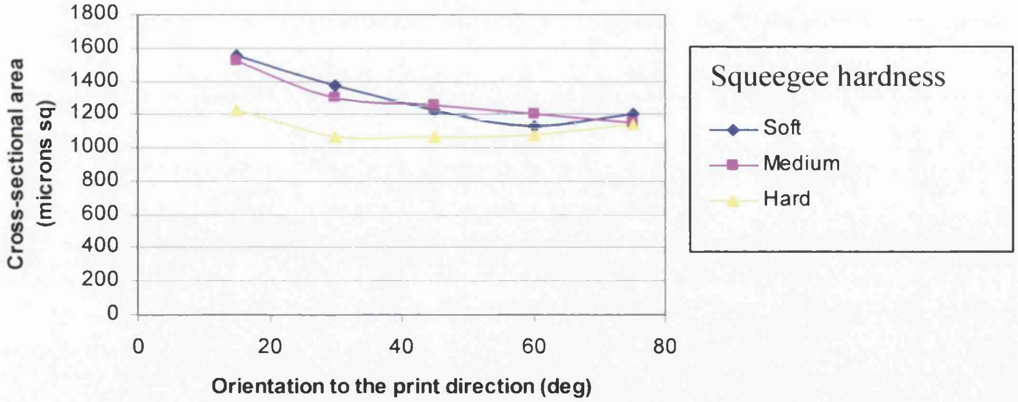
Figure 5.14 : The effect of the orientation on cross-sectional area and the interaction with the screen height



(a) 90μm wide lines

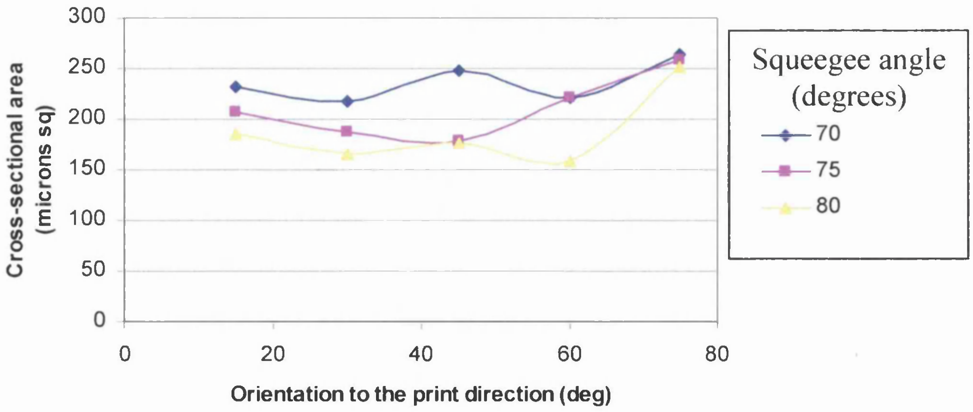


(b) 180μm wide lines

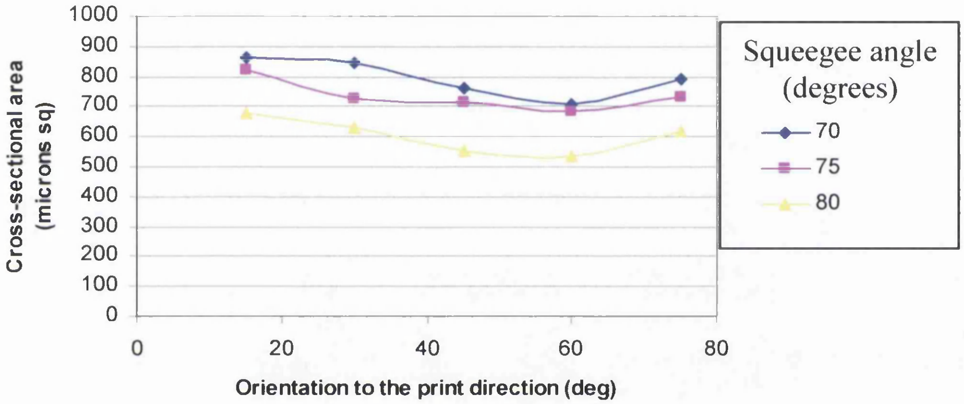


(b) 280μm wide lines

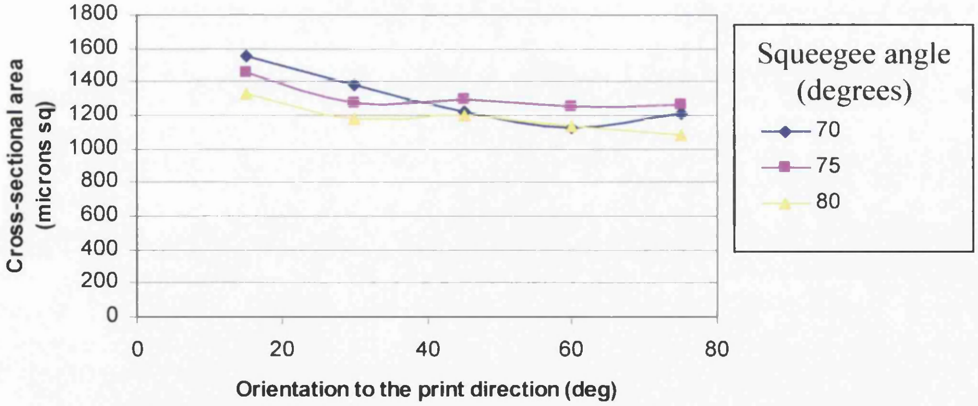
Figure 5.15 : The effect of the orientation on cross-sectional area and the interaction with the squeegee hardness



(a) 90µm wide lines

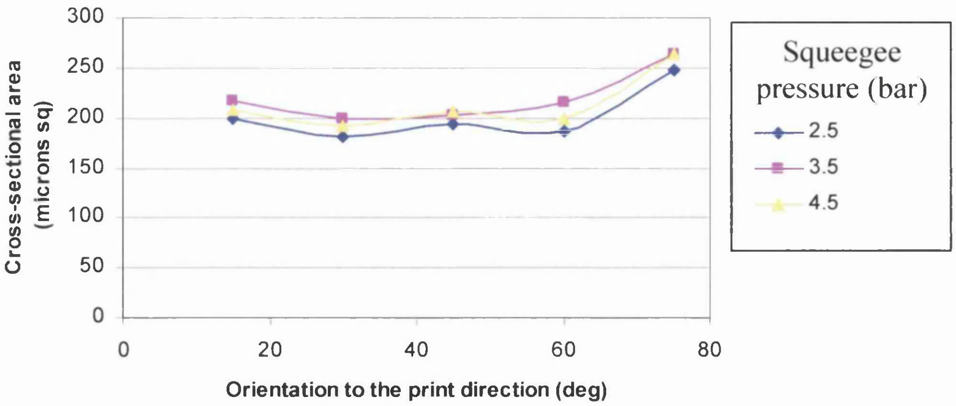


(b) 180µm wide lines

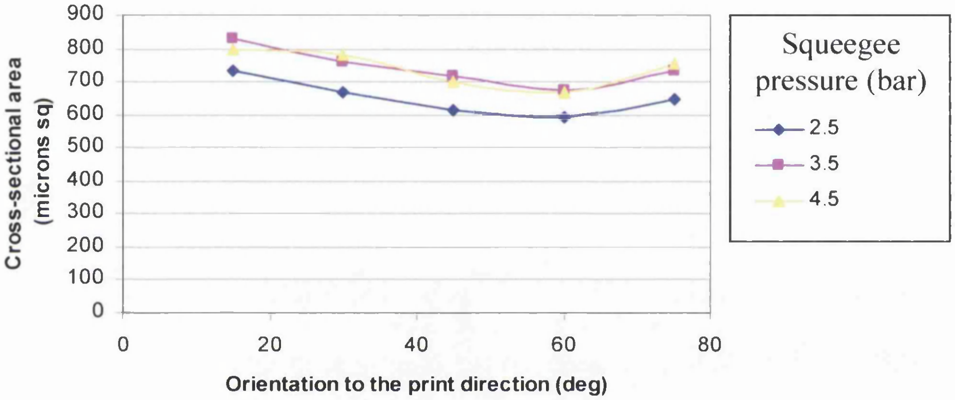


(b) 280µm wide lines

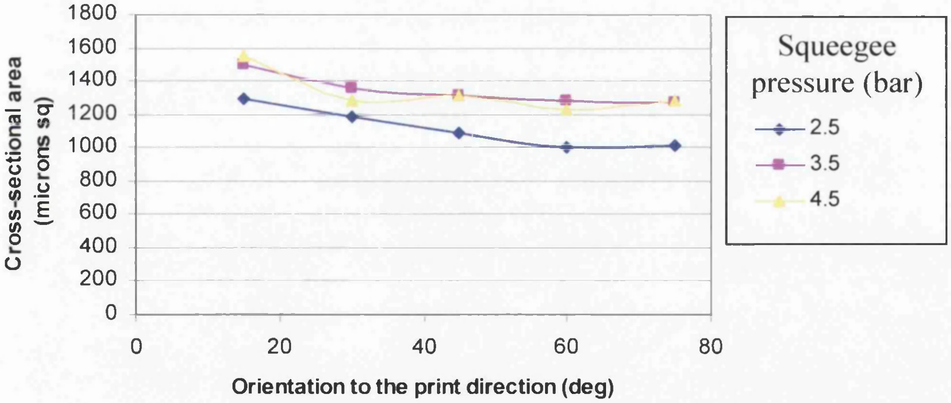
Figure 5.16 : The effect of the orientation on cross-sectional area and the interaction with the squeegee angle



(a) 90μm wide lines



(b) 180μm wide lines



(b) 280μm wide lines

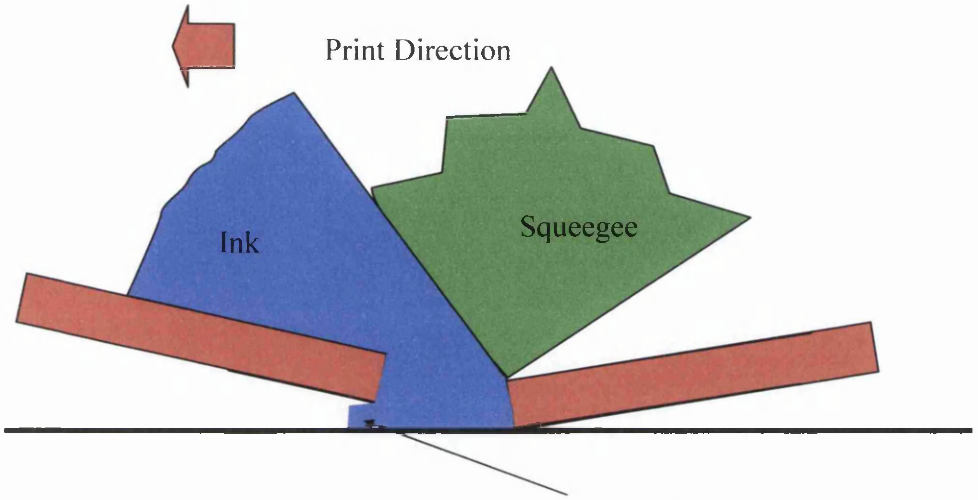
Figure 5.17 : The effect of the orientation on cross-sectional area and the interaction with the squeegee pressure

5.5.5 Discussion of the effect of orientation on line cross-sectional size

5.5.5.1 Orientation on line width

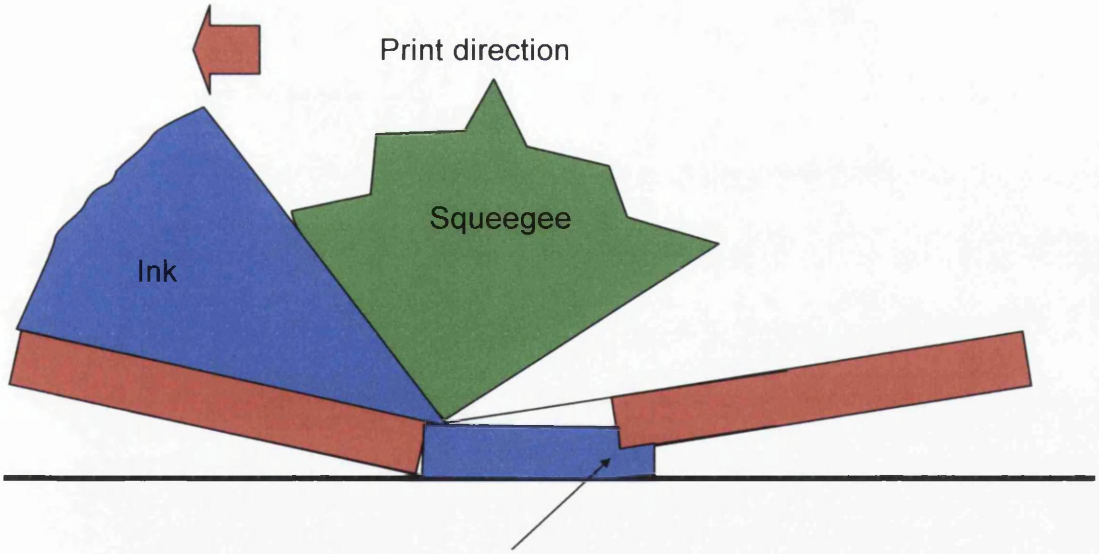
Figure 5.8 shows that the orientation relative to the print direction had a significant effect on line width. Lines printed at 15 degrees to the print direction were printed narrower than lines at 75 degrees to the print direction. This has been found in previous studies (1), although the phenomenon was not quantified or explained. There are several ways that the orientation could affect the line width and there is a need to consider further the action of the squeegee and the snapping off of the screen at the exact moment of printing. Several reasons why lines printed at 15 degrees to the print direction were narrower than lines 75 degrees to the print direction have been considered and are listed below:

- Ink spillage at the point of printing, there are two processes that could cause extra ink to flow onto the substrate at the point of printing.
  - Just before the line passes under the squeegee, ink could be pushed out of the hole in the stencil producing a larger line (Figure 5.18)
  - Just after the centre of the line has passed the squeegee and the screen is beginning to snap off the substrate ink could flow under the rising screen behind the squeegee, caused by the snap mechanism and the cohesion forces within the ink (Figure 5.31).
- Non-uniform stretching of the screen due to the snap off gap.
- Screen stretching due to the friction of the squeegee.
- More ink filling into the screen.



Ink is pushed in front of the screen by the pressure exerted within the ink due to the movement of the squeegee

Figure 5.18 : Illustration of ink being pushed out of a hole in the stencil, in front of the squeegee



Ink could flow under the rising screen behind the squeegee

Figure 5.19 : Illustration of ink being pulled out of a hole in the stencil, behind the squeegee

The cross-sectional area, and thus ink transfer, decreases from parallel to perpendicular to the print direction for the majority of printing conditions, Figures 5.13 to 5.17. This means that the increase in line width from 15 to 75 degrees to the print direction is unlikely to be due to an increase in ink transfer. Thus, the effect of orientation on line width would not be due to extra ink flow under the screen or more ink filling the screen and being transferred to the substrate.

This leaves the distortion of the mesh to be the most likely cause of the influence of orientation on line width. Previous studies have examined the drag force of the squeegee on the screen and the distortion of the image due to the snap (15). These were reviewed in Chapter 2. The findings from this study and previous studies were compared to further the understanding of the process.

The studies into the drag force and the distortion of the screen were printed with different conditions to those in this study. It is possible only to consider qualitative parameter effects and not to quantitatively compare the amount of distortion that would occur for each study. The actual changes in line width caused by the distortion were examined and the limitations of using qualitative analysis were considered.

The squeegee pressure had a large effect on the drag force on the squeegee. To a lesser extent the squeegee angle also had an effect. Thus, if the drag force was the reason for the lines being printed at different widths at different orientations then there would be an interaction between the squeegee pressure and the effect of the orientation. Higher squeegee pressures would result in higher drag and, thus, wider lines. Figure 5.11 and Figure 5.12 show there is no interaction between orientation and squeegee and angle or pressure. Therefore, the squeegee drag is unlikely to be the cause of the effect of orientation on line width.

An in-depth study into the stretching of the screen during screen printing was undertaken by Jewell and is reviewed in Chapter 2 (15). This study showed there was a difference in the stretching between the print direction and perpendicular to the print direction. In the centre of the screen, the strain perpendicular to the print direction was small and occasionally negative for some conditions. The strain in the print direction was positive. It was found to be about 0.1 to 0.2mm over a 400mm long screen. This is a strain of about 0.025% to 0.05%.

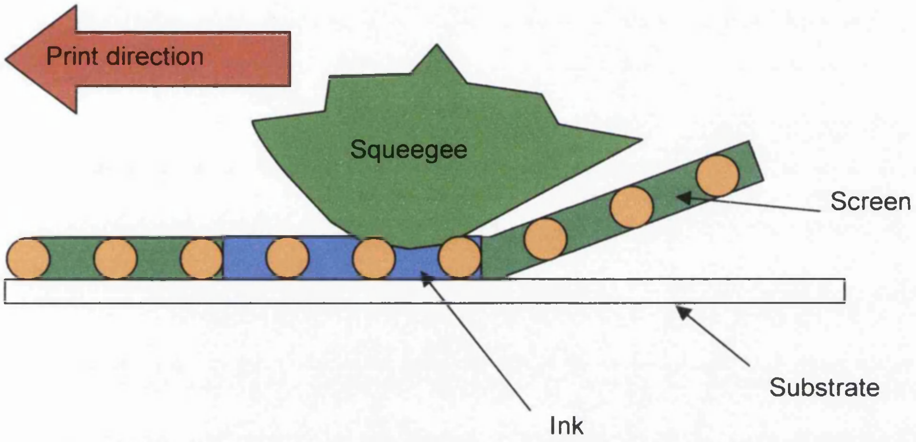
This can be compared to the increase in line width found in this study, but there are some considerations. The snap-off gap used in this study was 6mm compared to 3mm used by Jewell (15). The screen tension used in this study was 20N/cm compared with two values of 17 and 25N/cm used by Jewell (15). The screen size and squeegee were also different. These factors may all affect the actual comparison, but it is possible to show that due to the difference in strain there is likely to be a difference in line width. For a similar strain over a screen length of 1.5m, that was used in this study, then the increase in length would be 7μm to 15μm. This is very similar to the increase in line width found in this study due to the orientation of the line. The difference between the 15 degrees and 75 degrees was between 5μm and 20μm. This shows that the effect of orientation on the printing process is caused by the non-uniformity of strain of the mesh in the print and transverse directions.

5.5.5.2 Orientation on area

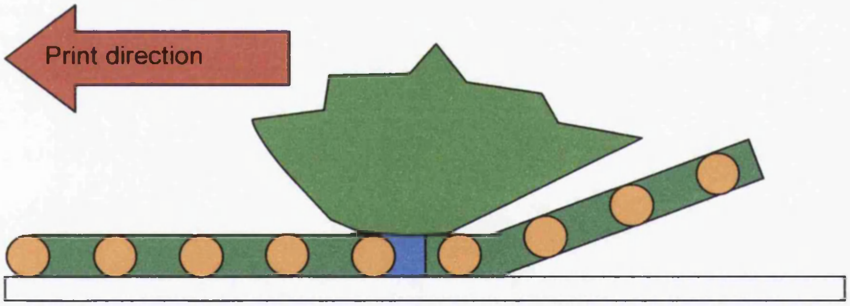
Under the majority of conditions, a slight decrease, or no change, in area occurred from parallel to perpendicular to the print direction. The exception to this was the 90μm wide lines printed for the squeegee experiment. Below is a hypothesis as to why the decrease in area occurs and is illustrated in Figure 5.20.

The stencil supports the squeegee for lines printed parallel to the print direction since the two sides of the line, on the stencil, are sufficiently close to support the squeegee. For lines printed perpendicular to the print direction the size of the line in the plane of the squeegee is the length of the line. The squeegee in this case is not supported by the stencil and follows the height of the mesh as opposed to the stencil, Figure 5.20 (a). Larger ink transfer occurs where the squeegee is supported by the stencil as opposed to the mesh only, since more ink is held in the screen.

For the 90μm wide lines, the width of the line is so small that the squeegee could also be supported by the stencil perpendicular to the squeegee plane as well as parallel to it (Figure 5.20 (b)). The increase in area may occur due to the widening of the line caused by the stretching of the screen, as described in Section 5.5.5.1.



(a) Wide lines, the squeegee is not supported by the stencil.



(b) Narrow lines, the squeegee is supported by the stencil.

Figure 5.20 : Illustration showing that the squeegee, for lines perpendicular to the print direction, is supported by the stencil for narrow lines, not for wide lines

5.5.6 The effect of orientation on line continuity

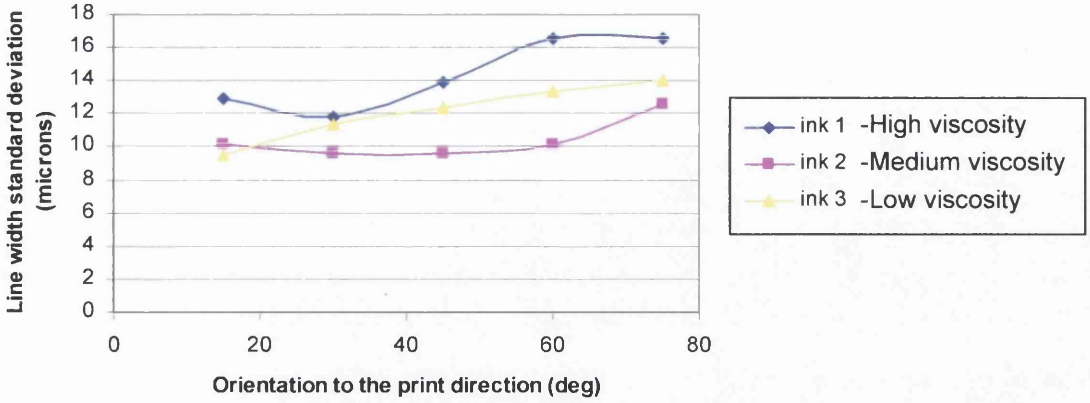
The effect of the line orientation on the continuity of the line width is shown in Figures 5.21 to 5.25. The full results are presented in a similar manner to the width and cross-sectional area results. This enables the investigation of the interaction between continuity, process parameters and orientation. Section 5.4.2 showed that a change of ±3μm would be significant for smooth lines and a change of about ±8 to 10μm was significant for rough edged lines.

Figure 5.21 shows the effect of orientation on line width standard deviation for the ink experiment. The results show a slight increase from parallel to perpendicular to the print direction. This is about 4μm for the 90μm and 280μm wide line and about 2μm for the 180μm wide lines. These results do not constitute a significant difference in line continuity.

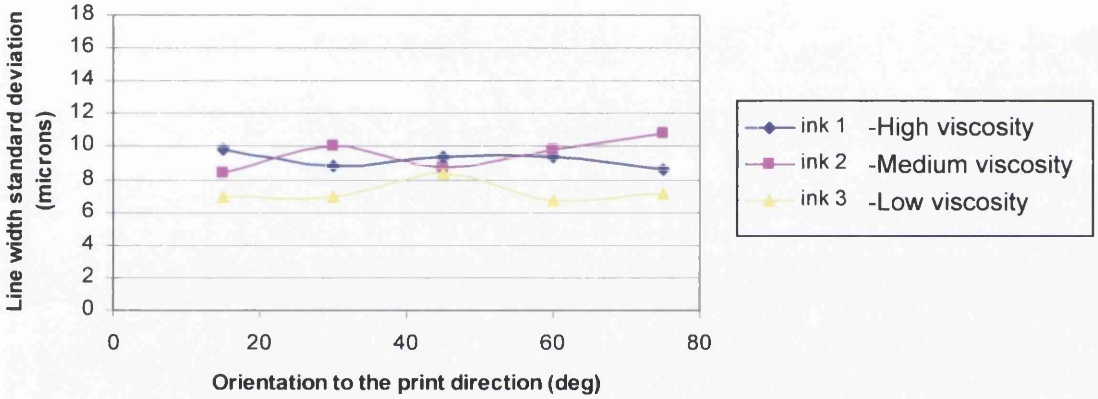
Figure 5.22 shows the effect of orientation for the screen experiment. No significant effect of orientation on continuity is shown for any line width. There is an effect of the stencil roughness on line continuity, with rougher stencils producing poorer line edge quality, this is discussed in Section 5.7.

Figures 5.23 to 5.25 show the effect of the squeegee parameters on orientation. The variation for a change in orientation was about ±2μm for smooth lines and about ±4 μm for rough lines. This, therefore, does not constitute a significant change in line continuity. Therefore it is not possible to conclude that line orientation had an effect on line continuity for the squeegee parameters. The squeegee parameters also had very little effect on line continuity, although this will be examined in more detail in Section 5.6.

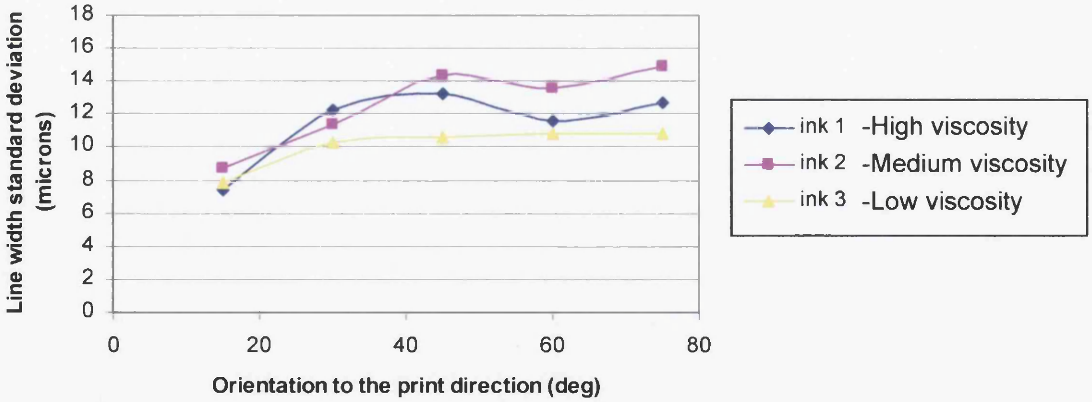
Orientation has no significant effect on line continuity. Some process parameters have shown they effect line continuity and these are investigated further in Section 5.



(a) 90µm wide lines

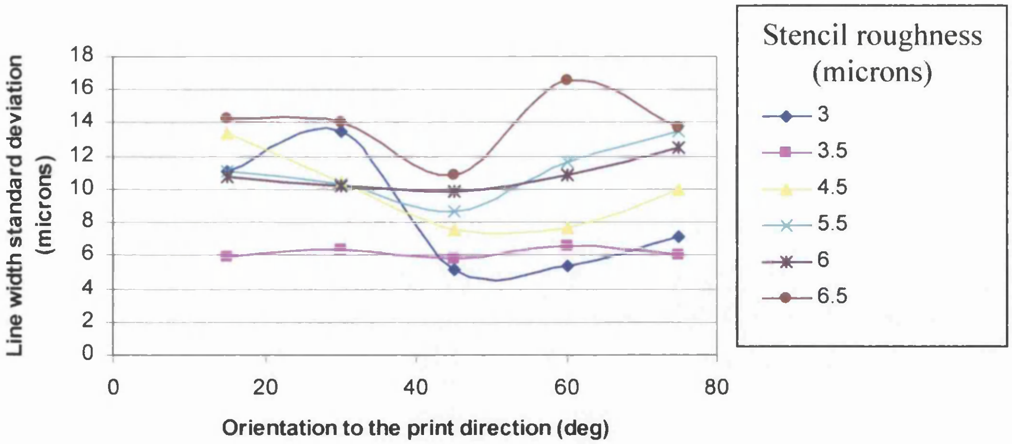


(b) 180µm wide lines

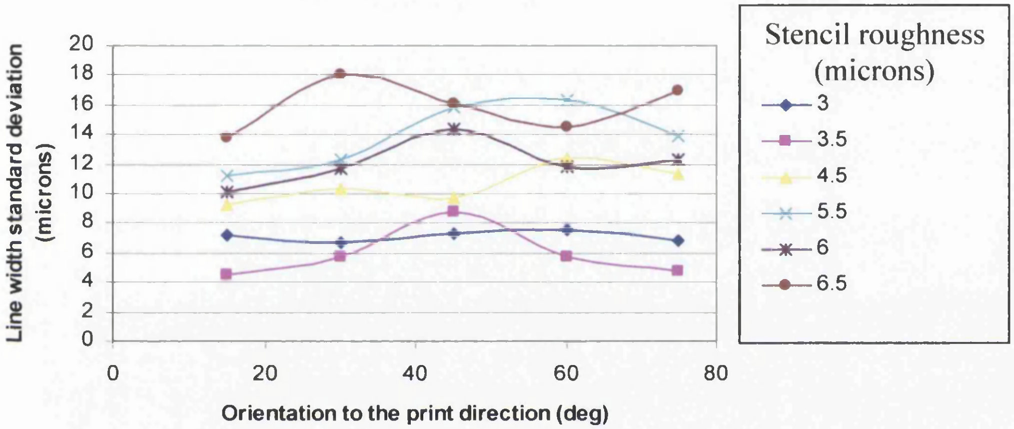


(b) 280µm wide lines

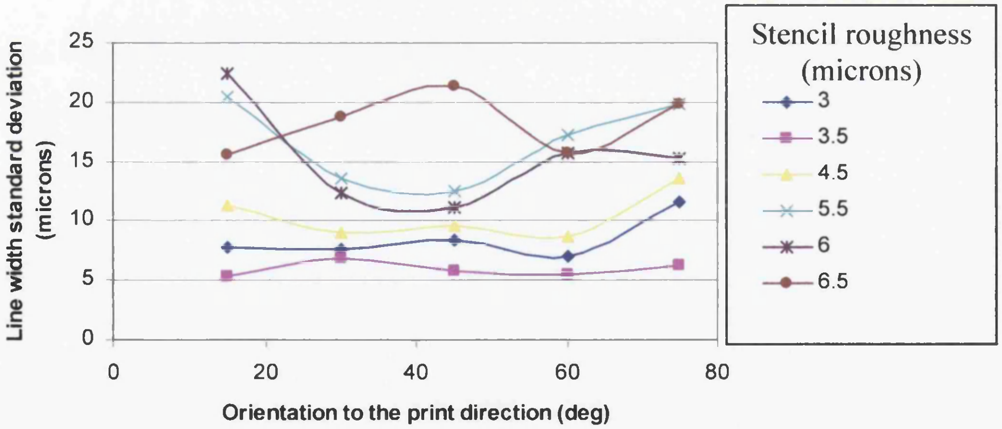
Figure 5.21 : The effect of the orientation on line width standard deviation and the interaction with the ink type



(a) 90μm wide lines

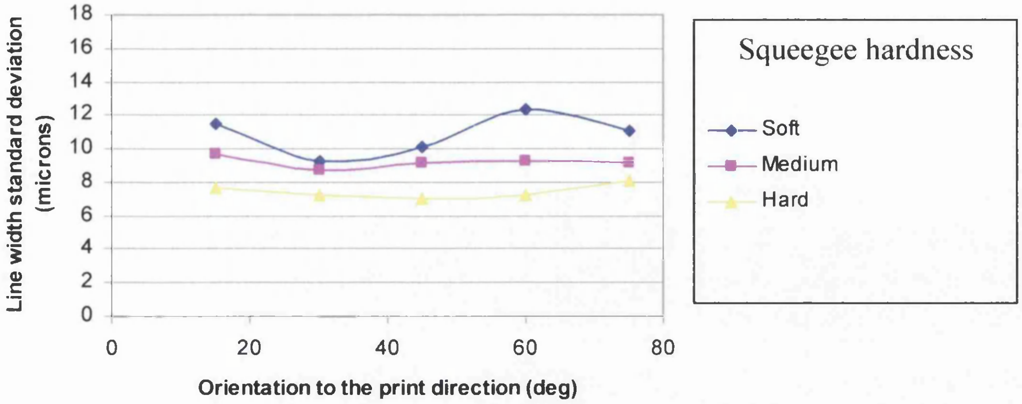


(b) 180μm wide lines

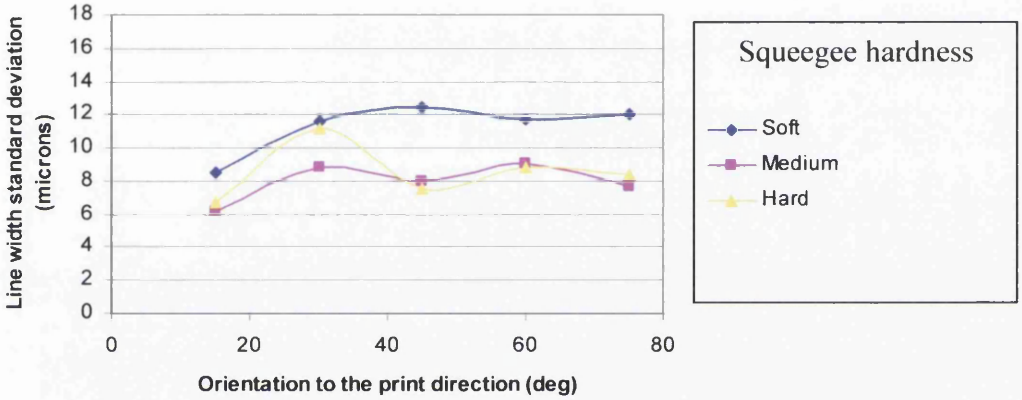


(b) 280μm wide lines

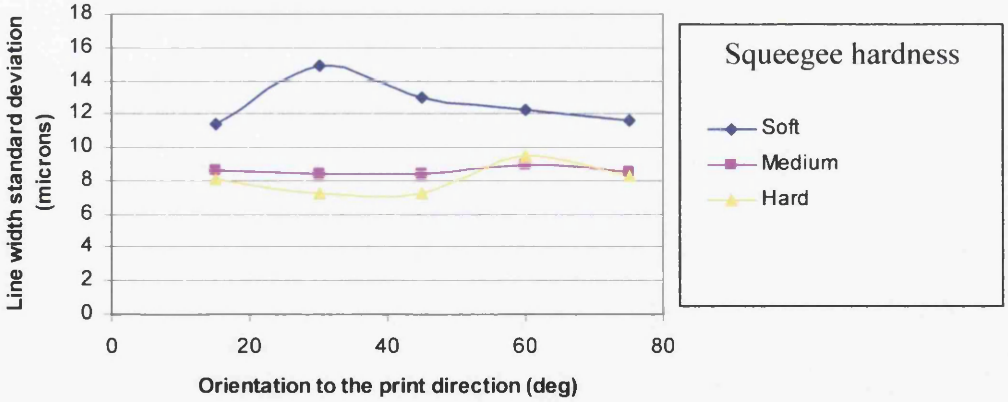
Figure 5.22 : The effect of the orientation on line width standard deviation and the interaction with the stencil roughness



(a) 90μm wide lines

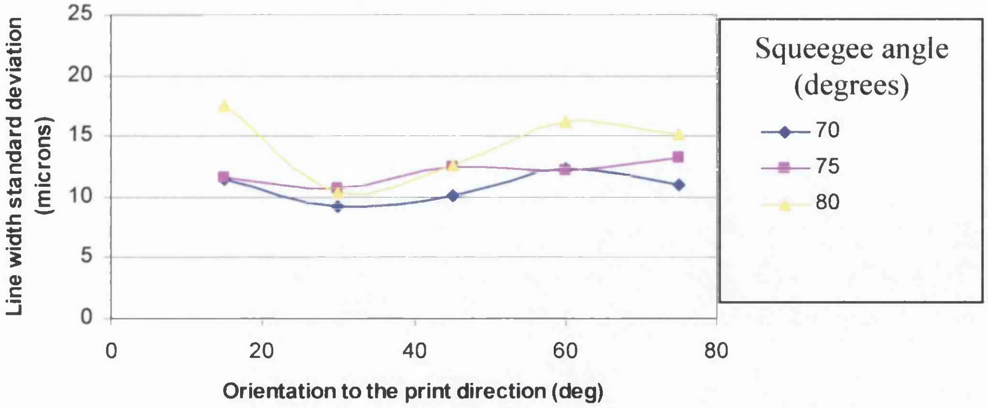


(b) 180μm wide lines

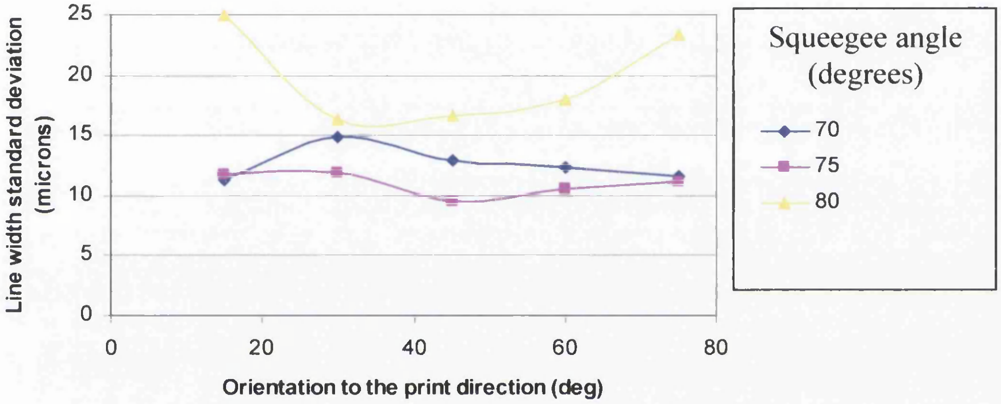


(b) 280μm wide lines

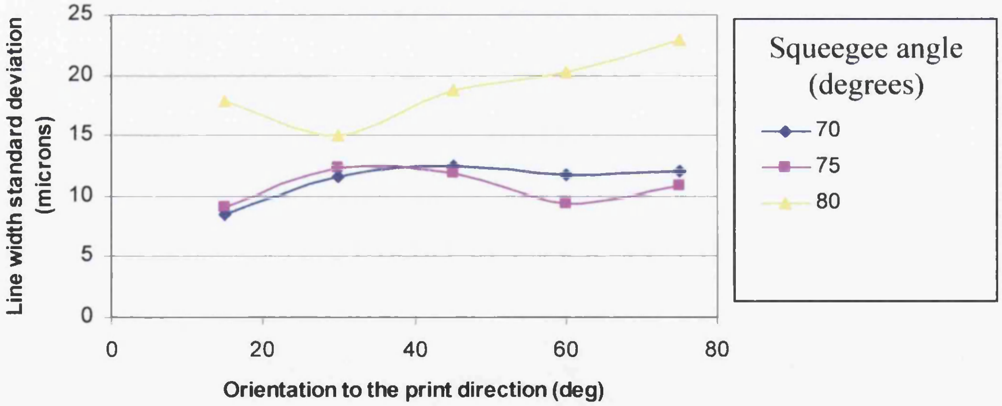
Figure 5.23 : The effect of the orientation on line width standard deviation and the interaction with the squeegee hardness



(a) 90μm wide lines

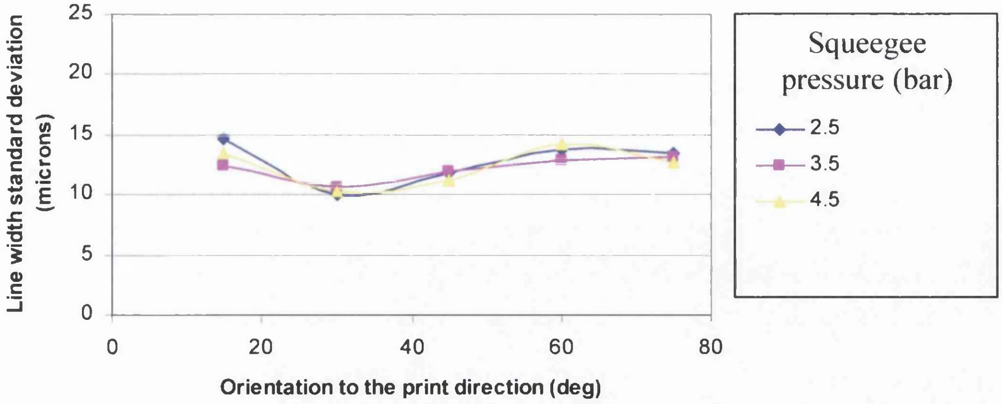


(b) 180μm wide lines

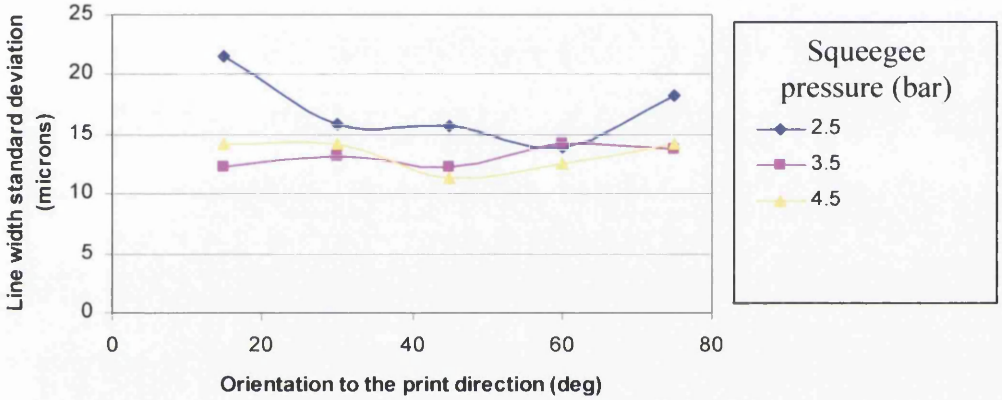


(b) 280μm wide lines

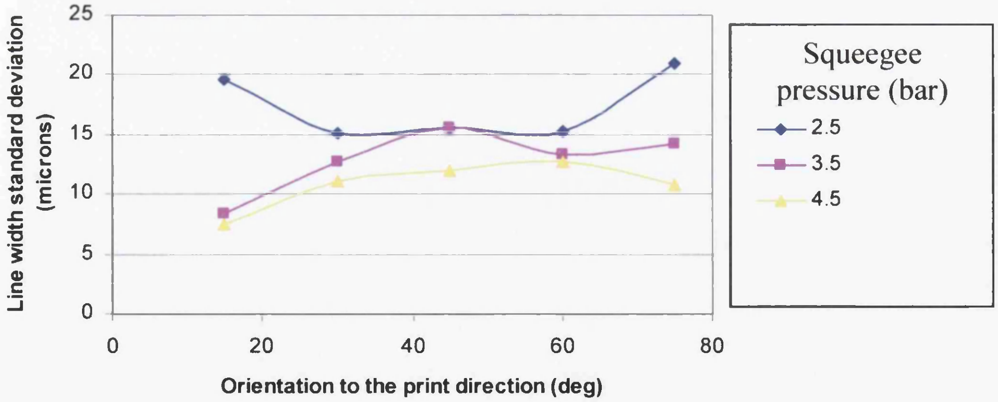
Figure 5.24 : The effect of the orientation on line width standard deviation and the interaction with the squeegee angle



(a) 90μm wide lines



(b) 180μm wide lines



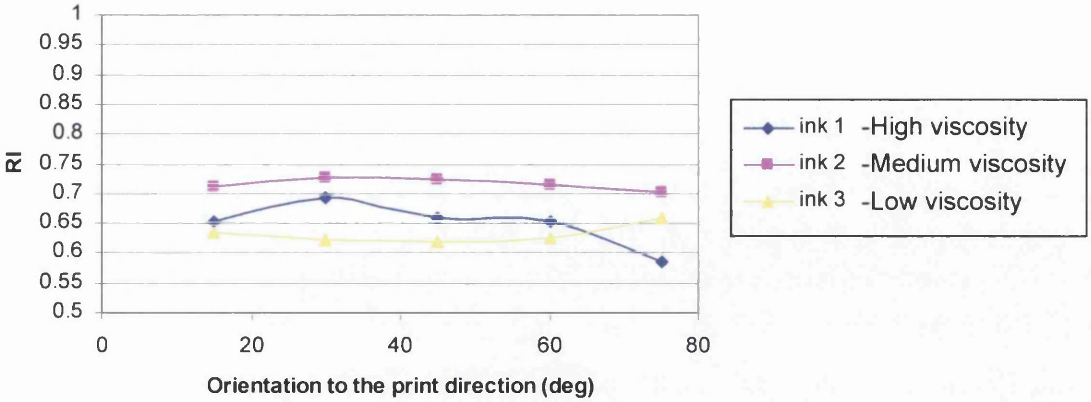
(b) 280μm wide lines

Figure 5.25 : The effect of the orientation on line width and the interaction with the squeegee pressure

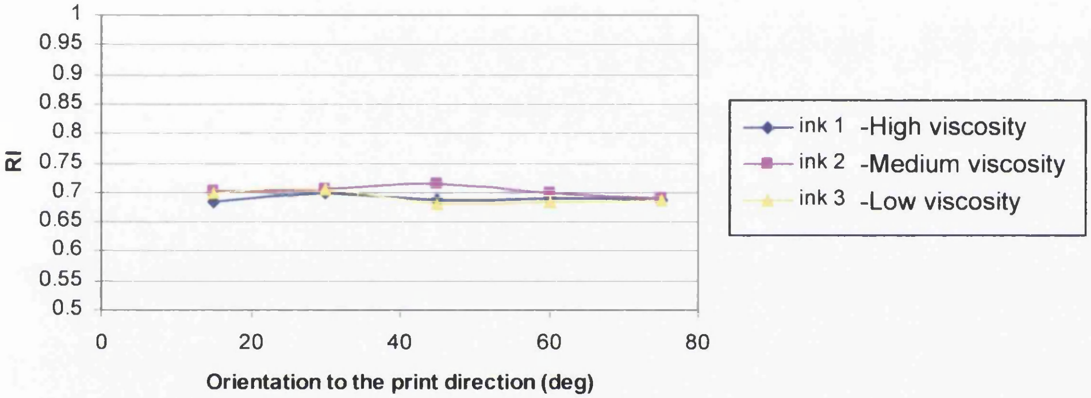
5.5.7 The effect of orientation on line cross-sectional shape

First interactions between the process parameters and orientation on RI are presented. During the study it was noticed that orientation had an effect on the line cross-sectional shape. Details of this and a preliminary theory as to why it occurs is given after the results for RI.

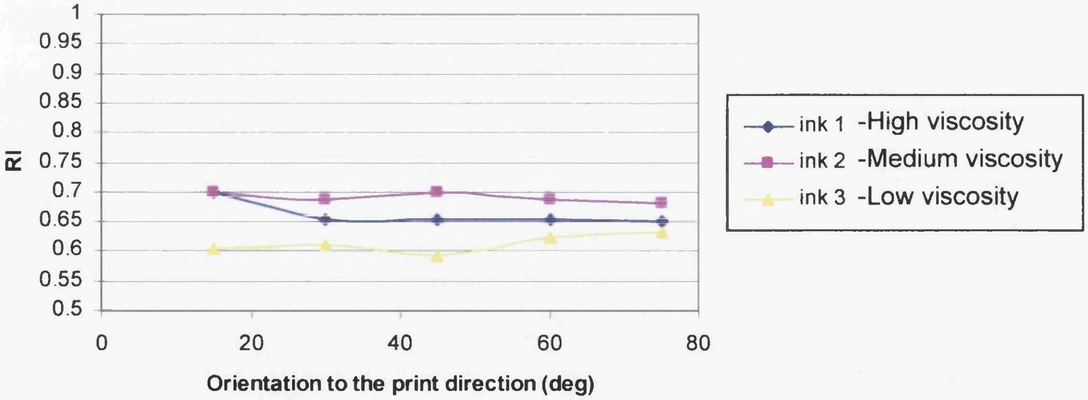
Orientation has very little effect on RI (rectangular index) as shown in Figures 5.26 to 5.30. Full results are shown to demonstrate that there was no significant interaction between orientation and line width and orientation and process parameters on RI. The ink type had the largest effect on RI and this interacted with line width. This is examined further in Section 5.7. For the screen and squeegee results neither the process parameters nor the orientation had an effect on RI.



(a) 90μm wide lines

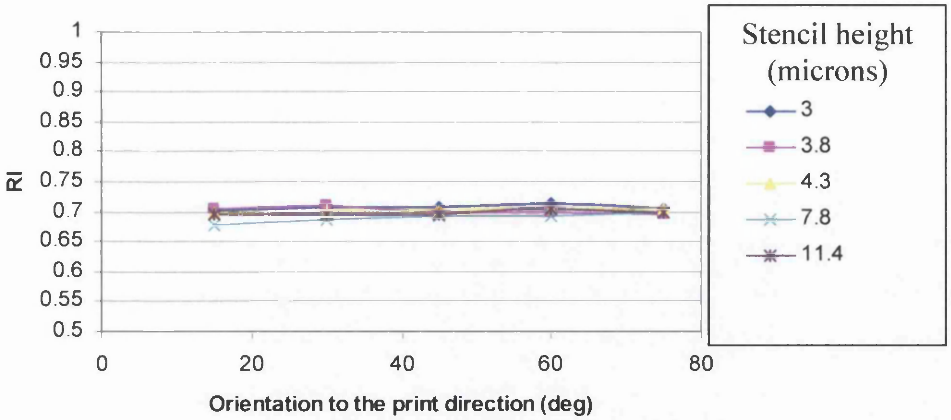


(b) 180μm wide lines

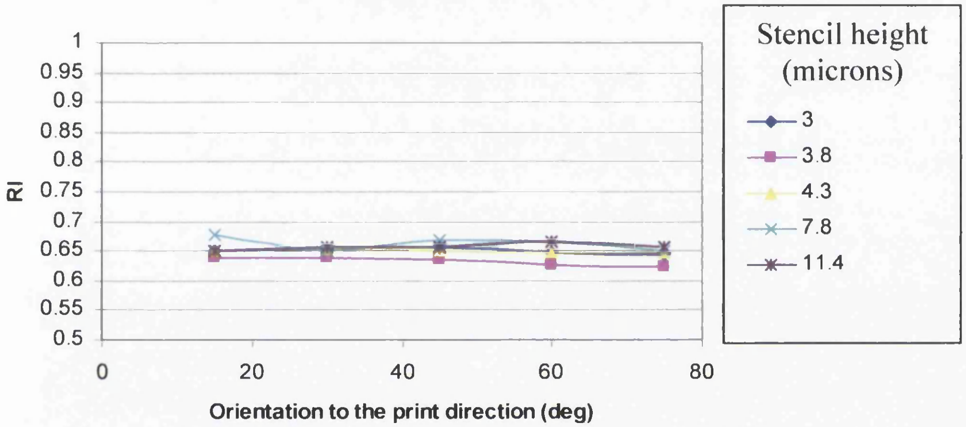


(b) 280μm wide lines

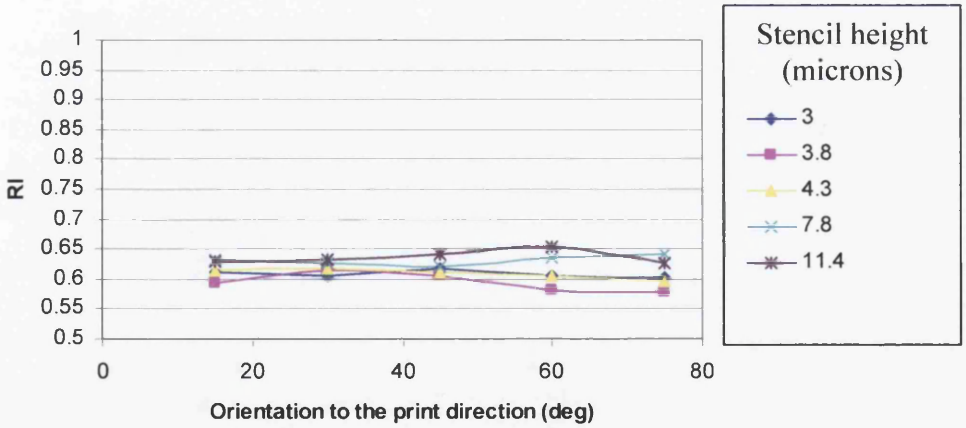
Figure 5.26 : The effect of the orientation on the rectangular index and the interaction with the ink type



(a) 90µm wide lines

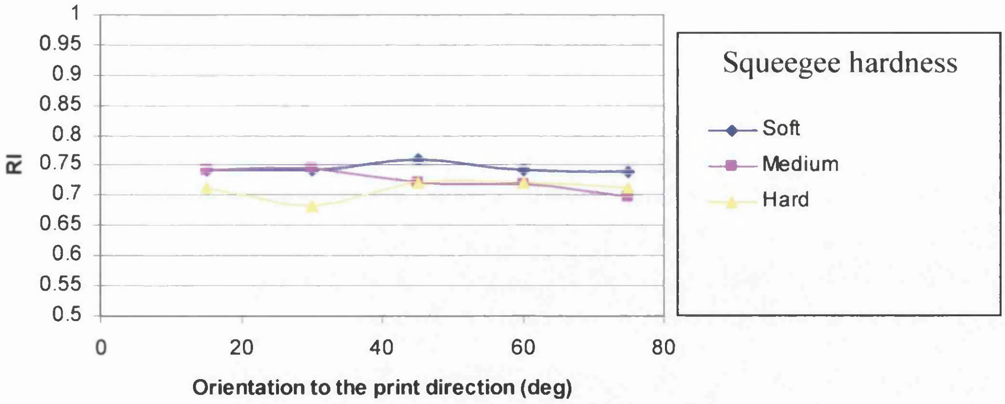


(b) 180µm wide lines

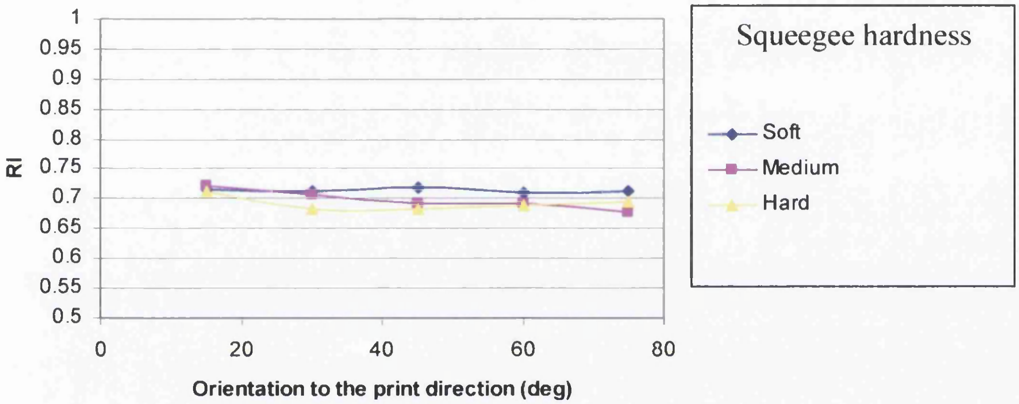


(b) 280µm wide lines

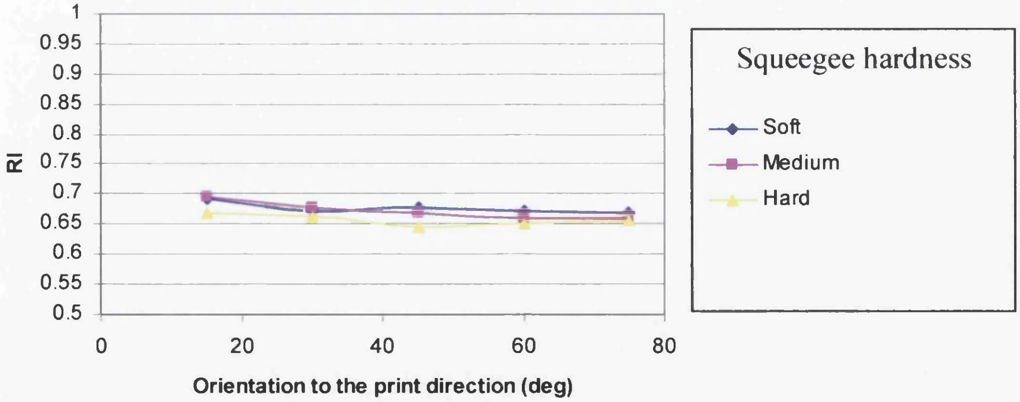
Figure 5.27 : The effect of the orientation on the rectangular index and the interaction with the screen height



(a) 90µm wide lines

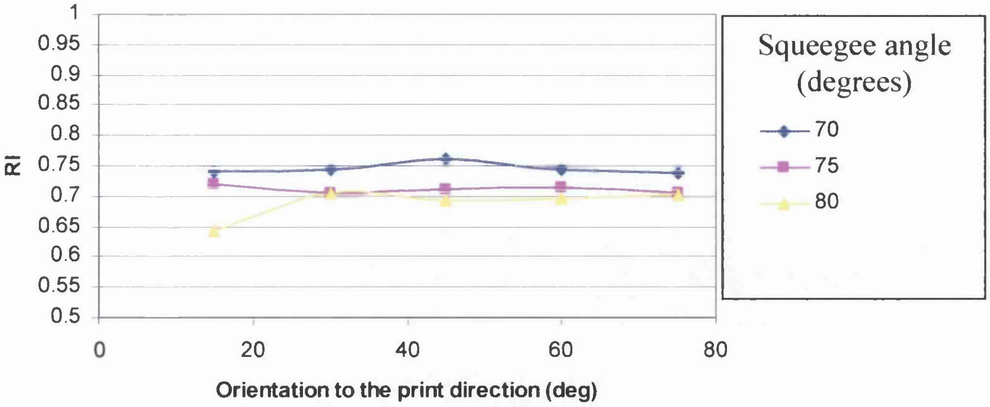


(b) 180µm wide lines

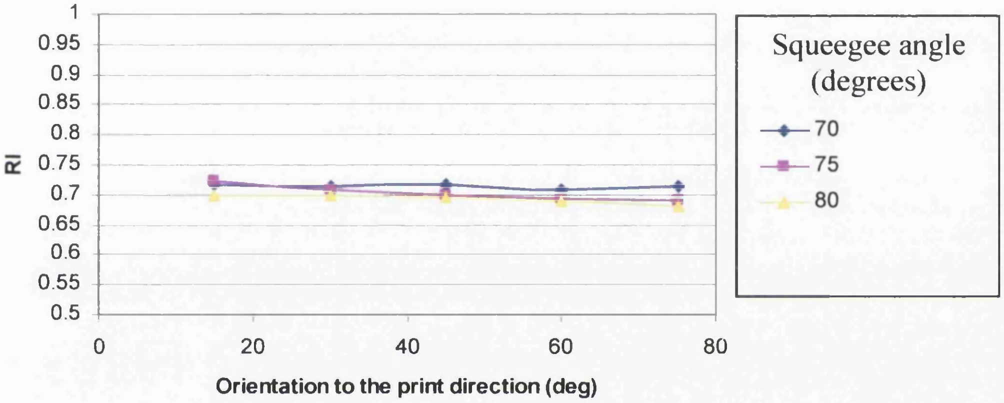


(b) 280µm wide lines

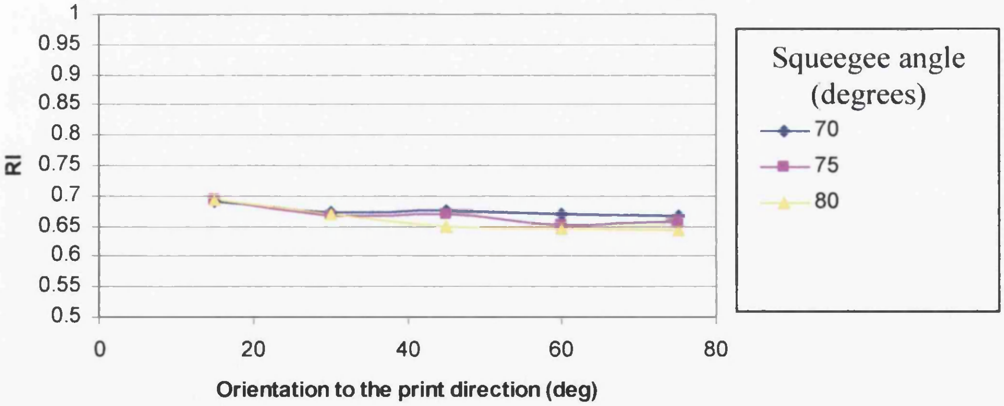
Figure 5.28 : The effect of the orientation on the rectangular index and the interaction with the squeegee hardness



(a) 90μm wide lines

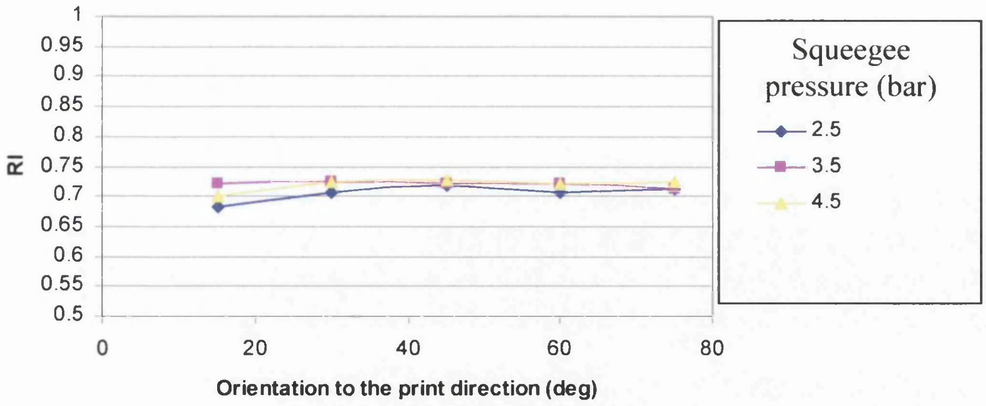


(b) 180μm wide lines

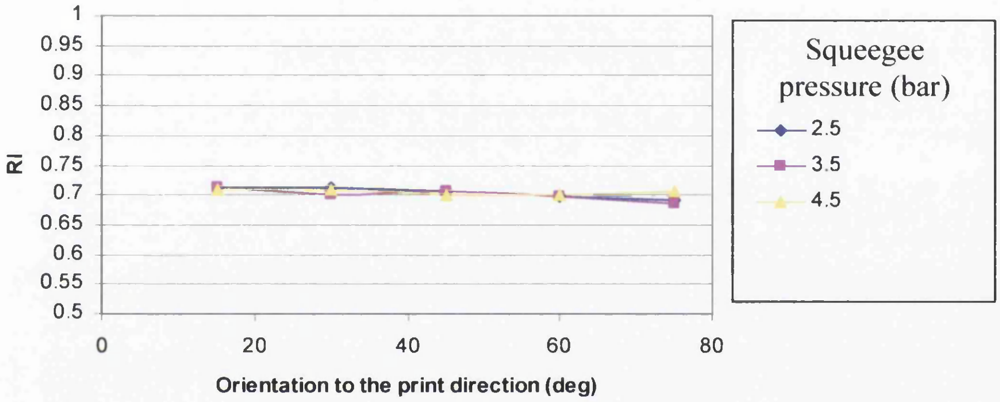


(b) 280μm wide lines

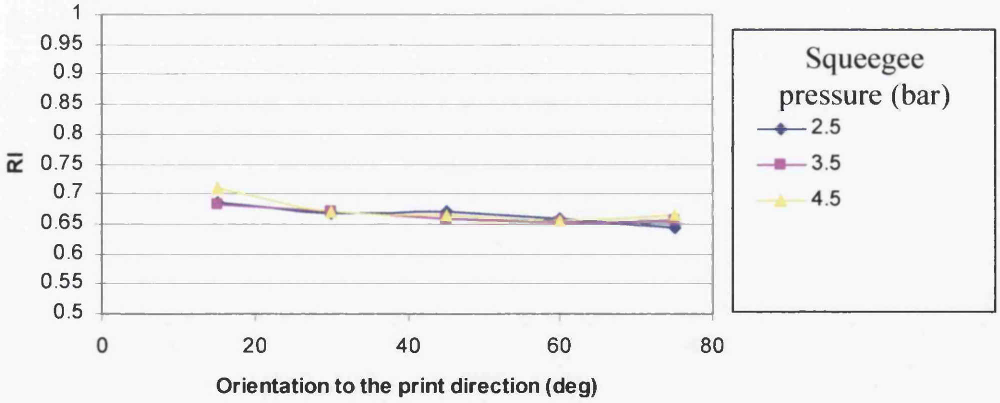
Figure 5.29 : The effect of the orientation on the rectangular index and the interaction with the squeegee angle



(a) 90μm wide lines



(b) 180μm wide lines



(b) 280μm wide lines

Figure 5.30 : The effect of the orientation on the rectangular index and the interaction with the squeegee pressure

5.5.7.1 The effect of orientation on line cross-sectional shape

During this study it was noticed that not all the cross-sections for lines printed at 75 degrees to the print direction were symmetrical, but they were close to symmetrical for lines printed at 15 degrees to the print direction. The phenomenon is described and an example is shown, further examples are shown in the Appendix C, followed by a suggestion as to why this may occur. This result is of interest as it may reveal something about the process physics and thus could be studied as a continuation to this work.

Figure 5.31 shows three cross-sections of a line at 15, 45 and 75 degrees to the print direction. An increase of the rounding of the top left hand corner of the line is shown. This was the side that is printed first. The amount of rounding was different for the lines examined. Appendix C shows lines printed with different conditions and line widths. The next section gives a hypothesis as to why this shape change occurs.

(a) Cross-section of a line 15 degrees to the print direction

(b) Cross-section of a line 45 degrees to the print direction

(c) Cross-section of a line 75 degrees to the print direction

Figure 5.31 : The effect of line orientation on line cross-sectional shape

For lines printed parallel to the print direction, the squeegee passes over the stencil edges bordering the line simultaneously, so the release at each edge of the line happens simultaneously. This makes the line symmetrical about its central vertical axis. This is confirmed by the cross-section of lines printed parallel to the print direction, Figure 5.32(a).

For lines orientated perpendicular to the print direction, the edge of the stencil bordering the rear of the line lifts off the substrate before the stencil bordering the front of the line. Below is a description of how the asymmetry in the shape of the line cross-section could occur due to the progressive release of the ink from the screen.

- The ink releases from the screen at the back of the line before the front, Figure 5.32 (b)
- At this point, the ink is drawn forwards due to cohesive forces within the ink, Figure 5.32(c)
- It finally releases completely from the screen at the front of the line, Figure 5.32 (d)

This results in the line being asymmetrical about its central vertical axis, Figure 5.32(e). This is shown by the cross-sectional shape of lines printed perpendicular to the print direction, Figure 5.32(c).

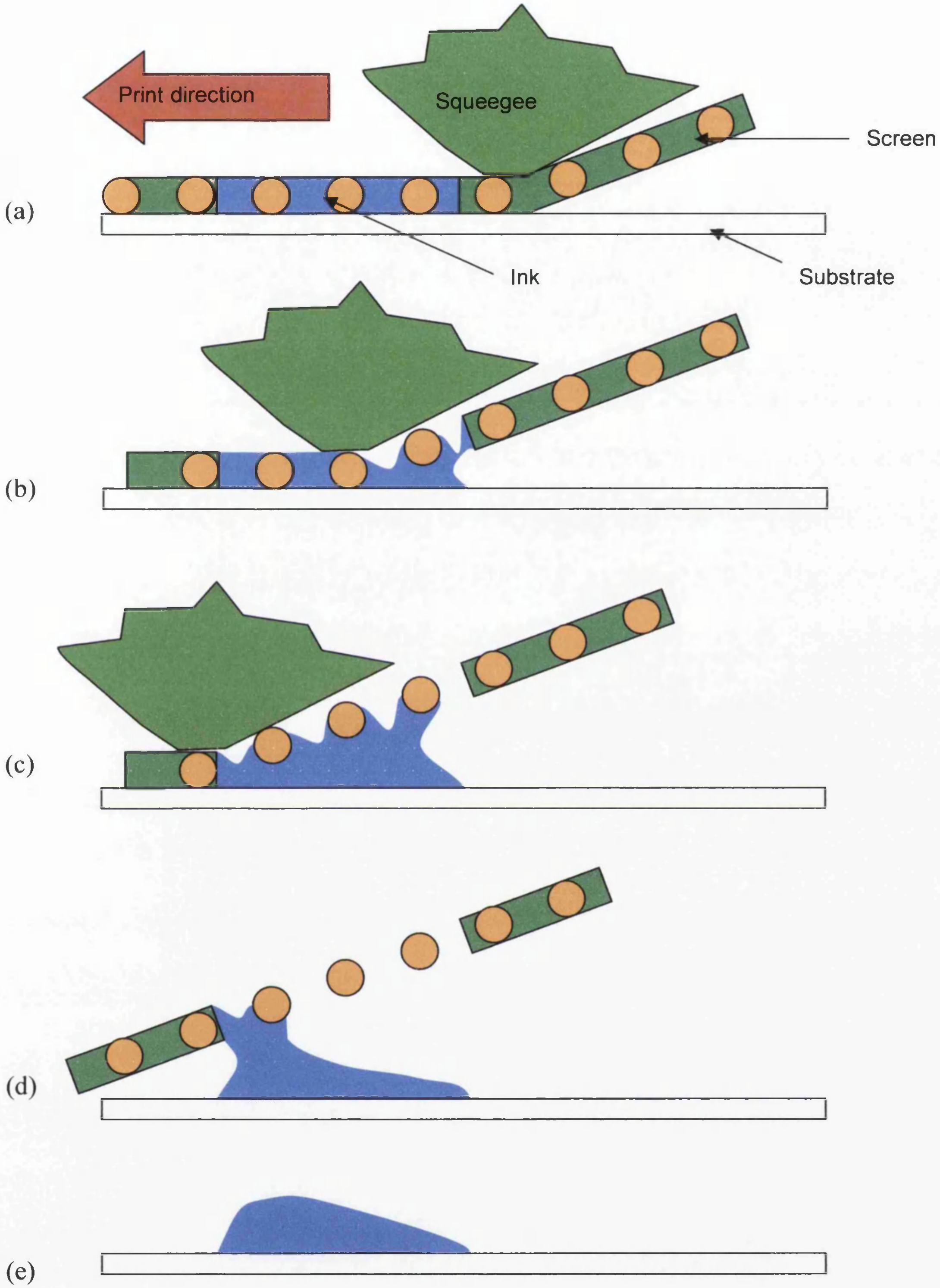


Figure 5.32 : The release of ink from the screen for lines orientated perpendicular to the print direction

5.5.8 Summary to the investigation into line orientation

This study showed that, for the conditions used, the increase in line width from parallel to perpendicular to the print direction was about 5µm to 20µm. This was due to the non-uniformity of the stretching of the screen. The decrease in cross-sectional area from parallel to perpendicular to the print direction was due to the squeegee being supported by the stencil for lines parallel to the print direction and not perpendicular. Lines printed parallel to the print direction were symmetrical about their central vertical axis, but some lines printed perpendicular were not. A theory has been postulated as to why this occurs.

The investigation into the other process parameters only examines a single orientation, as this allows a clearer presentation of the effect of the screen printing process parameters. This is shown in the next sections that are split into line size, line continuity and line cross-sectional shape to show the results more clearly.

5.6 Line cross-sectional size

This Section describes and discusses the trends exhibited in the results for the effect of the screen printing process parameters on line width and cross-sectional area. Lines were measured at 15 degrees to the print direction and at 5 line widths; 90µm, 120µm, 180µm, 280µm and 340µm. An investigation into the repeatability of the screen printing process showed a change of 5µm would be significant for the line width and 10% for cross-sectional area.

5.6.1 The effect of the squeegee parameters on line width and cross-sectional area

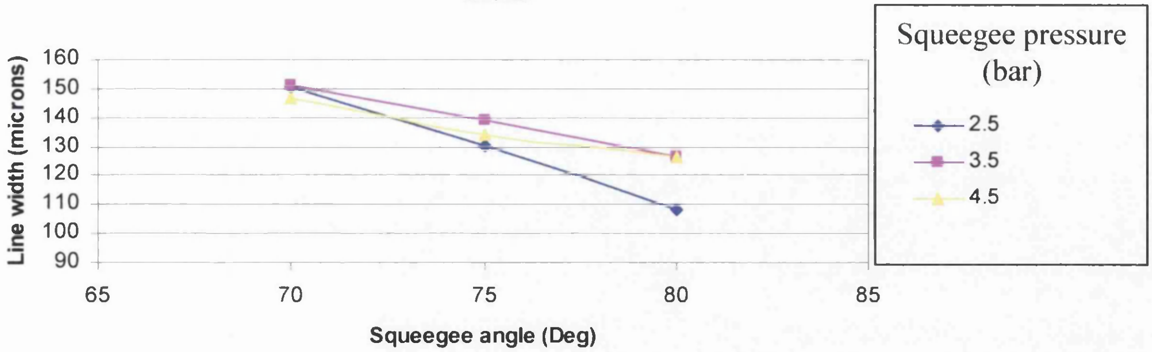
To show the trends due to the squeegee parameters only the results from 180µm lines are presented. Similar trends were obtained at other line widths, the results of which are shown in Appendix D. The interactions are presented, followed by the parameter effects.

5.6.1.1 Interactions

An interaction occurs when a parameter's effect on the process changes when another parameter setting is changed (18). The interactions between the squeegee parameters for line width and cross-sectional area are shown in Figure 5.33 and Figure 5.34. The interactions for the line width and the cross-sectional area show similar trends. The results suggest an interaction exists between the angle and the pressure; the angle has a slightly greater effect at 2.5 bar than at 4.5 bar. There was also an interaction between the squeegee angle and the squeegee hardness: the medium squeegee shows a different response to a change in the angle to the other two squeegee hardnesss. There was no interaction between the squeegee pressure and type.

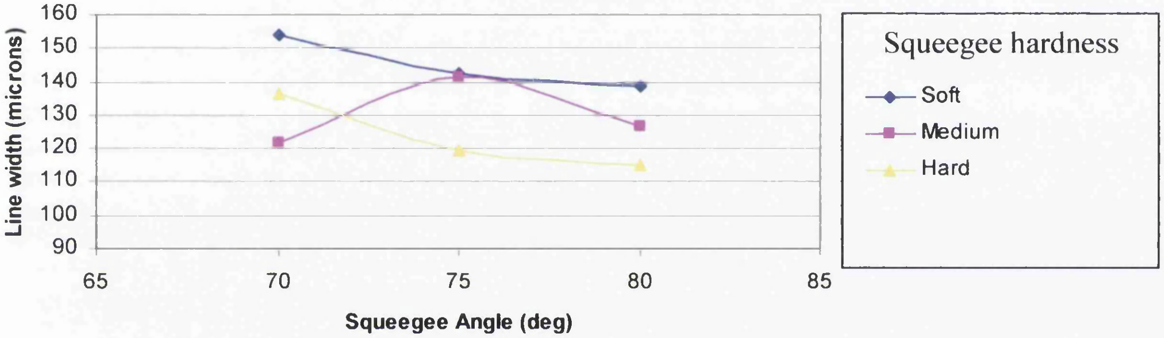
The interaction between the squeegee angle and the squeegee pressure occurs because less ink was transferred with a squeegee angle of 80 degrees and as a consequence the system was more sensitive to changes in squeegee pressure. The suggested interaction between the squeegee angle and the squeegee hardness occurs due to the drying in and is not in fact an interaction between the two parameters. This demonstrates how the drying in affected the results and it is not possible to gather reliable information without reducing the effect of the drying in on the results. The interactions between the parameters were small provided ink transfer was good (angles not close to the horizontal and low pressure), thus, the interactions can be ignored and the trends representing the effect of the parameters more clearly shown by the averaging technique described earlier in Section 3.5.1.1.

Interaction between squeegee angle and pressure for line width



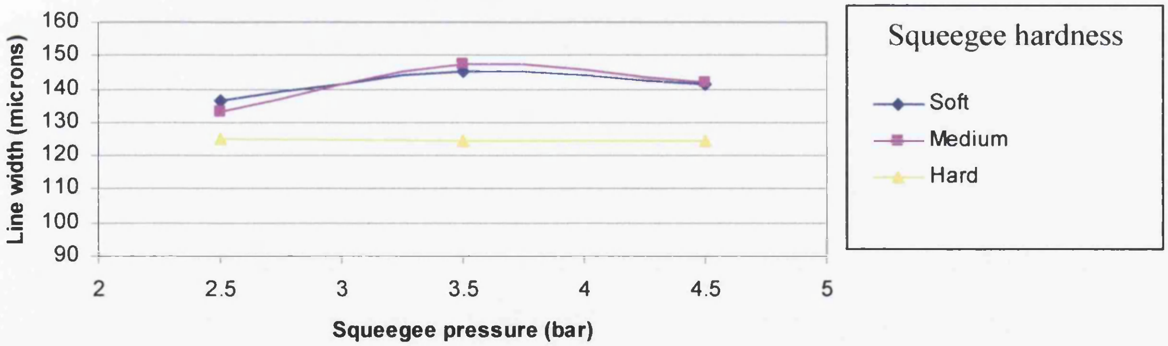
(a)

Interaction between squeegee type and angle for line width



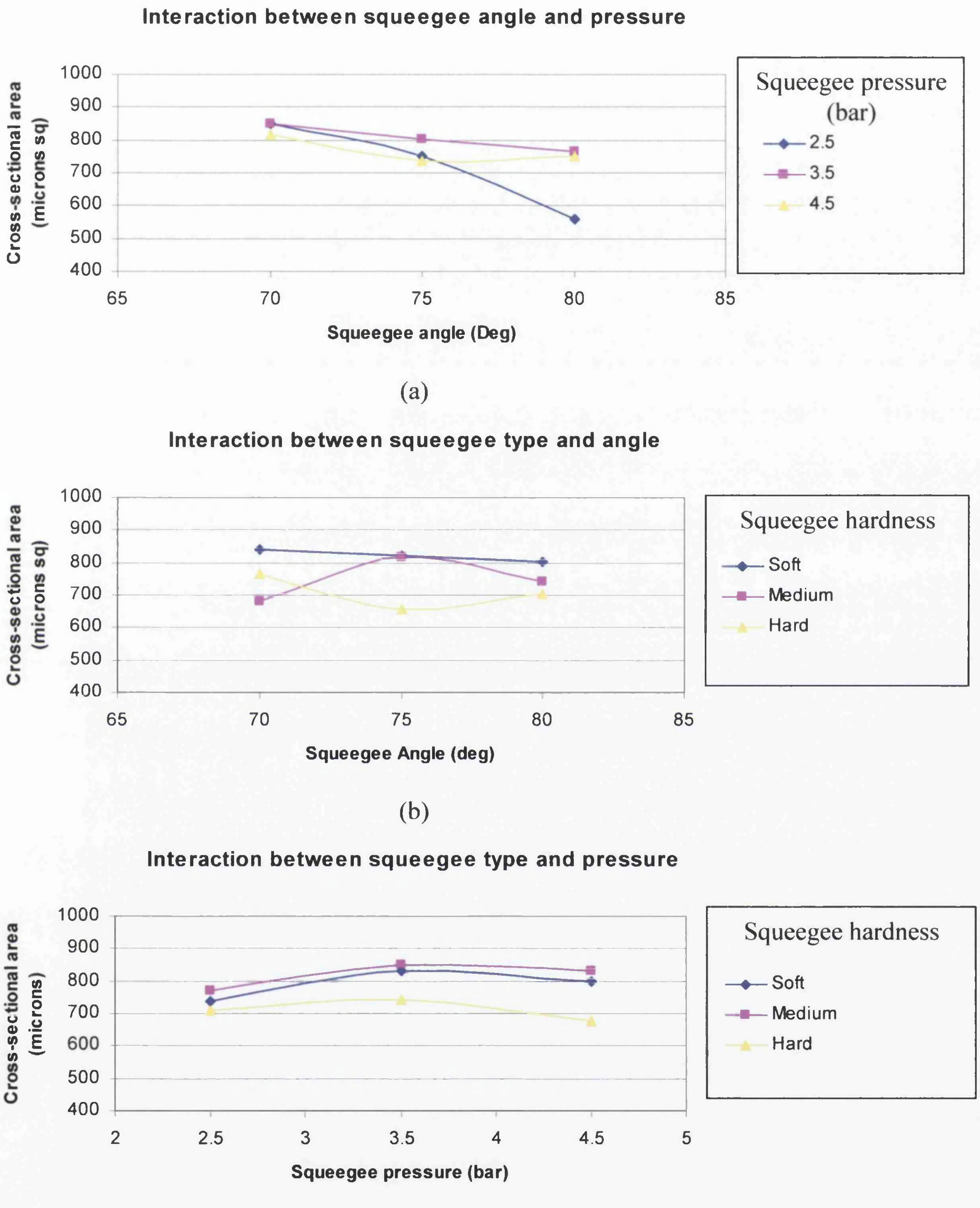
(b)

Interaction between squeegee type and pressure for line width



(c)

Figure 5.33 : The effect of Parameter interactions on line width for the 180μm wide lines



(a)

(b)

(c)

Figure 5.34 : The effect of Parameter interactions on the cross-sectional area for the 180μm wide lines

5.6.1.2 Parameter effects

Figure 5.35 and Figure 5.36 show the effect of the squeegee parameters on line width and cross-sectional area. These results were produced using the averaging technique described in Section 3.5.1.1. This reduced the effect of drying-in distorting the results. The results presented for the squeegee angle and pressure were averaged from images printed using the soft squeegee. The results presented for the squeegee pressure were an average of those printed at an angle of 70 degrees. This meant that for each process parameter level a total 15 measurement areas were averaged, 5 measurement areas recoded at 3 combinations of press settings.

Table 5.2 : Squeegee parameter levels

Parameter	Level 1	Level 2	Level 3
Squeegee hardness (Shore A)	65	74	84
Squeegee angle (deg)	70	75	80
Squeegee pressure (bar)	2.5	3.5	4.5

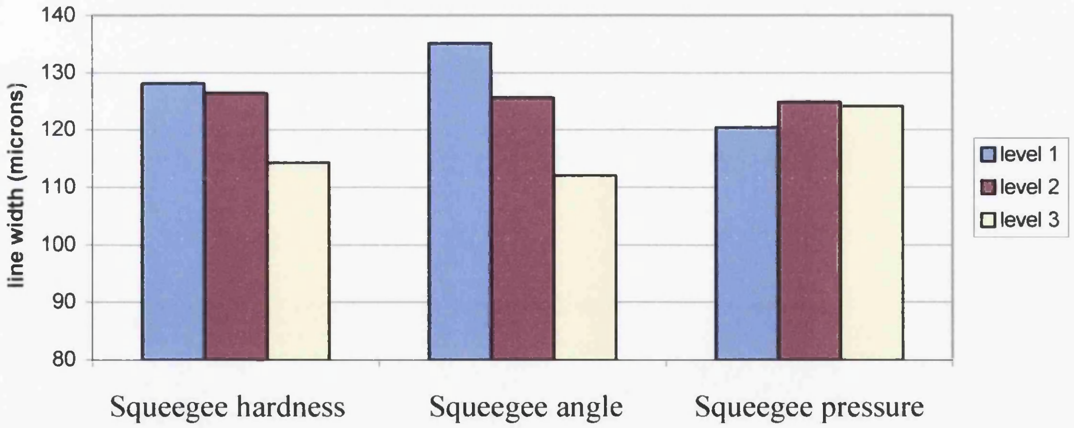


Figure 5.35 : The effect of the squeegee parameters on line width, the parameter levels are shown in Table 5.2.

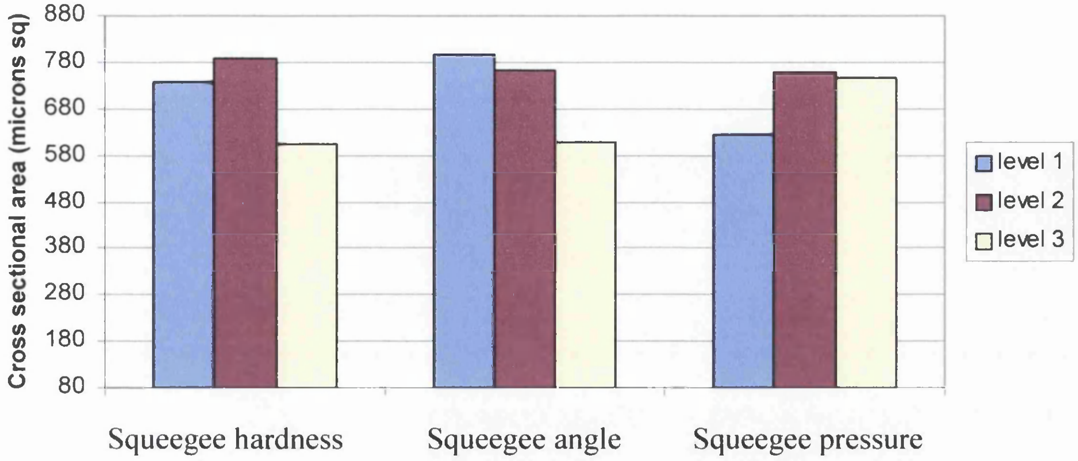


Figure 5.36 : The effect of the squeegee parameters on cross-sectional area, the parameter levels are shown in Table 5.2.

The results for the width and the cross-sectional area are very similar. The squeegee angle has the greatest effect on the line width and cross-sectional area, where angles closer to the horizontal produced wider lines. The squeegee hardness is also significant, softer squeegees produce wider lines. Squeegee pressure has a smaller effect on the system, a larger pressure producing wider lines.

5.6.2 The effect of the ink on line size

The results for line width are shown in Figure 5.37. The viscosity of the inks decreased from ink 1 to 3. Ink 2 had the highest surface tension and the other two had a similar surface tension, with ink 1 slightly lower.

The line widths measured were 90µm, 120µm, 180µm, 280µm and 340µm. Average line width gain was plotted against the film line width. Line width gain is the difference of the actual line width from the film line width. The results are presented in this manner to show the effect of changing line width more clearly. The lines printed with inks 1 and 2 are affected similarly by an increase in line width. A slightly wider line was printed by ink 1 than ink 2, apart from the 340μm wide line. The lines printed with inks 1 and 2 had more gain for thinner lines than for wider lines, whereas ink 3 had a similar line width gain for all the lines widths examined.

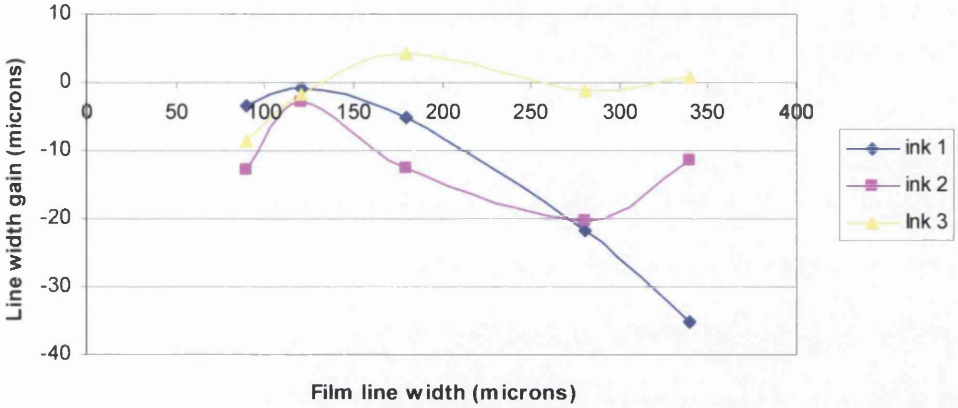


Figure 5.37 : The effect of the ink on line width

The height of the lines was shown to have a linear relationship with line width, Figure 5.38. Inks 1 and 3 appear to have a different effect to ink 2 for wider lines. The height is less for ink 2. This is shown again in the cross-sectional area, Figure 5.39. The inks had a very similar effect on cross-sectional area to the effect on height with ink 2 having different results to inks 1 and 3.

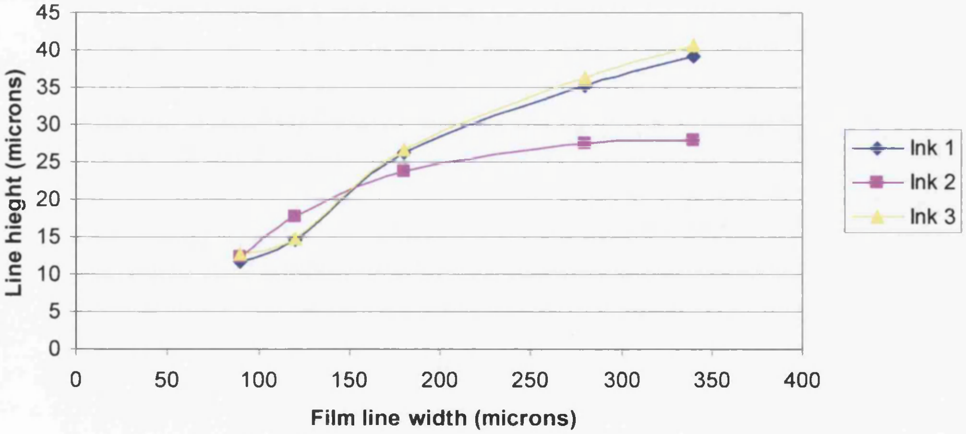


Figure 5.38 : The effect of the inks on line height

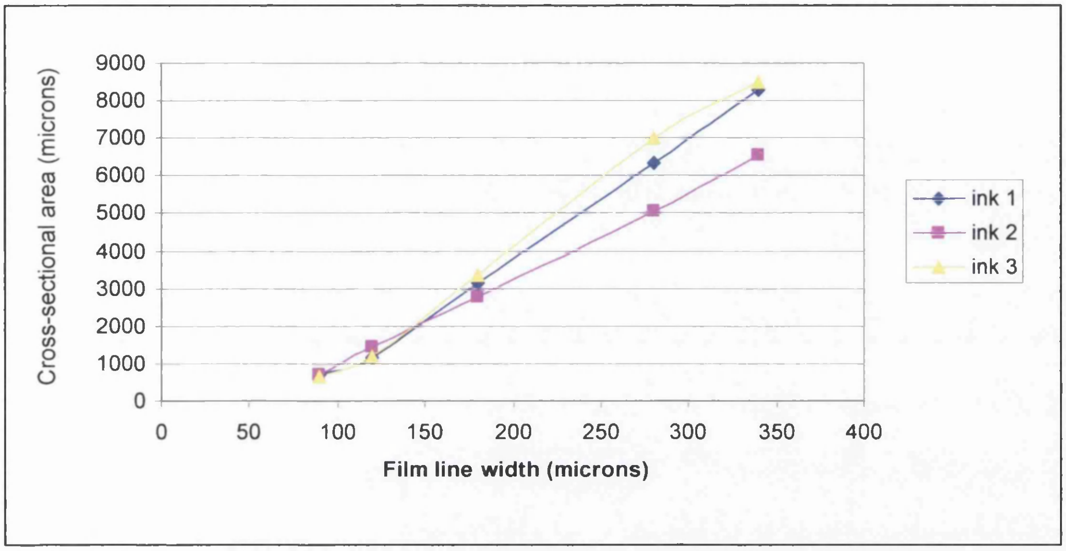
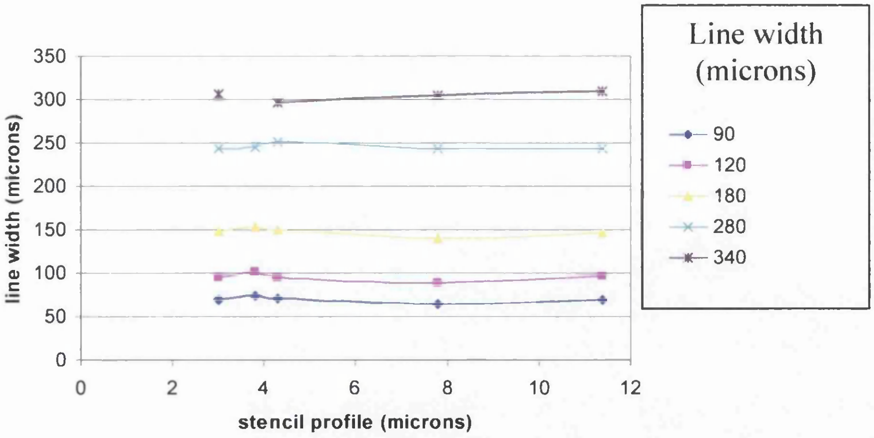


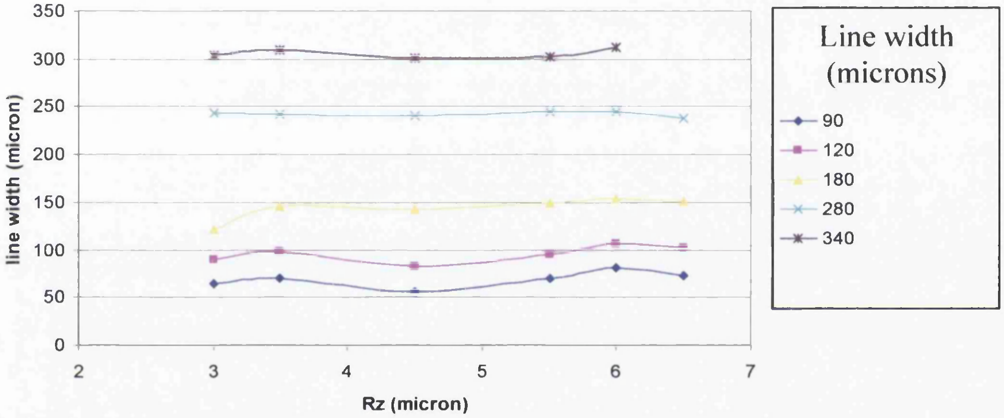
Figure 5.39 : The effect of the inks on cross-sectional area

5.6.3 The effect of the stencil parameters on line size

Printed line quality characteristics are examined against the stencil profile and the stencil roughness. Figure 5.40(a) shows the relationship between line width and stencil profile. The trends for the line widths examined are all very similar. There is little change of the line width as the stencil profile increases. Thus, the stencil profile has no effect on the line width. Figure 5.40 (b) shows that the stencil roughness has no effect on line width.



(a) The relationship between the stencil height and the printed line width



(b) Relationship between stencil roughness and line width

Figure 5.40 : The effect of the screen on line width

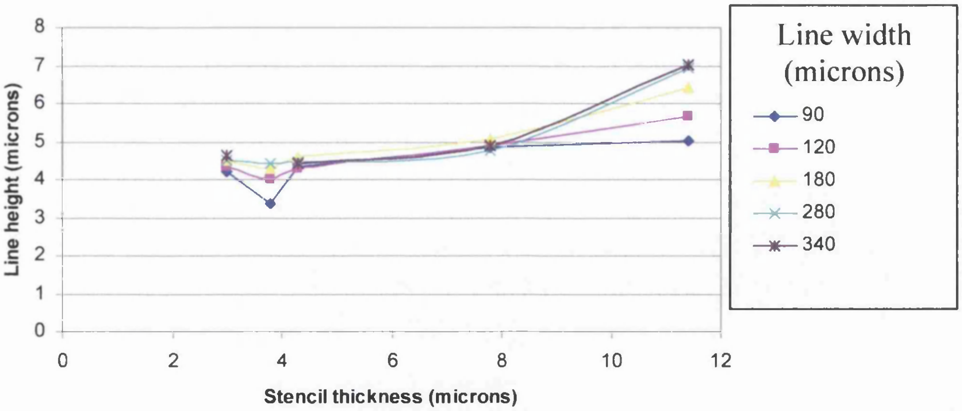


Figure 5.41 : The relationship between the stencil thickness and line height

The relationship between line height and stencil thickness is shown in Figure 5.41. This shows a direct relationship between line height and stencil profile. An increase of 1μm on the stencil profile relates to an increase of about 0.3μm in the height of the dry printed line. There is an interaction between stencil profile and line width. For all but the thickest stencil, line width has no effect on the height of the line but, at the largest stencil profile examined in this study, line width does have an effect on the line height. The effect of the stencil height on cross-sectional area is similar to that of line height, Figure 5.42. The same interaction exists and, thus, this is an interaction between the line width and stencil profile on ink transfer.

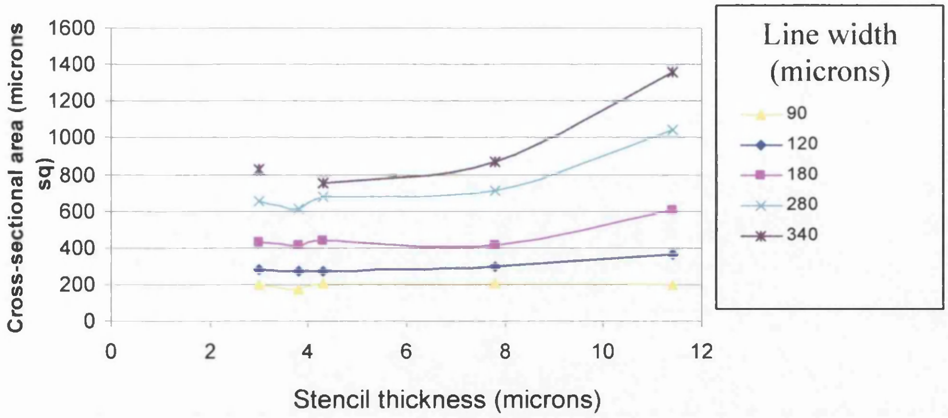


Figure 5.42 : Relationship between stencil thickness and cross-sectional area

5.6.4 Discussion of the effect of process parameters on line cross-sectional size

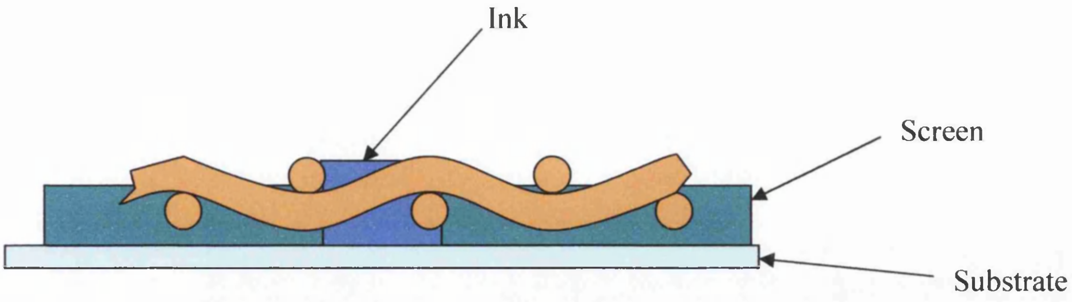
Cross-sectional area was shown in Section 4.2 to affect the resistance of a printed line. Line width affects how close the lines can be placed together. If the line spreads too much then connections will be made between two parallel lines. It is, therefore, important to characterise parameter effects on cross-sectional area and line width. This section first discusses trends that have been found in previous studies. These are used to prove that the measurement method correctly measured the lines. The second part discusses the effect of the squeegee on line size and relates the effect of the screen printing process parameters to results found in studies into tone gain. The effect of the ink on spreading and ink release is also discussed.

The cross-sectional area of the line is important as it determines the resistance of the printed line. Line width has also been examined because a large gain in line width may lead to connections between two parallel lines. The effect of screen printing process parameters on ink transfer has previously been investigated for graphics screen printing (12, 13). The results are mainly for the squeegee and screen parameters, but the relationship between ink transfer and line cross-sectional size and spreading has not been investigated. Theories have been put forward on the effect of the ink characteristics and these are compared to the results found by this study. The line width has been shown to have an effect on the release of the ink from of the screen and this is also discussed.

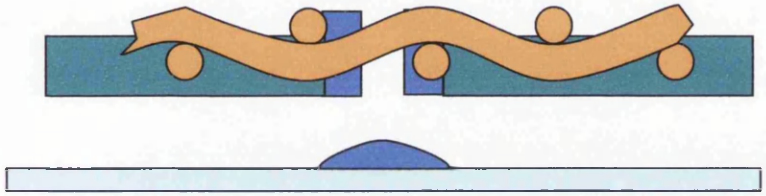
In graphic arts, printed dots of different sizes are used to create shades of colour on the substrate. Previously, the effect of process parameters on tone gain, the increase in dot size from the intended size, has been investigated is reviewed in Chapter 2. The results for the effect of the squeegee parameters on cross-sectional area found in this study are shown in Figure 5.36. A comparison of these results, with those found from investigations into graphic printing, show that the ink transfer affects line cross-sectional size and tone gain similarly. The squeegee angle has the greatest effect of the squeegee parameters on tone gain and ink transfer, it also has the largest effect of on line size. The next most significant parameter was the squeegee hardness.

The stencil height has a large effect on line height, but very little effect on line width. This means that stencil height affects ink transfer. The extra ink transferred during printing does not cause ink spreading, but only increases the height of the line. The extra ink transfer caused by increased stencil profile occurs due to the increased hole size, for holding ink, in the screen.

The line width had a large effect on ink transfer. This is because the width of the line is small compared with the volume in the mesh for the 90µm lines. This relates to a poor release of ink. This is shown in Figure 5.43. For wider lines the width was not significantly small compared with the volume of the mesh and good release of the ink is enabled. This is shown in Figure 5.44. Here, it is noted, that Rodriguez and Baldwin also examined this same effect for stencil printing (22).

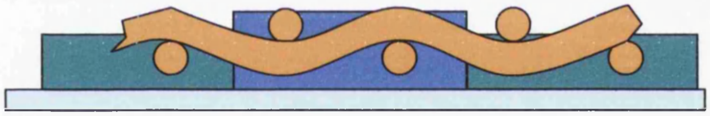


(a) Point in the print cycle where the screen and the substrate are in contact

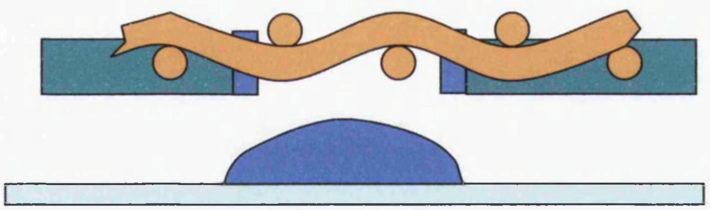


(b) After the print cycle, showing the ink remaining on the substrate

Figure 5.43 : Schematic of the ink release for a 90µm line



(a) Point in the print cycle where the screen and the substrate are in contact



(b) After the print cycle, showing the ink remaining on the substrate

Figure 5.44 : Schematic of the ink release for a 180µm line

It has been shown previously that inks with higher surface tension spread more on the substrate (3). This study did not find such a simple relationship between ink surface tension and ink spreading. Figure 5.37 and Figure 5.39 show the effect of the ink on ink transfer and spreading for the inks investigated in this study. Surface tension had a large effect on ink transfer for the wider lines but, for the 90µm and 120µm wide lines, the ink transfer was similar for the three inks.

The line width for the 90µm and 120µm wide lines was affected by the surface tension, since the ink transfer was the same. Inks with a lower surface tension spread more. At higher line widths, ink transfer and the viscosity affected the line width. Ink 2 produced thinner lines as less ink transfer occurred using this ink. The ink transfer for inks 1 and 3 was similar, but ink 3 produced wider lines. This suggests, that for wider lines, the viscosity is more significant than the surface tension for line width.

A good correlation between the results in this study and those from previous studies was found for the relationship between line cross-sectional size and process parameters. The parameters shown to increase ink transfer also have a similar effect on line width and cross-sectional area. The surface tension was shown to affect the ink transfer. The effect of ink spreading is explored further in Section 5.6.5 after the results for line cross-sectional shape have been presented.

5.6.5 Summary of line cross-sectional size

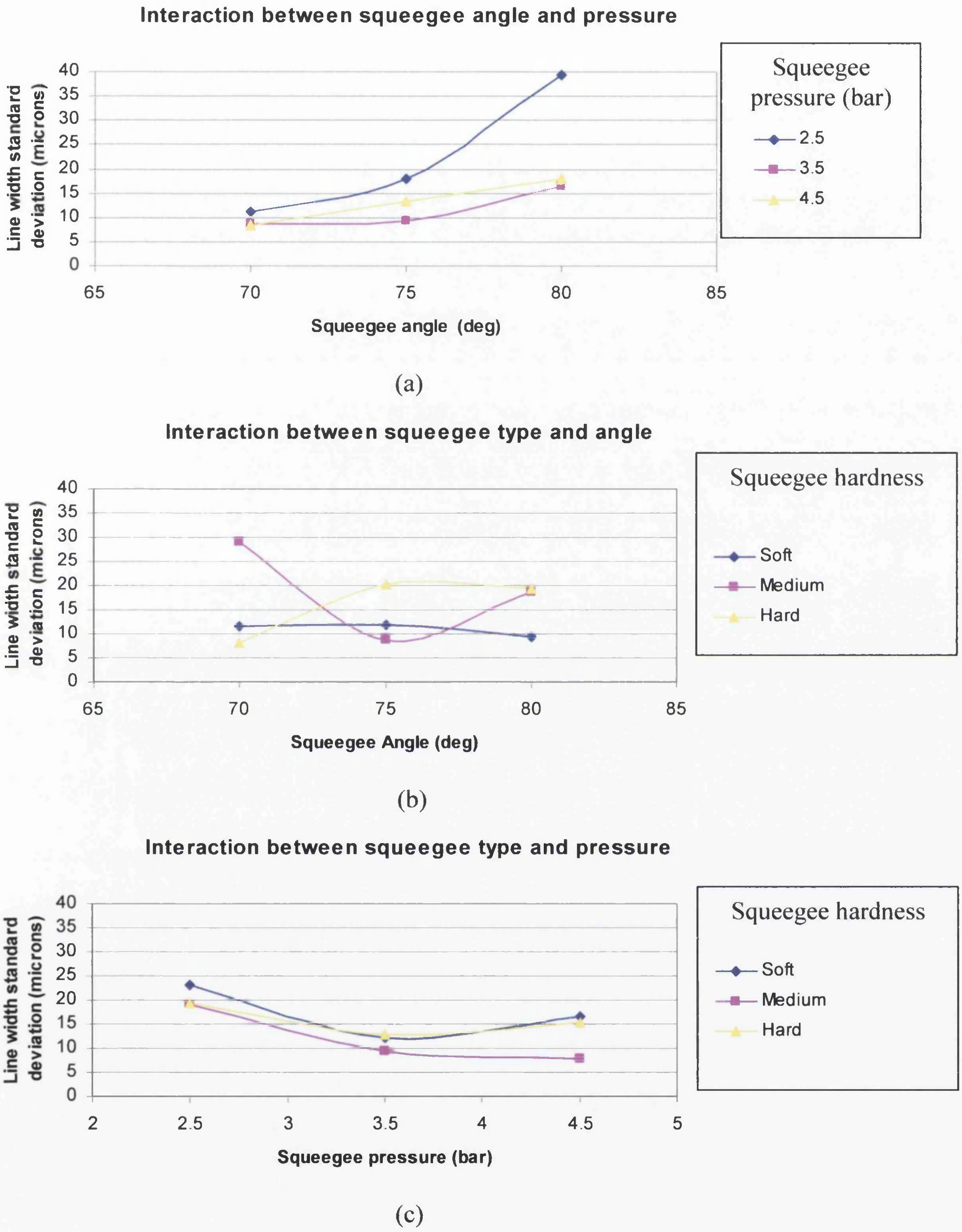
The effect of the screen printing process parameters on line size has been presented. The most significant squeegee parameter was the squeegee angle. Squeegee angles closer to the horizontal produced more ink transfer. Inks with higher viscosity and low surface tension produced wider lines, but actual ink transfer was affected by surface tension. Less ink transfer was obtained with inks of high surface tension. Stencils with larger heights produced more ink transfer. The measurement method was verified by using parameters previously investigated. The trends found for line width and cross-sectional area were similar to those found previously in ink transfer for graphic arts screen printing. The surface tension was shown to affect both the ink transferred and the spreading of the ink after printing.

5.7 Line continuity

It is important to know whether the line width is continuous along the length of the line. This enables the prediction of how close lines can be placed together. This section describes the results from investigating the effect of the process parameters on line continuity. A discussion is then given for the trends found in the results.

5.7.1 Effect of the squeegee parameters on line continuity

The interactions between the squeegee parameters were examined using the same method as used for line size. The results presented here, in Figure 5.45, are for the 180μm lines. The results for the other line widths are in Appendix D. The trends in the data are similar with an interaction suggested to exist between squeegee angle and pressure as well as between squeegee angle and hardness.



Interaction between squeegee angle and pressure

(a)

Interaction between squeegee type and angle

(b)

Interaction between squeegee type and pressure

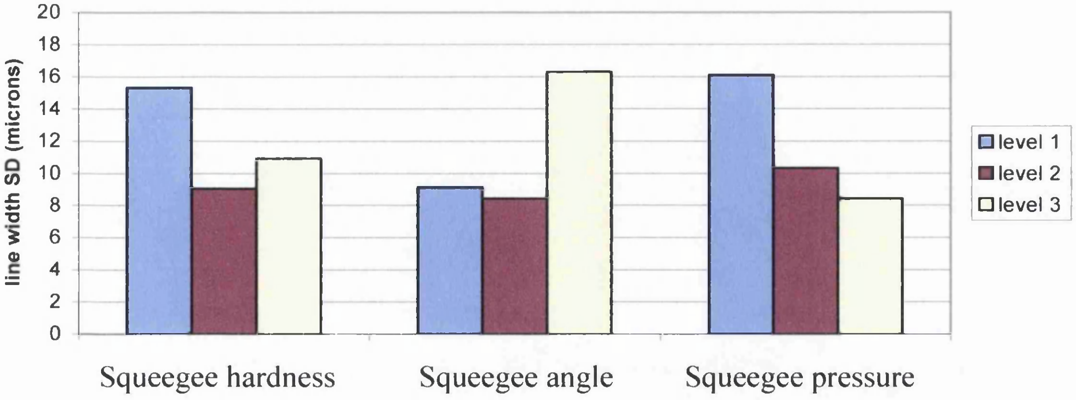
(c)

Figure 5.45 : The effect of parameter interactions on line width standard deviation for 180μm wide lines

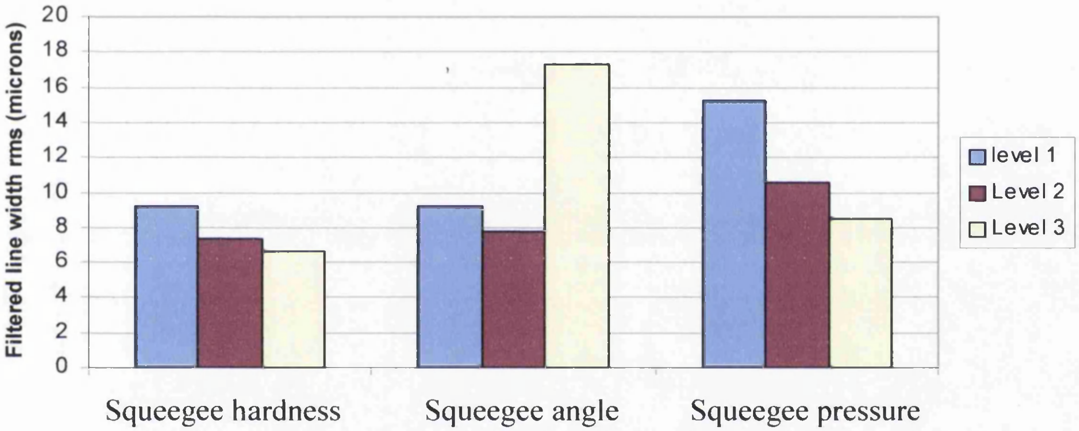
As before, the results were investigated using the technique described in Section 5.2.5, to minimise the effect of the drying-in. Squeegee hardess has the least significant effect on line edge quality of the three parameters examined. This is shown on Figure 5.46(a). Pressure was shown to have the smallest effect on average line width gain, but it has the greatest effect on the edge quality. The squeegee angle is shown to have a significant effect on line edge quality, with better edge quality obtained from printing with the squeegee closer to the horizontal. Figure 5.46(b) shows the effect of the press parameters on mesh marking. The squeegee hardenss has only a small effect on mesh marking. There are great similarities between the filtered and unfiltered data for the squeegee angle and pressure. This shows that mesh marking is the cause of the edge roughness caused by the squeegee angle and pressure. It shows that mesh marking occurs due to insufficient ink transfer.

Table 5.3 : Squeegee parameter levels

Parameter	Level 1	Level 2	Level 3
Squeegee hardness (Shore A)	65	74	84
Squeegee angle (deg)	70	75	80
Squeegee pressure (bar)	2.5	3.5	4.5



(a) The effect of the squeegee parameters on line width standard deviation,



(b) The effect of the squeegee parameters on mesh marking (filtered data)

Figure 5.46 : The effect of the squeegee parameters on line edge quality, the parameter levels are shown in Table 5.3.

5.7.2 Effect of the ink on line continuity

Figure 5.47 shows how the ink characteristics affect the edge roughness of the lines. The evidence suggests that the edge roughness was dependent more on the ink viscosity than the surface tension for thinner lines, although the result is barely significant. The lower the viscosity the smoother the edge of the lines for fine lines. For wide lines the inks used do not have a different effect on the edge roughness of the line.

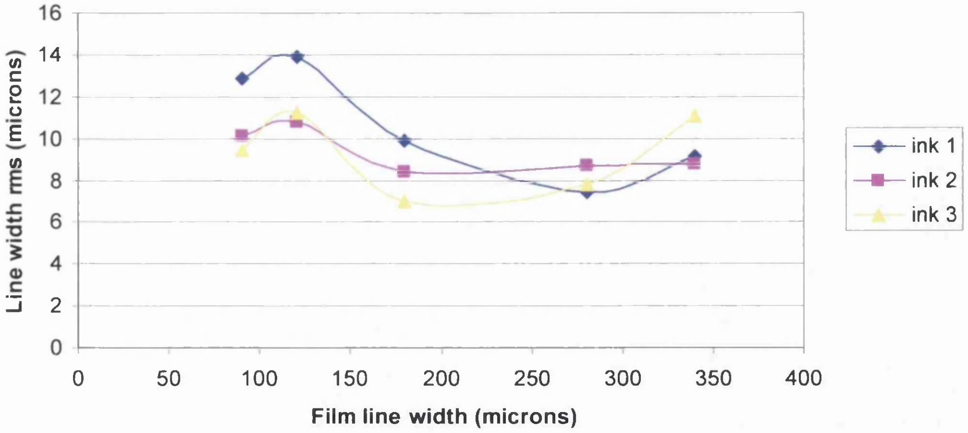


Figure 5.47 : The effect of the inks on line edge quality

5.7.3 Effect of the screen on line continuity

The effect of stencil roughness on line quality is shown, Figure 5.48, as a scatter plot of line edge quality against stencil roughness of all the line widths examined. A strong trend is shown in the plot, illustrating that a rougher stencil will produce a line with a worse edge quality. It also shows that all the line widths have a similar edge quality for the same stencil Rz. This shows that stencil roughness effects the edge of the line.

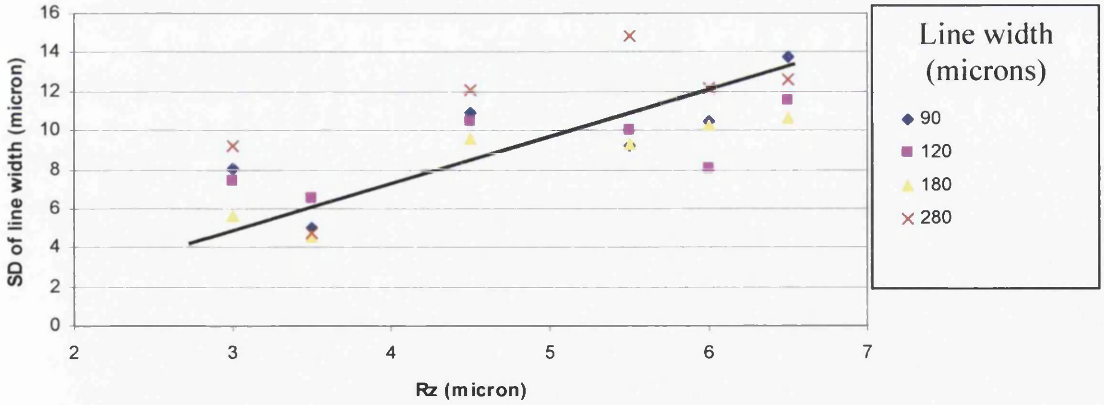


Figure 5.48 : Relationship between stencil roughness and edge quality

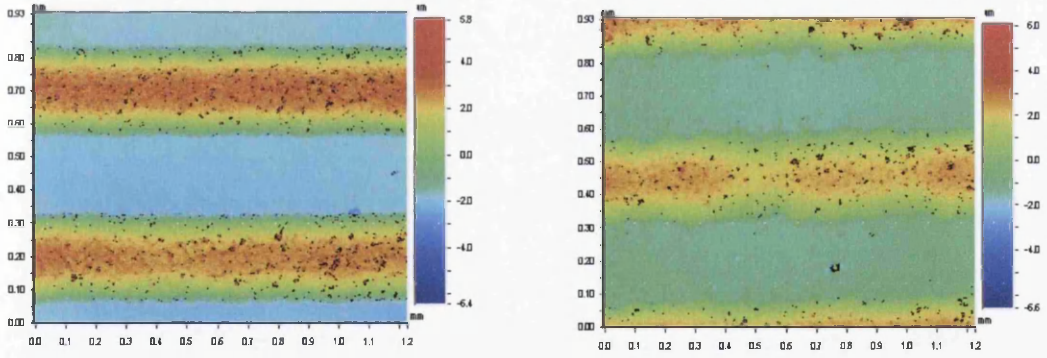
5.7.4 Discussion of the effect of process parameters on line continuity

Two patterns of poor line continuity were found to exist, as described in Section 4.3. These were high frequency patterning, termed edge rippling, and a lower frequency patterning termed mesh marking. This section describes why these exist and methods that can be used to reduce them and, thus, to improve line quality.

5.7.4.1 Edge rippling

Edge rippling is deviations in line with a frequency close to the mesh count (number of threads per unit length) of the screen used. Due to the frequency of the marking being similar to the mesh count, it is was suspected that the screen was the principle cause of this phenomenon.

The results indicated that the roughness of the screen was the most significant screen printing process parameter on the edge rippling, this is shown in Figure 5.48. The rougher the underneath of the stencil the more edge rippling lines exhibit. Figure 5.49 shows two lines, one printed through a smooth stencil and one printed through a rough stencil. The rippling effect is visible on the line printed through the rough stencil.



(a) Smooth stencil (b) Rough stencil

Figure 5.49 : Illustration of different edge qualities printed through stencils of different roughness

This effect of stencil roughness has been investigated previously and it has been shown that the stencil coating smoothes out the roughness of the mesh (14). A thicker stencil applied to the mesh makes the print side of the stencil smoother. A flatter, smoother stencil produces a better seal with the substrate and this does not allow ink to seep out around the edges of the stencil. A rough stencil leaves small gaps under the screen, these are shown in Figure 5.50. Ink spreads from these gaps causing the high frequency defects or edge rippling (14).

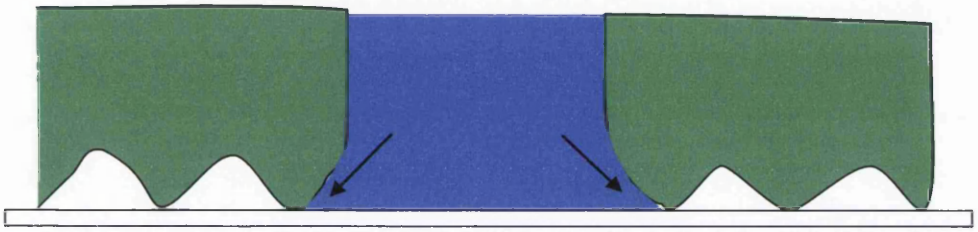


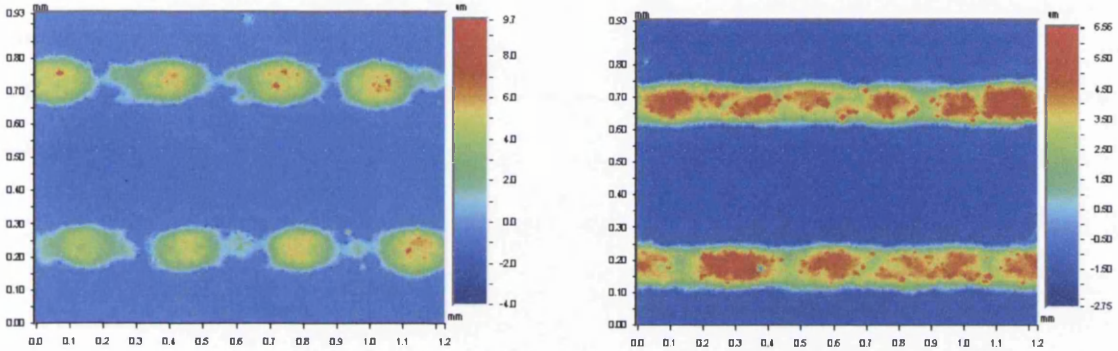
Figure 5.50 : Illustration of gaps where ink can be pushed by squeegee to produce rippling along the edge of a line

As the roughness of the screen is the only screen printing process parameter to significantly affect the edge rippling, it is not possible to introduce corrective measures if the screen is not sufficiently smooth. This demonstrates the importance of manufacturing the screen to the correct quality to ensure good line reproduction.

5.7.4.2 Factors affecting mesh marking

Mesh marking is low frequency undulations along the length of the line. It was shown in Section 4.3 that the frequency of the undulations was dependent on the orientation of the line to the mesh. Lines printed at 15 degrees to the mesh had a lower frequency pattern than those printed at 45 degrees.

The results, Figure 5.46, showed that the screen printing process parameters that affected ink transfer also affected the mesh marking, with the squeegee pressure being the most significant screen printing process parameter on mesh marking. Unless the printing pressure is sufficient to create a good contact between the screen and substrate insufficient ink will be transferred and a poor quality line will be produced. This occurs at the lowest pressure investigated in this study. At higher pressures, the screen is pushed onto the substrate sufficiently and good ink transfer occurs. Figure 5.51 shows examples of lines printed at 2.5 bar and 4.5 bar, illustrating the difference between the two pressures. The line printed at 2.5 bar is incomplete, while the line printed at 4.5 bar has good edge characteristics.



(a) Example image at 2.5 bar
(low pressure)

(b) Example image at 4.5 bar
(high pressure)

Figure 5.51 : The effect on the printed image of insufficient squeegee pressure and, therefore, insufficient ink transfer.

The squeegee angle has been shown in previous studies, as it also was in this study, to have a significant effect on ink transfer (13). This is linear, with angles closer to the horizontal producing more ink transfer. This is the same result as was found for the effect of the squeegee angle on mesh marking, Figure 5.46.

To understand why mesh marking occurs, and therefore, how to remedy it, there is a need to consider what part of the screen printing process creates mesh marking. There are two main stages to the process of ink transfer in screen printing. These are the filling of the mesh with ink and the release of the ink, from the mesh, onto the substrate. During the screen printing process the pressure from the action of the squeegee fills the screen with ink. The pressure does not force ink through the screen onto the substrate as the stencil forms a seal with the substrate. The ink is released from the screen as a consequence of the adhesion forces between the ink and substrate. Therefore, the squeegee pressure and angle influence the filling of the mesh with ink, as oppose to the release of the ink from the screen. Therefore, the mesh marking is due to insufficient filling of the mesh with ink.

Further information on the cause of the patterning of mesh marking was obtained by examining the patterns that occur due to the interaction between the stencil and the mesh. This is shown in Figure 5.52. The mesh partially blocks part of the line, causing a small aperture, where ink does not flow easily. Previous work has shown that if an aperture is too small then ink does not transfer properly onto the substrate (22). This would produce the characteristic rectangles as exhibited by mesh marked lines.

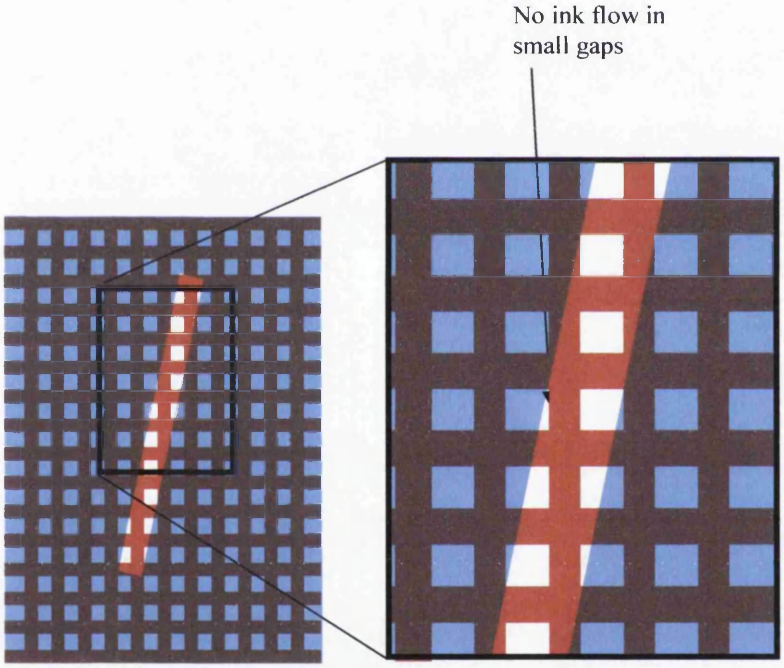
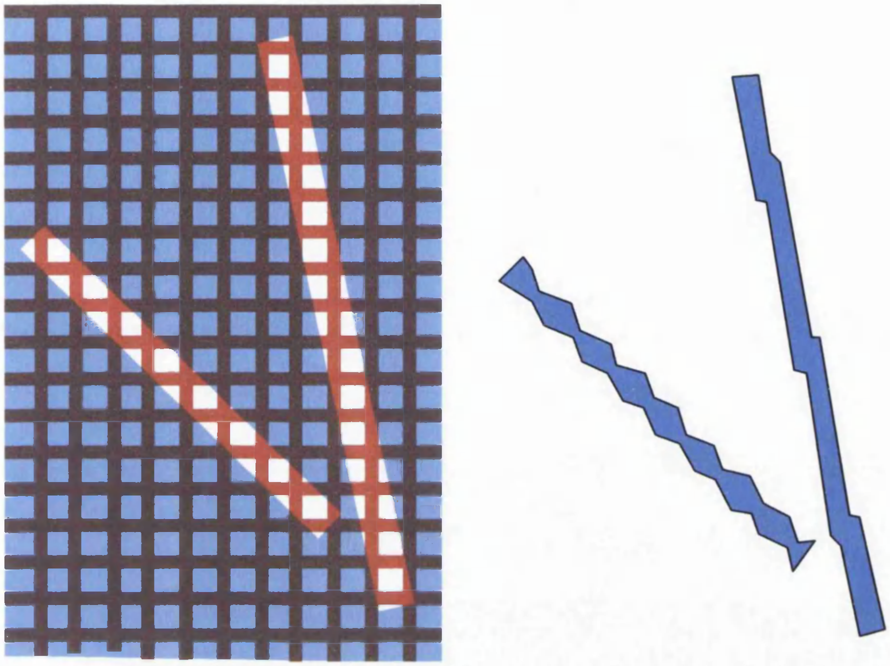


Figure 5.52 : The partial blocking of the line by the mesh

It was also shown, Section 4.3, that the frequency of mesh marking was affected by the orientation of the line to the mesh. How this occurs is demonstrated in Figure 5.53, interaction of the mesh with the line changes as the orientation of the linen changes. At

45 degrees to the mesh the partial blocking occurs closer together, than at 15 degrees to the mesh. This would cause a higher frequency patterning.



(a) Mesh and screen pattern of lines at 45 and 15 degrees to the mesh

(b) Schematic of mesh marked lines printed at 45 and 15 degrees to the mesh

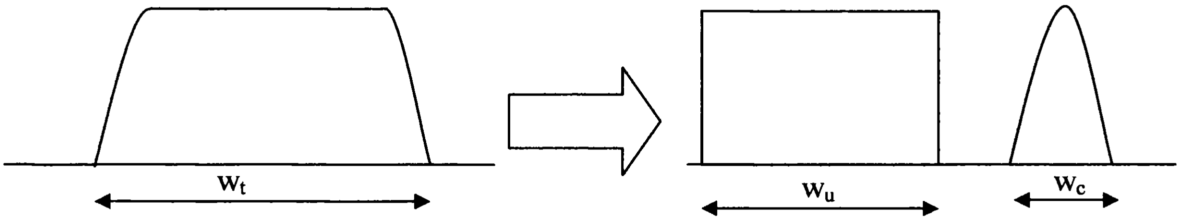
Figure 5.53 : The influence of line orientation on the patterning of mesh marking

Mesh marking is affected by insufficient filling of the screen during the printing process. Thus, it is possible to use the screen printing process parameters on the press to remedy poor edge quality due to mesh marking.

It is important to be able to measure and distinguish between edge rippling and mesh marking, as once the screen is produced little can be achieved to reduce the affect of edge rippling, but poor line quality due to mesh marking can be remedied. It should also be noted that a good line quality was achieved, with smooth screens, using the correct press settings for all line width printed in this study. Therefore, with the correct process control lines of 90μm can be reproduced with straight edged lines.

5.8 Line Cross-sectional shape

The cross-sectional shape of the line was investigated because it was hoped that it would reveal information on a correlation between line width and cross-sectional area. A new parameter, the rectangular index was derived to investigate the relationship between line width and cross-sectional area. It was, also, considered that more information on the shape of a line could be obtained by considering that the cross-section of a line was made up of two components, as shown in Figure 5.54.



w_t is the total width of the line
w_u is the width of the line with a uniform height
w_c is the width of the curved section of the line

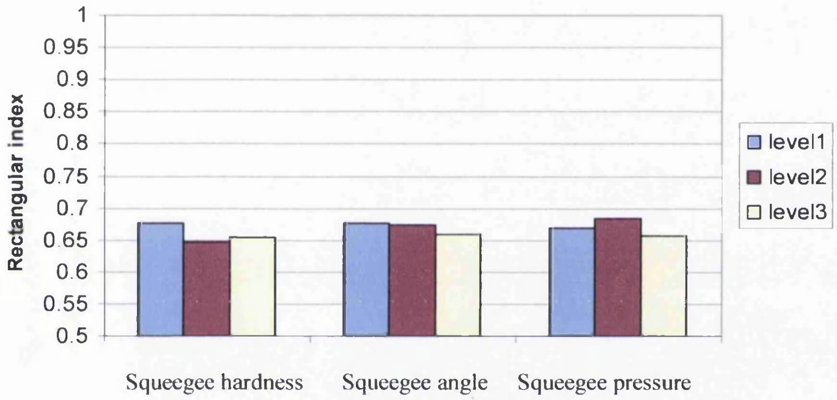
Figure 5.54 : Representation of a cross-section of a line split into a curved and a flat section

5.8.1 Squeegee parameters on line cross-sectional shape

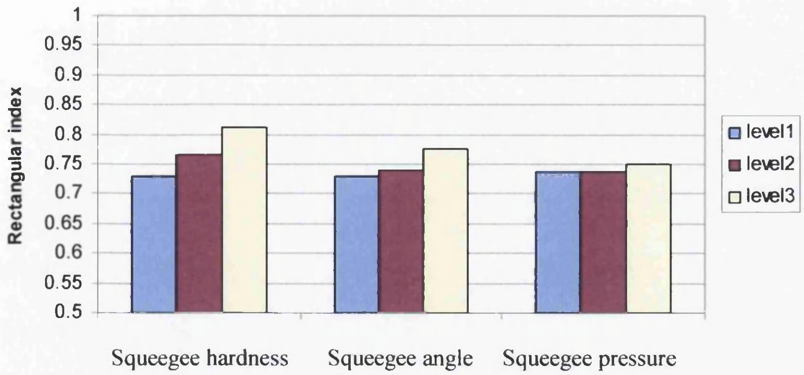
The effects of the screen printing parameters on the rectangular index are shown in Figure 5.55 (a) and (b) for the 180μm and 340μm wide lines respectively. Figure 5.55 (a) shows that the screen printing process parameters examined have very little effect on the cross-sectional shape for the 180μm wide lines. This is representative of the results for the 90μm to 280μm wide lines. For the conditions printed the rectangular index is generally lower than 0.67. Figure 5.55 (b) shows that the squeegee hardness has a small effect on cross-sectional shape for the 340μm wide lines. The squeegee angle and pressure have no effect on the cross-sectional shape. The rectangular index for the 340μm lines is larger than the rectangular index for the 180μm lines.

Table 5.4: Squeegee parameter levels

Parameter	Level 1	Level 2	Level 3
Squeegee hardness (Shore A)	65	74	84
Squeegee angle (deg)	70	75	80
Squeegee pressure (bar)	2.5	3.5	4.5



(a) 180μm wide lines



(b) 340μm wide lines

Figure 5.55 : The effect of the squeegee parameters on cross-sectional shape, the parameter levels are shown in Table 5.4

Assuming that the squeegee parameters have no significant effect on rectangular index, for widths up to 280µm, allowed the examination of line width and rectangular index. Figure 5.56 shows how line width affects rectangular index for the results found in this study. The spread for the 340µm line is larger. There is no simple trend between rectangular index and line width. Rectangular index increases slightly from 90µm to 280µm. From 280µm to 340µm there is a large increase in rectangular index. This suggests that from 90µm to 280µm there is no flat section, but there was for lines with a width of 340µm. Examining the cross-sections of lines at these widths can show this.

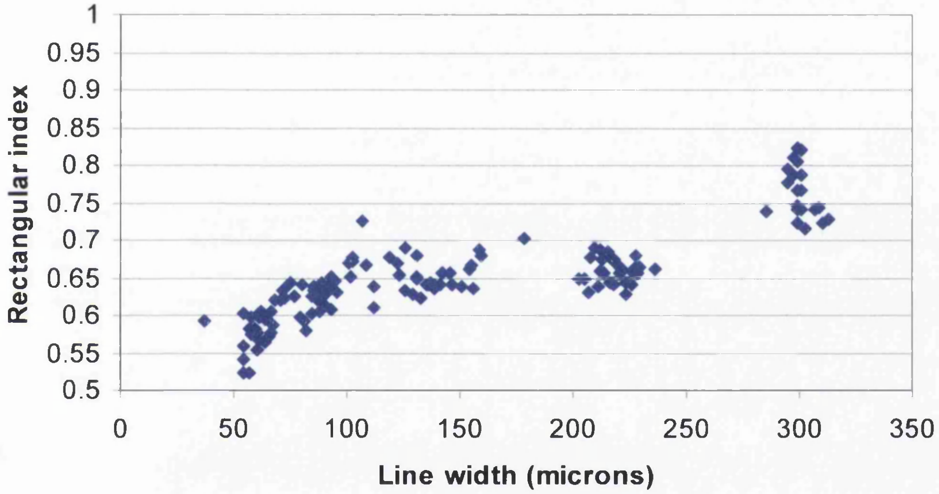
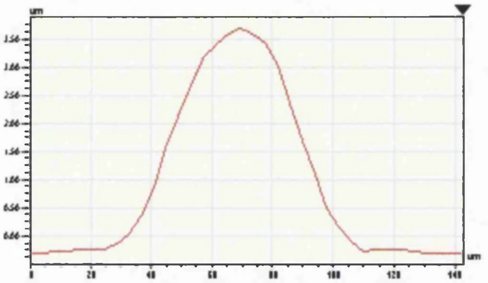
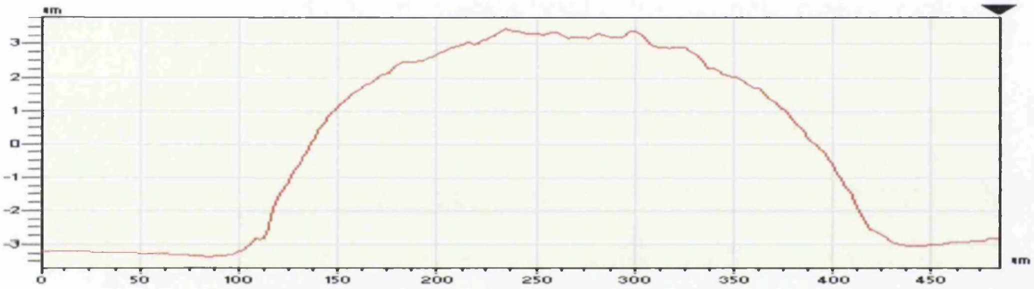


Figure 5.56 : The effect of line width on cross-sectional shape

Figure 5.57 (a) and (b) show cross-sections of a 90µm and 340µm line respectively. The difference between a line with only a curved section and a line with a curved and flat section can be seen.



(a) 90µm line



(b) 340µm line

Figure 5.57 : The effect of line width on the cross-sectional shape of the line

The influence of line width on the cross-sectional shape of lines was studied further by investigating the influence of line width on the width of the curved part of the line, w_c. To carry out this investigation an estimate of the rectangular index for a line with no flat section was required. As an objective method of finding the width of the curved section was derived in Section 4.4.4, but this required a knowledge of the rectangular index. The formula used to find w_c is repeated in Equation 5.3 below, the derivation is given in Section 4.4.4.

$$w_c = 3w_t(1 - \mathrm{RI}) \qquad \text{Equation 5.3}$$

It was considered that lines with a width of 90µm would have no flat section present in the cross-section. This was proved by visually examining line cross-sections and is shown in Figure 5.57. The averaged result for rectangular index with no flat section in the cross-section, found from the 90µm wide lines, was 0.64.

Figure 5.58 shows that the width of the curved section is linearly related to line width from 90µm to 280µm and equal to line width. This shows that from 90µm to 280µm only a curved section exists in the line. For lines with a width of 340µm, w_c has a greater range and varies between 160µm to 260µm and suggests that a curved and a flat section exists.

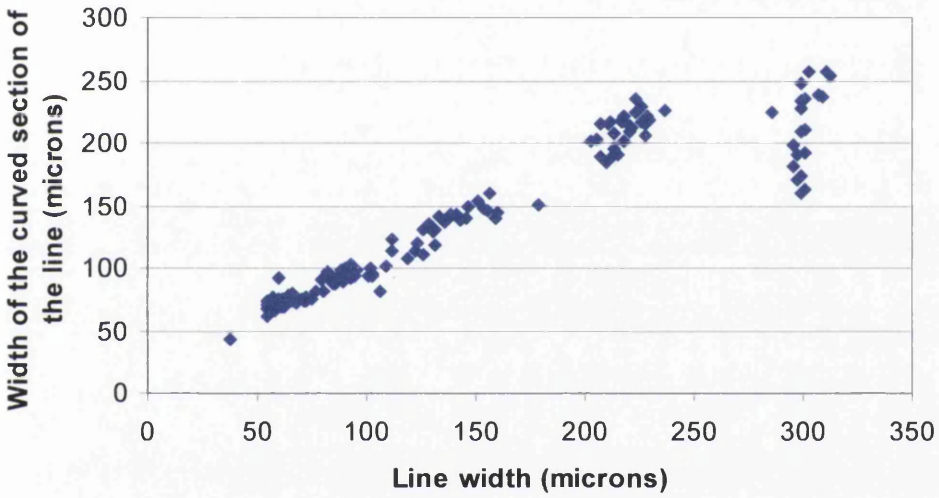


Figure 5.58 : Relationship between w_c and line width

5.8.2 The effect of the ink parameters on line cross-sectional shape

Figure 5.59 shows the effect of the line width on rectangular index for the inks investigated in this study. Inks 1 and 3 show a different trend to ink 2. The rectangular index, for inks 1 and 3, increases for lines with a width of 90µm to 180µm. Whereas, the rectangular index for ink 2 is constant for lines with a width of 90µm to 180µm and increases for lines 180µm to 340µm. This suggests that for inks 1 and 3, from 90µm to

180μm wide lines, the length of the flat section increased, but does not change, over the same range, for ink 2.

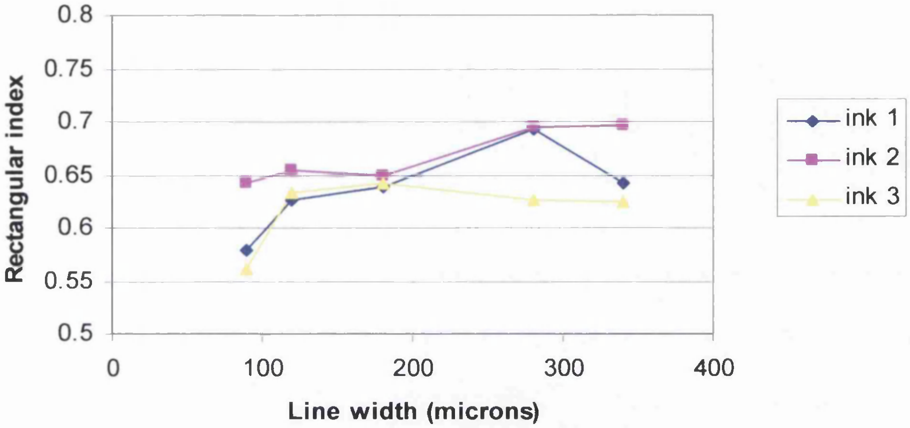


Figure 5.59 : The effect of line width on rectangular index for the inks examined

The results were investigated further by plotting the width of the flat section, w_u, against line width, Figure 5.60. The width of the flat section increases as line width increases for inks 1 and 3. Whereas, for ink 2 the width of the flat section is close to zero for lines with a width below 180μm and the width of the flat section increases with line width for lines above 180μm.

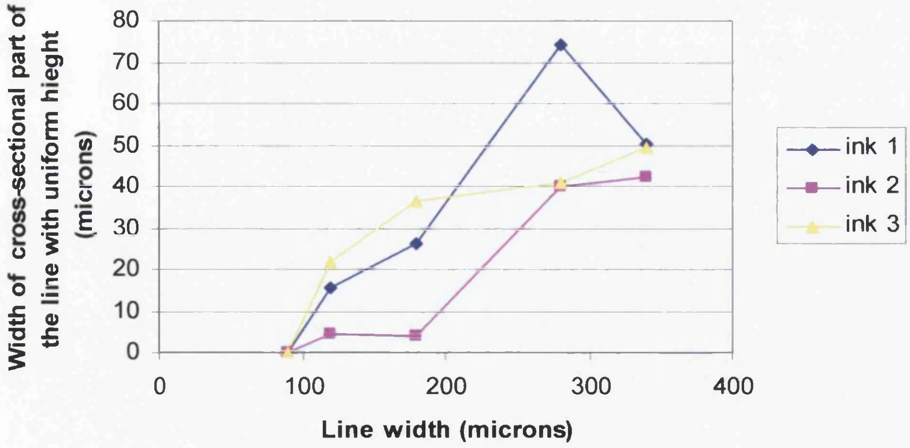


Figure 5.60 : The effect of line width on w_u for the inks examined

5.8.3 The effect of the screen on line cross-sectional shape

The effect of the stencil height on rectangular index is shown in Figure 5.61. This shows that the stencil height has very little effect on the rectangular index. This also implies that the stencil roughness has no effect on rectangular index because the same screens were used for both. In the range of lines examines, line width has no effect on cross-sectional shape. This is shown further in Figure 5.62 which shows the effect of the line width on the length of the curved section, w_c, for all the data in the stencil experiment.

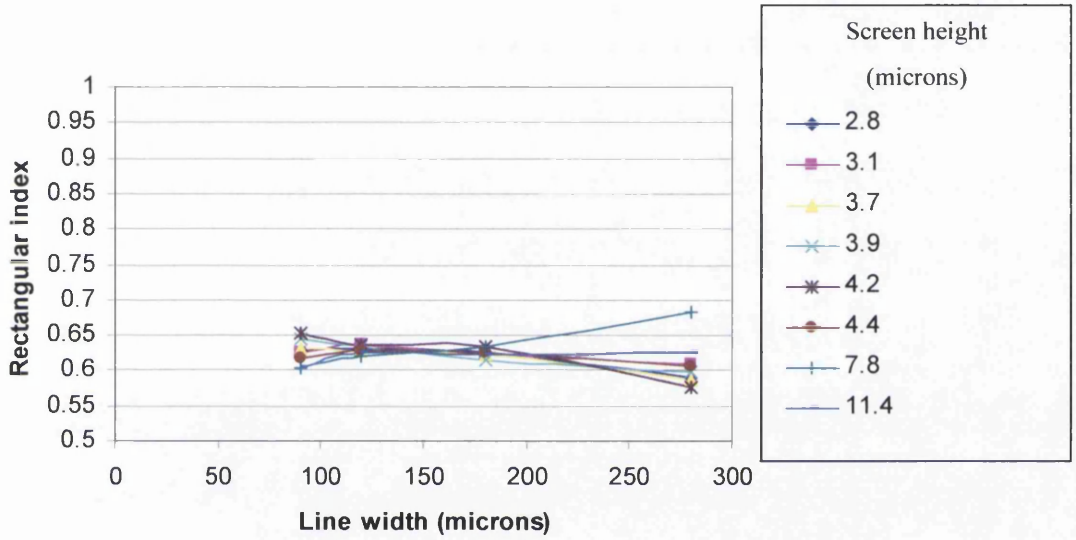


Figure 5.61 : The effect of the line width on rectangular index for different screen heights

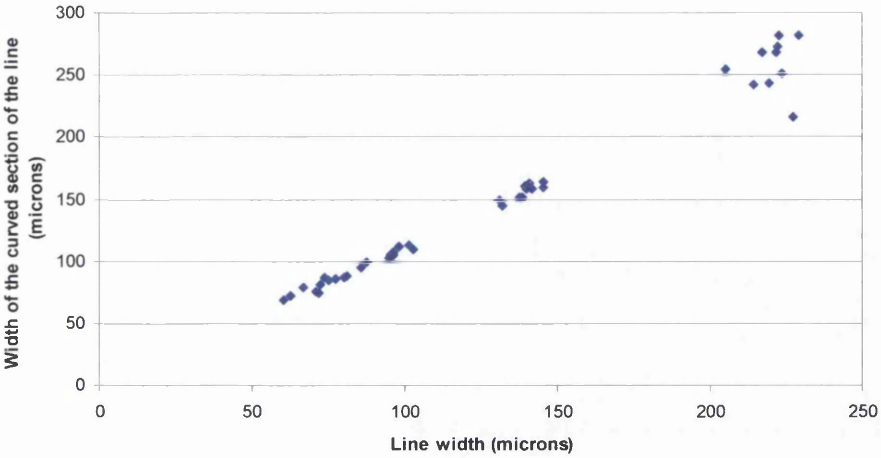


Figure 5.62 : The effect of the line width on w_c for all the screens

5.8.4 Discussion of the process parameters on line cross-sectional shape

Two parameters were identified as having a significant effect on line cross-sectional shape. These were the surface tension of the ink and the line width. The ink type was found to be the only screen printing process parameter that had a significant effect on the cross-sectional shape of the line. Lines printed with an ink of higher surface tension had a lower rectangular index for small line widths than lines printed with an ink of low surface tension.

To explain this, the effect of wetting and non-wetting inks was studied. If the ink flows on contact with the substrate then it will spread forming a low wide line. If the ink does not spread on contact then the line will remain tall compared with its width. The cross-sectional shapes of wetting and non-wetting ink are shown in Figure 5.63 and schematically in Figure 5.64. This shows how surface tension affected Rectangular index. The cross-sectional area of the ink for a wetting line, Figure 5.64(a), occupies less of the surrounding rectangle than a non wetting line, Figure 5.64(b).

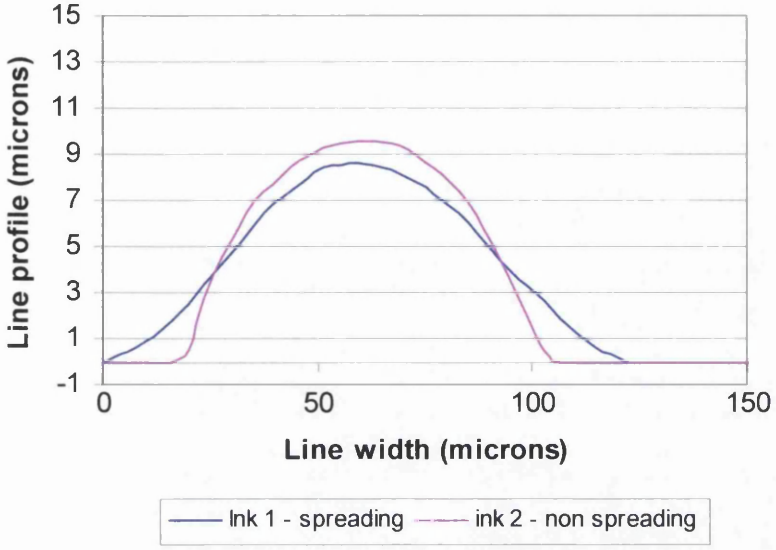
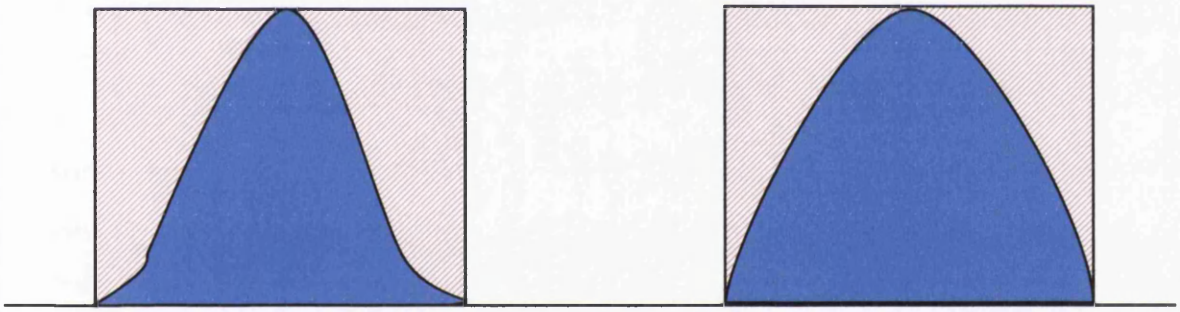


Figure 5.63 : The line cross-sectional shape of the spreading and no-spreading inks



(a) Spreading

(a) Non-spreading

Figure 5.64 : The effect of ink spreading on line cross-sectional shape

Figure 5.19 shows that there is an interaction between line width and the surface tension of the ink, as inks 1 and 3 show a different effect to ink 2. For inks with high surface tension, rectangular index is comparatively low for the 90μm wide lines, but increases as line width increases. For ink 2, with a low surface tension, the rectangular index value is constant until the line width was approximately 280μm. This shows that for inks of high surface tension, the flat section of the line exists at lower line widths than for inks with low surface tension.

After the line is printed, the ink flows for wetting inks (low surface tension). This reduces the height of the line. The spreading flattens the top of the line, Figure 5.63. Non-wetting inks (high surface tension) hold their cross-sectional shape, with a high contact angle as shown in Figure 5.64(a). For non-spreading inks, the flat section does not exist until the ink is wide enough for the stencil not to interact with the centre of the line. The spreading of the ink causes the difference between the wetting and non-wetting inks.

5.9 Prediction of cross-sectional area from line width

5.9.1 Introduction to the prediction of cross-sectional area from line width

The work in this study has shown that it is not possible to assume that line height is uniform across the width of the line for fine lines. The investigation into line cross-sectional shape carried out has shown that under the majority of conditions lines have a cross-section resembling an inverted quadratic up to a width of 180μm wide. The parameter shown to significantly affect the cross-sectional shape was how easily the ink spreads after printing. The ink spreading is governed by the free surface energies of the substrate and ink. It is, therefore, possible to study the relationship between cross-sectional area and line width by investigating lines printed using the same ink and substrate.

The aim of the work described in this section was to determine if it was possible to predict cross-sectional area from line width. Work was carried out to determine any direct relationships between line width and cross-sectional area. It was found this could be achieved by investigating mesh marked lines due to the large variation of width over the length of the line. A mathematical model was also derived that describes the relationship between line width and cross-sectional area for fine lines.

5.9.2 Empirical trends between line width and cross-sectional area

The results from the experiment described in Chapter 3 were investigated for a correlation between line width and cross-sectional area, line width and line height, and, line width and rectangular index. Line profiles were investigated to determine any relationship that existed over the length of a line.

The correlation of line width with cross-section area, line height and rectangular index along the length of a line has been determined by investigating the complete profiles along the length of the line. The correlation between data sets has been quantified using r-squared, which defined in Equation 5.4. r-squared is a measure, from 0 to 1, of how well one set of data can be predicted from another (54). A r-squared value of 0.8 means that 80% of the change in one variable can be predicted by the other and an r-squared vale of 1 means one variable can be completely predicted by the other.

$$\text{r-squared} = r^2 = \frac{\operatorname{cov}(X,Y)}{\sigma_X . \sigma_Y} \qquad \text{Equation 5.4}$$

Where

$$\operatorname{cov}(X,Y) = \frac{1}{N}\sum (X_i - X_{mean})(Y_i - Y_{mean})$$

X_i is the ith values of data set X

Y_i is the ith values of data set Y

X_{mean} is the mean of data set X

Y_{mean} is the mean of data set Y

σ_X is the standard deviation of data set X

σ_Y is the standard deviation of data set Y

N is the number of points in each data set

Six lines were used to investigate the correlation between line width and cross-sectional area. These are 2 smooth edged lines (labelled S1 and S2), 2 edge rippled lines (labelled R1 and R2) and 2 mesh marked lines(labelled MM1 and MM2). Figure 5.65 shows the correlation of line width with cross-section area, line height and rectangular index. There was no correlation of line width with cross-section area, line height and rectangular index for the smooth lines. This was because there is no change in line width and, therefore, no information can be obtained.

The line width does vary along the length for the rippled lines, although there was no correlation of line width with line height and rectangular index. For line R1 there was a slight correlation with cross-sectional area, although a very weak one. On further investigation it was shown that this line was very slightly mesh marked as well as having edge rippling.

There was no significant relationship between the line width for the mesh marked lines and line height and rectangular index. There was though a reasonably significant correlation between the line width and the cross-sectional area.

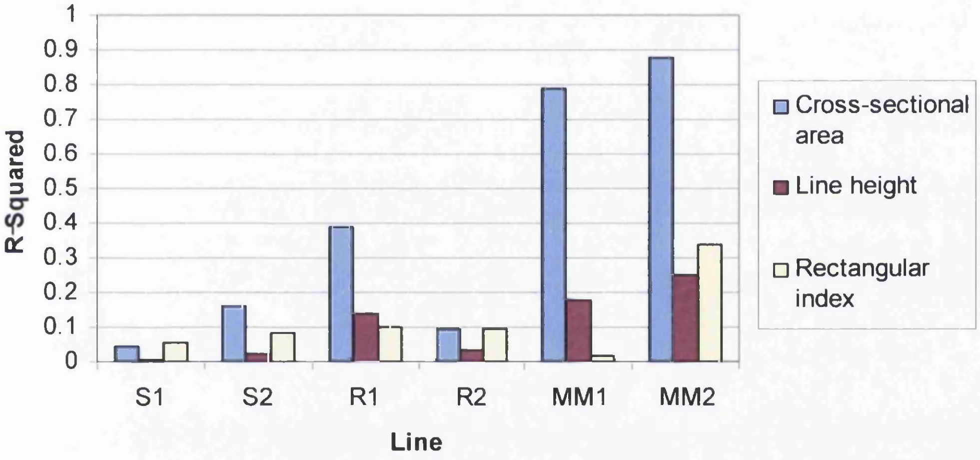


Figure 5.65 : The correlation of line width with 3D parameters for the six lines examined

The correlation existed between cross-sectional area and line width for the mesh marked lines, as opposed to the other line classes, due to the large variation in the line width that occurs for mesh marked lines. The fact that there was a sufficient variation of line width along the length of mesh marked lines for a correlation to exist between line width and cross-sectional area has been used to investigate the relationship between line width and cross-sectional area.

A wider variety of printing conditions has been investigated by examining 5 mesh marked lines of different widths and heights. The r-squared values are shown in Figure 5.66. This shows that for all the lines examined there was a correlation between the line width and the cross-sectional area. There was also a slightly weaker correlation between the width and the height. No correlation was found between line width and rectangular index. This suggests the lines examined had only curved sections and no flat section.

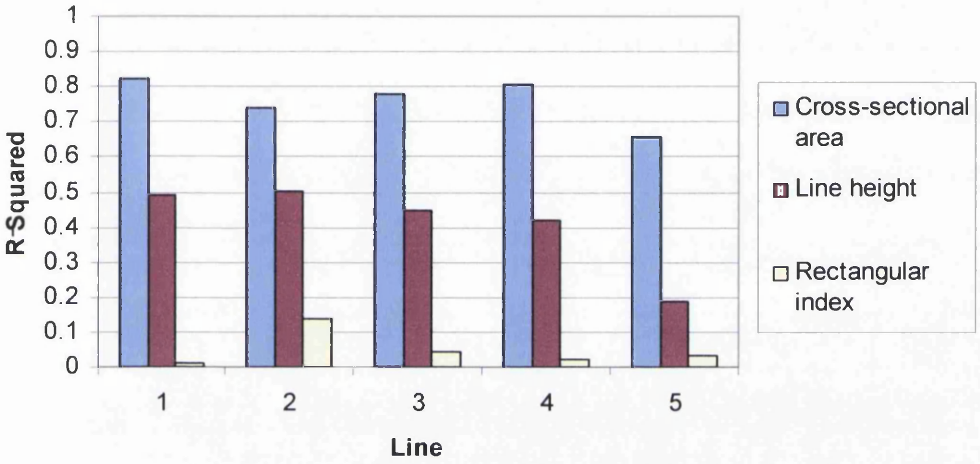


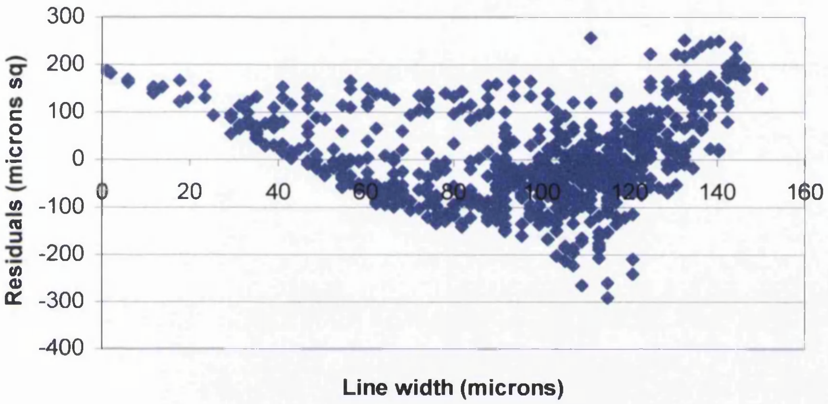
Figure 5.66 : The correlation of line width with 3D parameters for the mesh marked lines

The correlation between line width and cross-sectional area was investigated further by examining the residuals for the correlations obtained. The residuals from a correlation are the deviation of each point within a data set from the regression line. This is calculated using Equation 5.5. The residuals are a measure of how well the trend line fits the data along the length of the data. It can be used to show if the correct assumptions were made about the relationship between the two variables. In this case it can be used to determine if a linear fit was the best or if a quadratic would improve the modelled relationship.

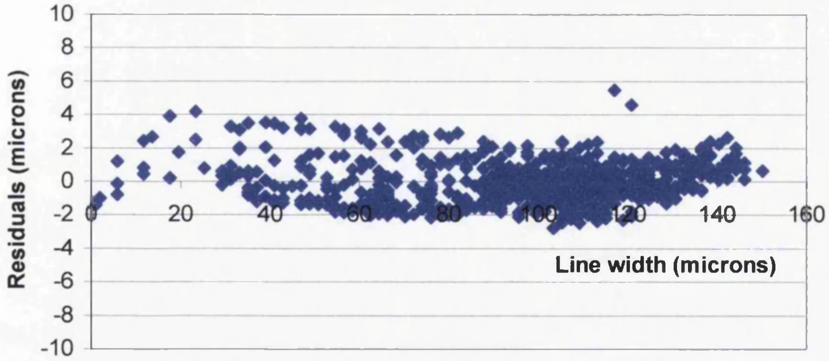
Residual = $Y_i - (\textit{predicted value of } Y \textit{ from } X_i)$ Equation 5.5

Figure 5.67 shows a representative of the residuals found for the line width versus the line height, and, line width versus the cross-sectional area. This shows that the trend between the width and the height is close to a linear pattern within the range examined as the variation in the residuals is similar for all the widths.

The trend between the width and the cross-sectional area is not linear. The residuals for the lower and higher line width are higher than those for the middle line width. This is the trend in residuals expected if the relationship was actually quadratic, or higher order. A schematic, Figure 5.68, shows how this occurs.



(a) The residuals of line width with cross-sectional area



(a) The residuals of line width with line height

Figure 5.67 : The residuals of line width with 3D parameters for a representative of the mesh marked lines

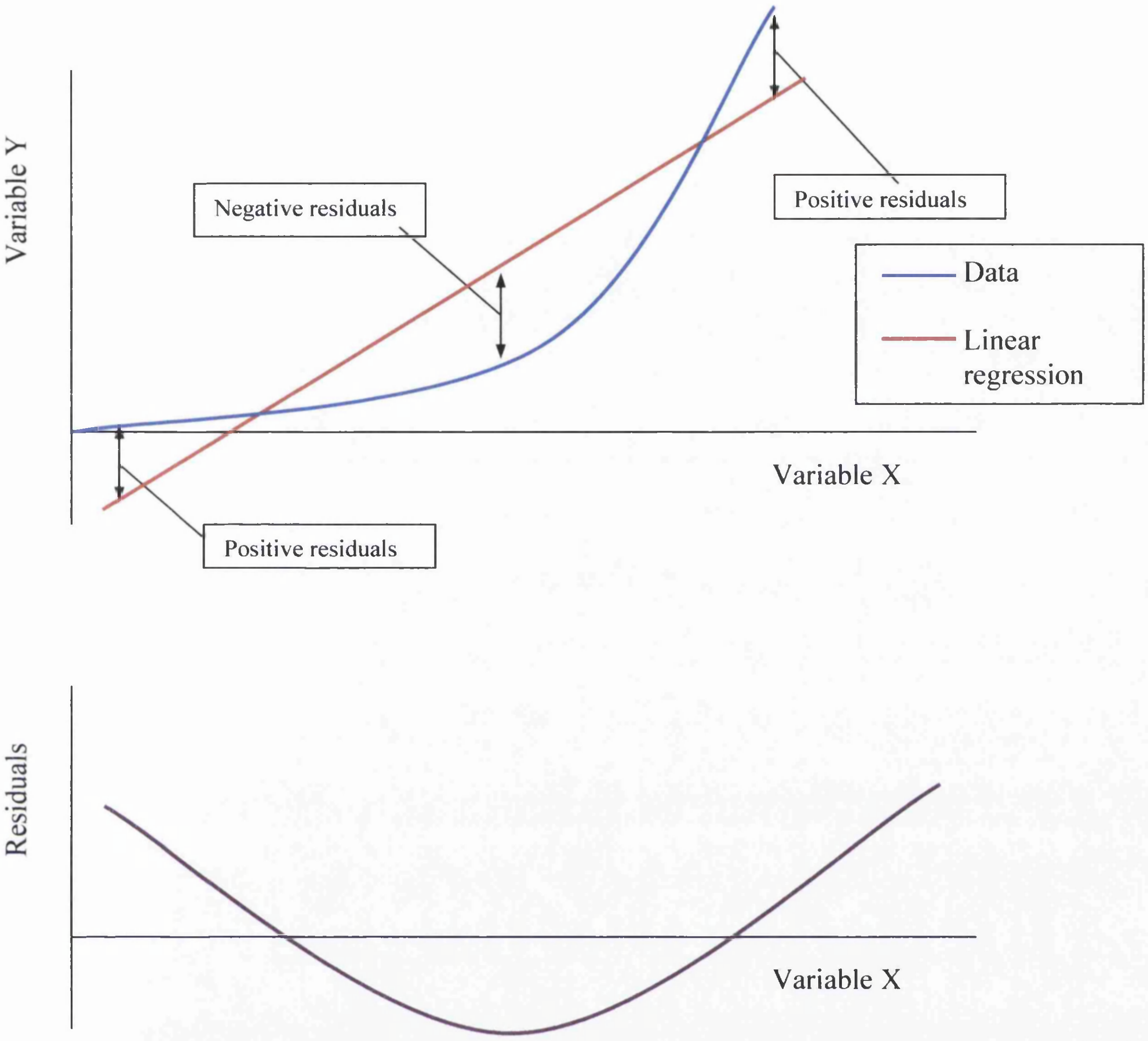


Figure 5.68 : Schematic illustrating the residuals for a linear regression model for two variables actually related quadratically

A better correlation between the width and the cross-sectional area could be obtained by using polynomial curve fitting. Figure 5.69 shows the average r-squared value for the five mesh marked lines for polynomials of different power. This shows a polynomial gives a better correlation than a linear relationship and a quadratic curve is sufficient to give a line of good fit. The residuals of the 5 mesh marked lines for a quadratic fit have been plotted, Figure 5.70, to demonstrate that a quadratic fit is the best model for the relationship between line width and cross-sectional area.

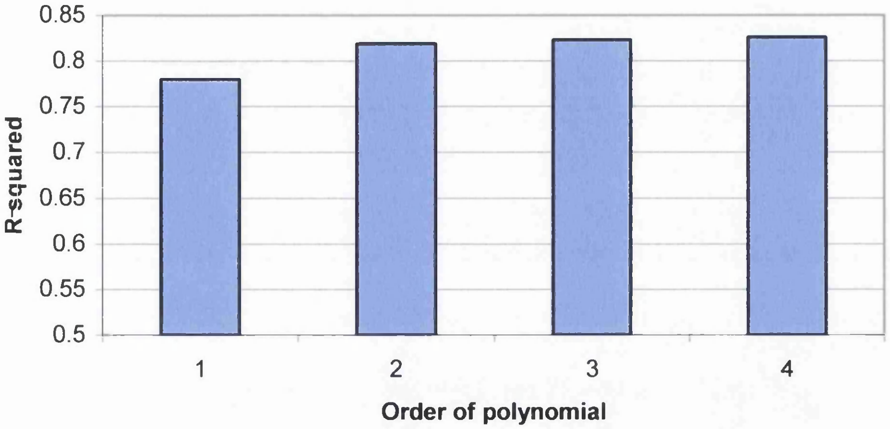


Figure 5.69 : The increase in correlation by using a polynomial for the regression line for the mesh marked lines

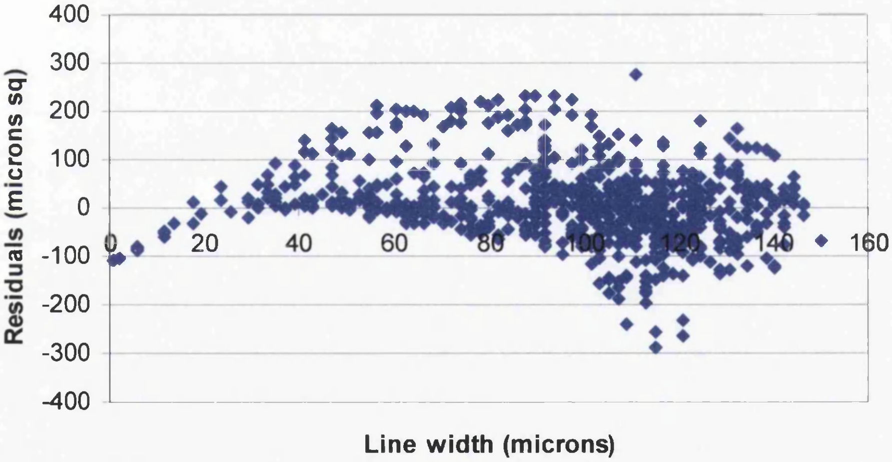


Figure 5.70 : Residuals for line width and cross-sectional area using a quadratic model

5.9.3 Relating line width and cross-sectional area

The empirical study showed that there was

- a quadratic relationship between line width and cross-sectional area
- a linear relationship between line width and line height.

Below a mathematical model of the relationship between cross-sectional area and line width is derived based on the assumption that line width is linearly related to line height, therefore:

$w = a.H + c$ Equation 5.6

Where,

w is line width
H is Line height
a and c are constants

From the definition of rectangular index, as shown in Section 4.

Cross-sectional area $A = RI.\ w.\ H.$ **Equation 5.7**

Rectangular index was constant for an averaged data set over the changes in line width that occur due to mesh marking, Figure 5.39. Therefore, within the width range that RI is constant it is possible to develop a model for the cross-sectional area.

$A = (aW^2 + cW).RI$ Equation 5.8

Where,

A is cross-sectional area

RI is Rectangular index

If it is assumed that at zero width the height is also zero; the regression line passes through the origin. Then c is zero and Equation 5.8 becomes

$$A = RI.a.W^2 \qquad \text{Equation 5.9}$$

Since width is linearly related to height and cross-sectional area is related to height and width, then area is quadratically related to width. This fits with the empirical analysis that found that the cross-sectional area was quadratically related to the line width.

6.5.3 Discussion

There are many advantages to producing a method to predict the cross-sectional area from the line width. Two-dimensional measurement is cheaper and faster than three-dimensional measurement. It could also lead to in-process monitoring of lines using 2D measurement and thus fast evaluation of cross-sectional area. This study has characterised a new relationship between line width and cross-sectional area for fine lines. There are though some limitations that have to be considered and overcome if this could be used as a practical model.

It is important to note that the correlation found was obtained using averaged data. The spread of the data is such that it is not possible to predict individual values of cross-sectional area or height from line width as the correlation between a variable and averaged data is often higher, than the correlation to individual values. Therefore, this can only be considered as a model for average height and cross-sectional area. For example, if the relationship between line width and cross-sectional area is characterised for a set of conditions, ie a particular rectangular index. This could be used to predict the average cross-sectional area over the whole sample from a set of line width data. It would, though, not be possible to state that for a width of w then the area would be A.

5.10 Closure

A study has been made into the effect of screen printing process parameters on fine line reproduction and a comprehensive investigation into the repeatability of screen printing to reproduce them. The investigation into the repeatability revealed information to determine the sample size required to ensure the results were representative of the line being measured. This was found to be much larger for rough as oppose to smooth edged lines, but a large sample size for all lines ensured confidence in the results.

The effect of the orientation of the lines to the print direction and to the mesh was investigated and orientation was the only parameter that had an effect on line width and cross-sectional area. No significant interaction between the orientation and the process parameters was found. The effect of the process parameters on the line quality characteristics was investigated and their interaction with line width. The parameters of mean, standard deviation and rectangular index, identified in Chapter 4, were used to measure the line size, continuity and cross-sectional shape respectfully. The results were used to find a correlation between the line width and the height and the cross-sectional area. The trends found in the results were discussed and the theories postulated for why they occur. The trends between line width and cross-sectional area were investigated and a relationship was found that could predict the cross-sectional area from line width.

A summary of all the conclusions from this work, from the development of the line measurement method and analysis into fine line reproduction is given in the next Chapter.

Chapter 6

Conclusions and Recommendations

6.1 Summary of completed work

An experimental programme was conducted that investigated the most significant screen printing process parameters. These were the squeegee angle, squeegee pressure, squeegee hardeness, the ink characteristics and the screen roughness and height. The total number of screen printing process parameter conditions investigated was 49.

Appropriate measurement methods have been developed to ensure the objective measurement of line quality characteristics. These were the cross-sectional size of the line and the continuity of the cross-sectional size along the length of the line. The cross-sectional shape of the line was also investigated, as it was useful in determining a new correlation between line width and cross-sectional area for fine lines.

The measurement methods developed have been used to extract and analyse results from the printed images obtained by the experimental programme. The investigation into orientation examined three line widths (90µm, 180µm and 280µm) at five line orientations (15, 30, 45, 60 and 75 degrees) to print direction. The investigation into the specific influence of screen printing process parameters examined five line widths (90µm, 120µm, 180µm, 280µm and 340µm). Repeat readings were taken to ensure the results were representative of the line printed and a total of over 3200 measurements were made.

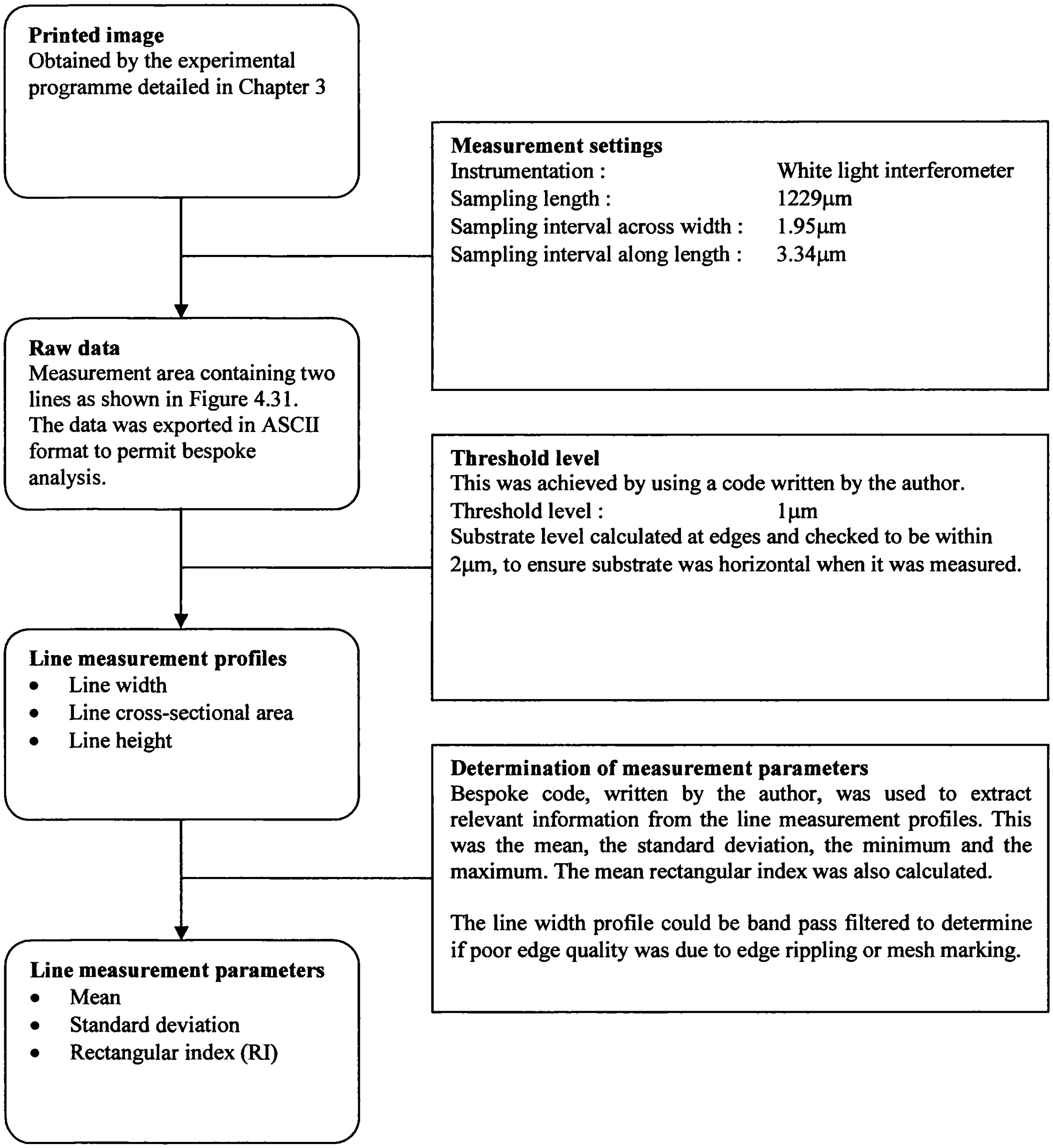
A summary is given, here, of the conclusions obtained by this study.

6.2 Conclusion from the work completed within this study

6.2.1 Development of a measurement system

A measurement methodology has been developed that objectively measured screen printed fine lines and this was necessary because no proven methodology existed. The aims were to measure the two- and three-dimensional characteristics of fine lines that affect their functionality and repeatability. This allows not just the characterisation of fine lines but a further study to correlate the line width and the cross-sectional area to find out if it was possible to predict line cross-sectional area from line width. A summary of this method is given in Figure 6.1 and described in detail at the end of Chapter 4. The other main findings were :

- White light interferometry was found to be the best technique to digitally record the line. This was because it could measure a three-dimensional profile of the line and, therefore, obtain profiles for line width, line height and cross-sectional area.
- Lines were split into three classes; smooth-edged, rippled-edged and mesh-marked. Rippled edge lines had edge distortion at the same frequency as the mesh. Mesh marked lines had a wavelength of approximately 2.5 times the mesh wavelength for lines orientated at 15 degrees to the print direction. These two forms of defect could be distinguished using filtering.
- The parameters to best describe the quality of screen printed lines were the mean to characterise the cross-sectional size and the standard deviation to characterise the continuity.
- A new system to measure the cross-sectional shape of the line was developed. This was called the rectangular index (RI) and is the relative size of the cross-sectional area of the line compared to a rectangle of the same width and height. This compares the actual cross-sectional area of the line with the system used for wider lines by considering the line to be a rectangular cross section.



Printed image
Obtained by the experimental programme detailed in Chapter 3

Measurement settings
Instrumentation : White light interferometer
Sampling length : 1229μm
Sampling interval across width : 1.95μm
Sampling interval along length : 3.34μm

Raw data
Measurement area containing two lines as shown in Figure 4.31. The data was exported in ASCII format to permit bespoke analysis.

Threshold level
This was achieved by using a code written by the author.
Threshold level : 1μm
Substrate level calculated at edges and checked to be within 2μm, to ensure substrate was horizontal when it was measured.

Line measurement profiles
- Line width
- Line cross-sectional area
- Line height

Determination of measurement parameters
Bespoke code, written by the author, was used to extract relevant information from the line measurement profiles. This was the mean, the standard deviation, the minimum and the maximum. The mean rectangular index was also calculated.

The line width profile could be band pass filtered to determine if poor edge quality was due to edge rippling or mesh marking.

Line measurement parameters
- Mean
- Standard deviation
- Rectangular index (RI)

Figure 6.1, Flow chart showing the steps of the fine line measurement system. This shows how the line measurement parameters were obtained from the printed image

6.2.2 Investigation into the repeatability of screen printing

A study of the repeatability of screen printing was made to ensure a sufficient sample size was examined. This ensured the results were representative of the line measured. The following conclusions were found during the investigation of the repeatability.

- Rough edged lines were found to be less repeatable than smooth edged lines.
- Roughness of edge quality was linked to ink transfer. Thus it is possible to repeatability reproduce fine lines provided sufficient ink transfer is achieved.
- Process repeatability was characterised and the uncertainty was found to be ±5μm for line width and ±10% for cross-sectional area. In the line width standard deviation, the uncertainty was ±3μm for straight edged lines and ±8 to 10 for lines with poor edge quality.

6.2.3 The study of the influence of line orientation

An investigation was undertaken to determine the effect of orientation on line quality. The following conclusions were found during.

- Lines printed perpendicular to the printed direction were wider than those printed parallel to the print direction. The increase was approximately 5 to 20μm. This was shown to be due to the non-uniformity of the stretching of the screen.
- Under the majority of conditions a slight decrease, or no change, in cross-sectional area occurred from parallel to perpendicular to the print direction. The cross-sectional area decreased from lines printed parallel to perpendicular to the print direction. This was due to the squeegee being supported by the stencil for lines parallel to the print direction and not perpendicular.
- The cross-sectional shape of lines is affected by orientation to the print direction. Lines printed parallel to the print direction are symmetrical about their central vertical axis. Lines printed perpendicular to the print direction have a more rounded rear edge than at the front, making them asymmetrical about their central vertical axis. A theory was postulated for this phenomenon based on the progressive release of the ink, from the screen, across the line width during the snapping off of the screen.

6.2.4 The study of the effects of the process parameters

A study was made into the effect of process parameters on the reproduction of the screen printed fine lines. The parameters were chosen that had been shown to have an effect on screen printing from work carried out in the graphic screen printing.

- Mesh marking was shown to be due to insufficient ink transfer onto the substrate. This occurred due to the interaction between the mesh and the stencil at the edge of the line. Increasing ink transfer reduced mesh marking.
- Screen printing process parameters had a similar effect on the cross-sectional size of the line, as on ink transfer and tone gain. Parameters known to produce more ink transfer in graphic printing produced wider lines with a greater cross-sectional area.
- Of the parameters examined, the line width and surface tension of the ink affected the cross-sectional shape of the line. Inks with higher surface tension spread more after printing and produced wider, lower lines. This caused them to have a higher rectangular index.

6.2.5 Prediction of the cross-sectional area from the width

It is much easier to measure the width of the line rather than the line cross-sectional area. It is, therefore, very useful to discover whether it is possible to predict the cross-sectional area from the width of the line, enabling simpler measurement. This study involved a detailed study of the correlation of line width and area and the conclusions from this work were:

- The correlation between line width and cross-sectional area for fine lines was found to be quadratic.
- A model that related line width to cross-sectional area for mesh marked lines was proposed. This involved knowing the rectangular index of the line and assuming that line width is quadratically related to cross-sectional area.

6.3 Recommendations

A new measurement system was produced that objectively quantified the quality of screen printed lines, using the three-dimensional profile of the lines. This was tested on known lines and used to characterise some of the main screen printing parameters. However, further knowledge of the process could be obtained by pursuing the following recommendations.

- Not all process parameters were investigated. However, most of the parameters not examined by this study had been investigated previously, but mainly just for line width. Further understanding could be obtained by examining the substrate, snap-off gap, screen tension. The snap-off gap and screen tension are predicted to have an effect on the change in line width due to orientation. The substrate has been examined previously and it was shown that the relative free surface energies of the ink and the substrate had an effect on ink transfer and ink spreading. Therefore, the substrate must be considered if characterising the process to form a prediction of cross-sectional area from line width.
- Only line widths up to 340μm have been examined. At this point, the ink is released well from the screen and the line height approaches a plateau. The cross-sectional shape of the line, though, was not close to a rectangle. Further analysis is required on wider lines to characterise their shape, to the point where it is acceptable to assume that the cross-sectional area approximates to a rectangle.
- A suggestion was made for a model to predict the three-dimensional characteristic of a line from line width was given. A through the run experiment needs to be done to determine the validity of the assumptions used to produce the model.
- The two- and three-dimensional measurement systems and the model to predict the cross-sectional area should be used to form a package to investigate and control fine line printing.
- The orientation affected the cross-sectional shape of the lines and a hypothesis was suggested, based on the progressive release of the ink from the screen, as to why this

occurred. A full analysis of this phenomenon may lead to a further understanding of the physics of the screen printing process.

Appendix A

Calibration circles used for the image processing

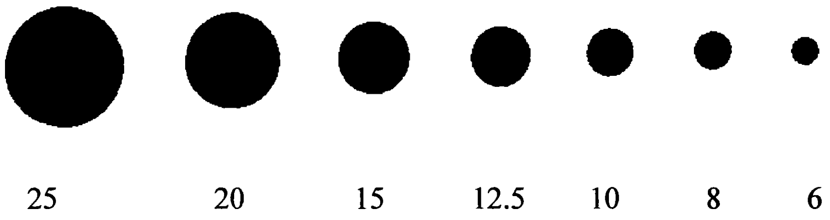


Figure A.1 : Circles used for the calibration. These are calibrated black circles on a glass slide that can be placed under the microscope to calibrate the image processing system.

Table A.1 : Diameters of circles used for the calibration

Circle Number	Diameter (μm)
6	0.1110
8	0.1460
10	0.1830
12.5	0.2280
15	0.2730
20	0.3630
25	0.4540

Appendix B

Modelling Line Shape

B.1 Introduction to modelling line shape

The derivation of the models for line cross-sectional shape are described in this section. Two methods were considered; Fourier series and building the line from regular shapes. These have been used to show how it was possible to calculate rectangular index (RI) using the models.

B.2 Fourier Series

The Fourier series is an expansion that relies on the fact that all periodic functions can be represented by an addition of sine and cosine curves. The full series is shown below in Equation B.1.

$$f(x) = a_0 + \sum_{n=1}^{\infty}\left(a_n \cos\left(\frac{N\pi}{L}\right)x + b_n \sin\left(\frac{N\pi}{L}\right)x \right)$$

Where

$$a_0 = \frac{1}{2L}\int_{-L}^{L} f(x)\,dx$$

$$a_n = \frac{1}{L}\int_{-L}^{L} f(x)\cos\left(\frac{N\pi x}{L}\right)dx$$

$$b_n = \frac{1}{L}\int_{-L}^{L} f(x)\sin\left(\frac{N\pi x}{L}\right)dx$$

Equation B.1

The cross-section of the line was considered as a periodic function, enabling the use of the Fourier series to model line cross-sections. The cross section was plotted and immediately followed by the negative of the cross section. This produces a periodic signal as shown in Figure B.1.

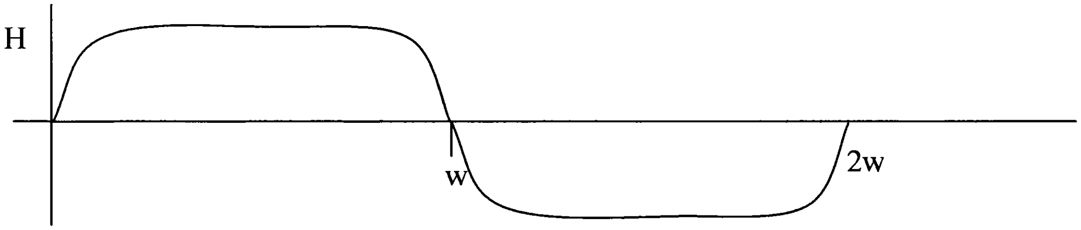


Figure B.1: Representing the width data so it could be easily analysed using the Fourier series

This curve is well suited to Fourier analysis since it is an odd function; it is symmetrical about the x-axis. Thus, all the cosine terms of the Fourier series solution are zero. The average of the signal is also zero thus a_0 is zero. The time period of the signal is twice the line width, therefore Equation B.1 can be expressed as

$$f(t)=\sum_{n=1}^{\infty} b_n \sin\frac{n\pi t}{w} \qquad \text{Equation B.2}$$

Where

$$b_n = \frac{1}{w}\int_{-w}^{w} f(t)\sin\frac{n\pi t}{w}dt$$

The curve within the limits of 0 to w represents the cross section of the line.

Using this method, a uniform distribution was represented by a square wave; the wavelength was 2w and the amplitude H. This is shown in Figure B.2. The Fourier series solution for the square wave has the constants

$B_1 = \frac{4H}{\pi}, B_2 = 0 \ , \ B_3 = \frac{4H}{3\pi}, \ \ B_4 = 0, B_5 = \frac{4H}{5\pi}$,....etc

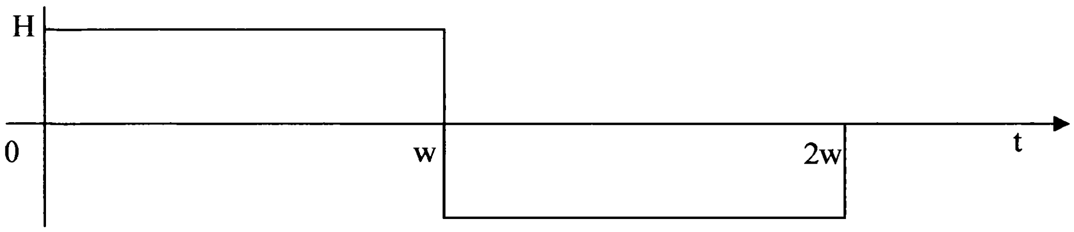


Figure B.2 : The signal use to represent a uniform cross section

A fine line with no flat section can be expressed as a sine curve

$$f(t) = H \sin \frac{\pi t}{w} \qquad \text{Equation B.3}$$

Where,

H is maximum line height

w is line width

t is the coordinate across the width of the line

The use of the Fourier series to model the line was examined theoretically to find how the cross-section affects the rectangular index. A sine curve was used to represent a cross-section with no flat section. The area from 0 to w for a sine curve with a period of 2w and an amplitude of H is

$$\text{Area} = \frac{2wH}{\pi} \qquad \text{Equation B.4}$$

Thus the rectangular index, using the Fourier series method, of the cross-section of a line with only a curved section is

$$\text{RI} = \frac{2}{\pi} = 0.636 \qquad \text{Equation B.5}$$

B.3 Regular shapes

Lines could be placed into classes of cross-section, described by how they could be made up by regular shapes. This would yield a range of patterns of cross-sections. Visually examining the cross-section of many lines it is evident that they are made up of two parts. There is a curved section at the edges and a flat section in the centre. This is shown in Figure B.3. To model the area of the cross-section it is possible to model the line in two parts. The curved section can be represented as a quadratic function or cubic. The flat section can be represented as a uniform distribution. Figure B.4 shows how a line can be split into these two parts.

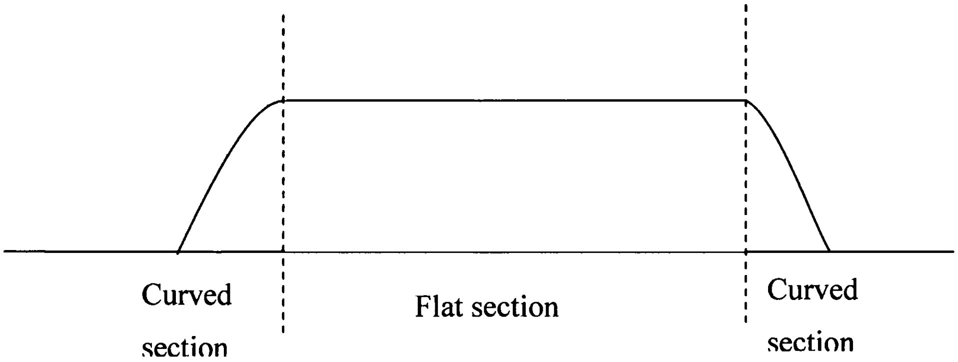


Figure B.3 : Flat and curved sections of a line

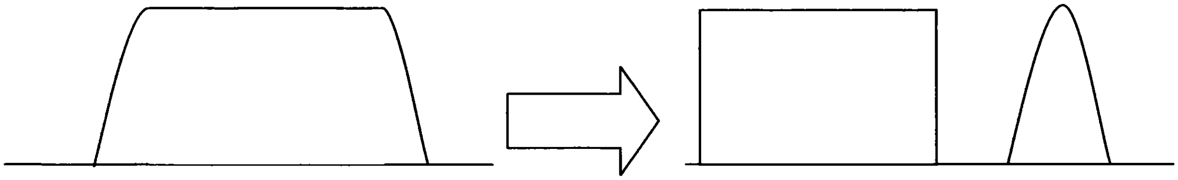


Figure B.4 : Representation of spitting the line cross-section into two components of a rectangular and a curved section

Initially a single inverted parabola was considered with no flat section. The equation for the curve is, therefore, $y = ax + bx^2 + c$. The area under this standard parabola, as shown in

Figure B.5, was found by integration from $x = 0$ to w. This simulates the width of the line. The area will represent the cross-sectional area found using the quadratic model. The other boundary condition required is that at $x = w/2$, $y = H$. This simulates the height of the line. This was then compared to the area of a uniform distribution found from $x = 0$ to w.

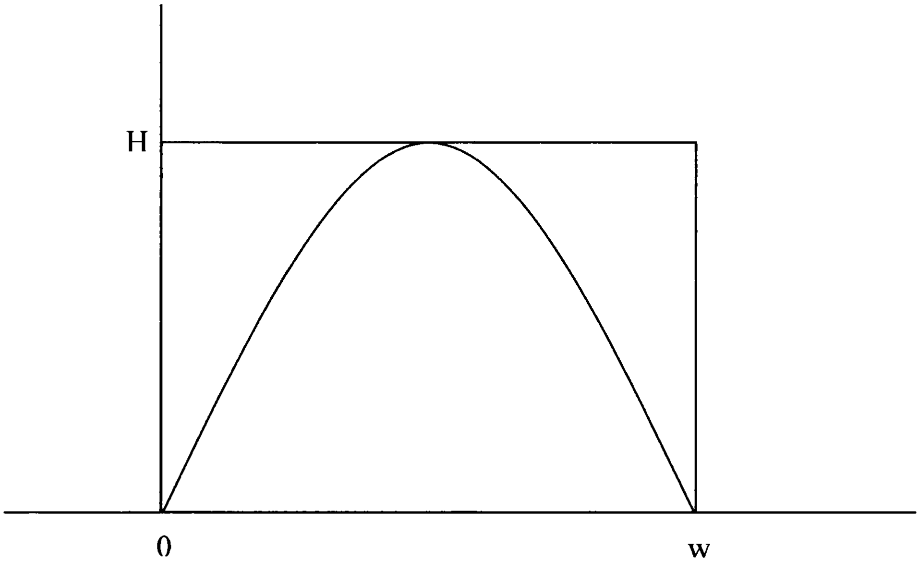


Figure B.5 : Parabola used to examine the line shape model

Curve described by

$y = ax + bx^2 + c$ Equation B.6

To solve for a , b and c

Initial boundary condition at $x = 0$ then $y = 0$, therefore $c = 0$

$y = ax + bx^2$ Equation B.7

Other boundary conditions at $x = w/2$ then $y = H$ and $x = w$ then $y = 0$, therefore

$$\frac{aw}{2}+\frac{bw^2}{4}=H$$ Equation B.8

$$aw+bw^2=0$$ Equation B.9

Solve as simultaneous equations for a and b

$$a=\frac{4H}{w}$$ Equation B.10

$$b=-\frac{4H}{w^2}$$ Equation B.11

Area Under curve $= \int_{-w/2}^{w/2} ax + bx^2 dx$

$$=\frac{bw^3}{3}+\frac{aw^2}{2}$$

$$=w^2\left(\frac{bw}{3}+\frac{a}{2}\right)$$ Equation B.12

Substitute in a and b

$$\text{Area} = w^2\left(-\frac{4H}{w^2}\frac{w}{3}+\frac{4h}{w}\frac{1}{2}\right)$$

$$=\frac{2Hw}{3}$$ Equation B.13

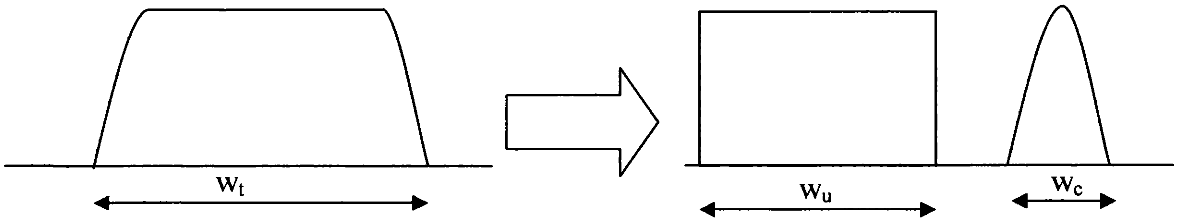
Therefore,

$$\text{Rectangular index} = \text{RI} = \frac{\text{Line cross - sectional area}}{\text{Width x Height}}$$ Equation B.14

$$=\frac{2\text{Hw}}{3}\bullet\frac{1}{\text{Hw}}$$

$$=\frac{2}{3}\approx 0.667$$

The analysis of a line with a curved and flat section was considered in a similar way. The length of the curved section is denoted by w_c and the length of the flat section is denoted by w_u. This is shown in Figure B.6.



Where,

w_t is the total width of the line

w_u is the width of the line with a uniform height

w_c is the width of the curved section of the line

Figure B.6 : The notation for the curved and flat sections

Area of the uniform distribution = $(w_c + w_u)$. h

Thus

$$\text{Modelled Area} = Hw_u + \frac{2Hw_c}{3} \qquad \text{Equation B.15}$$

$$\text{RI} = \frac{H\left(w_u + \frac{2w_c}{3}\right)}{H(w_c + w_u)}$$

$$= \frac{\left(w_u + \frac{2w_c}{3}\right)}{W_t} \qquad \text{Equation B.16}$$

Since $w_t = w_u + w_c$

$$RI = 1 - \frac{w_c}{3w_t} \qquad \text{Equation B.17}$$

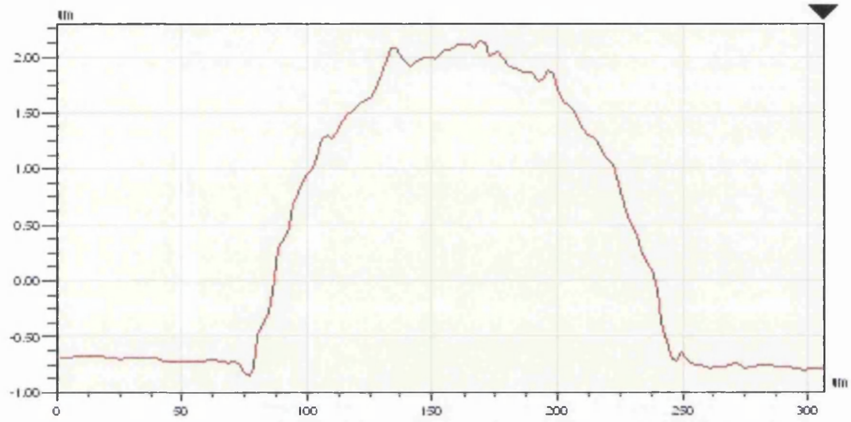
B.4 Closure

The derivation of two methods has been described. One method used the Fourier series to curve fit the shape of the line, the other used regular shapes to represent patterns in the cross-section of the line. The discussion of these two methods is given in Section 4.5.

Appendix C

Observations and Preliminary theory on the effect of orientation on line cross-sectional shape

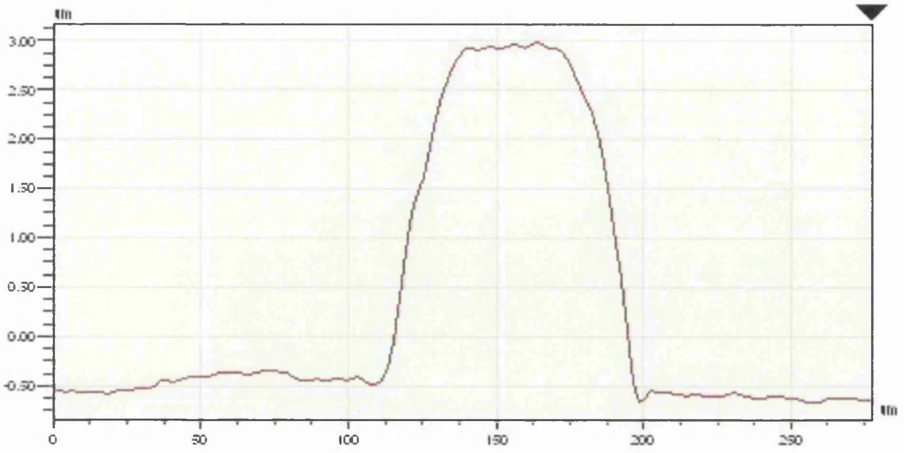
The figures show cross-sections of the line at 15 and 75 degrees to the print direction for lines of different width and printing conditions. An increase of the rounding of the top left hand corner of the line is shown. This was the side that is printed first. It is interesting to note that the amount of rounding was not the same for all prints, this suggests that the screen printing process parameters have an effect on this phenomenon.



(a) 15 degrees to the print direction

(b) 75 degrees to the print direction

Figure C.1 : Cross-sections for line 1



(a) 15 degrees to the print direction

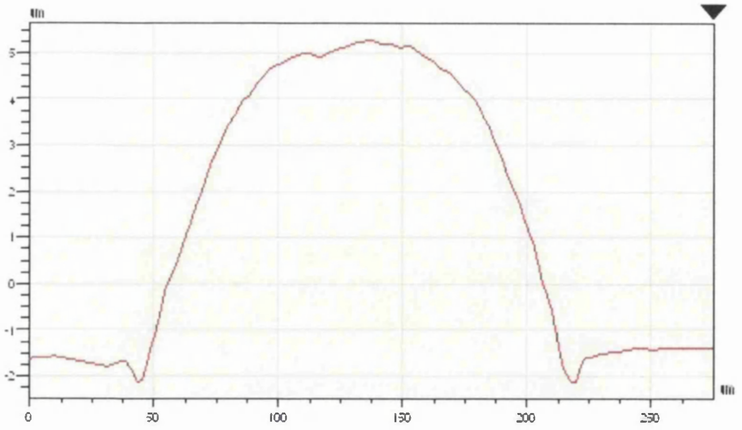
(b) 75 degrees to the print direction

Figure C.2 : Cross-sections for line 2

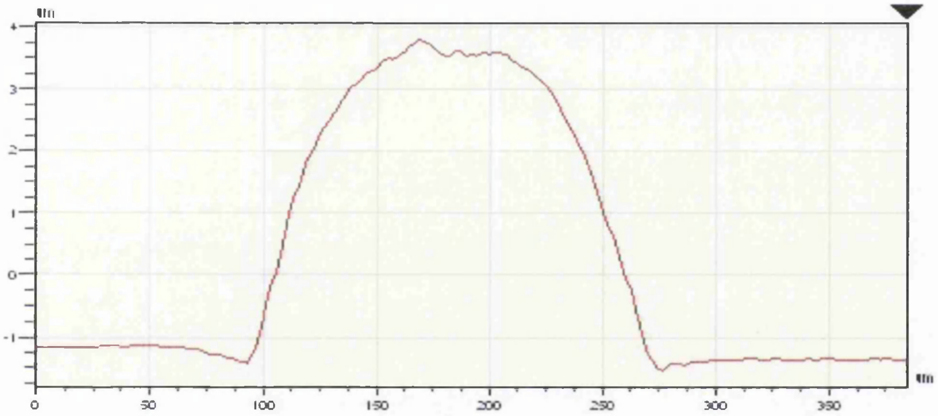
(a) 15 degrees to the print direction

(b) 75 degrees to the print direction

Figure C.3 : Cross-sections for line 3

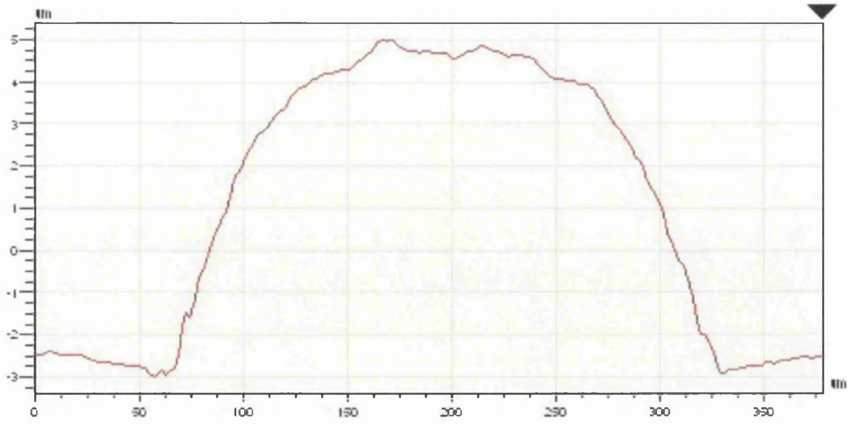


(a) 15 degrees to the print direction



(b) 75 degrees to the print direction

Figure C.4 : Cross-sections for line 4



(a) 15 degrees to the print direction

(b) 75 degrees to the print direction

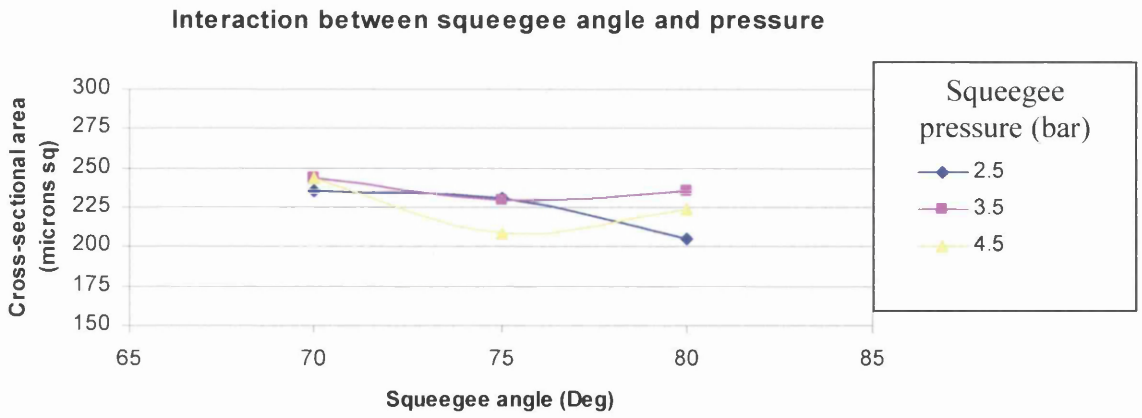
Figure C.5 : Cross-sections for line 5

Appendix D

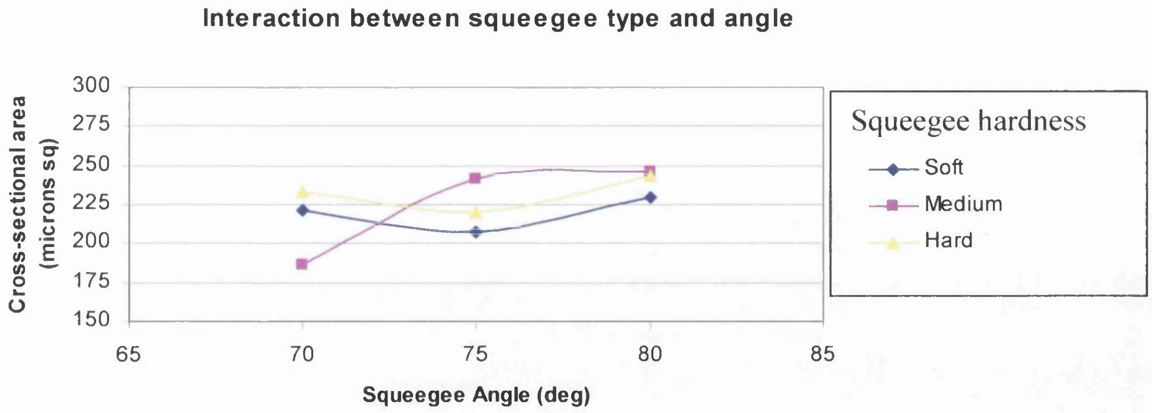
Full results from the investigation into the squeegee parameters

D.1 Introduction

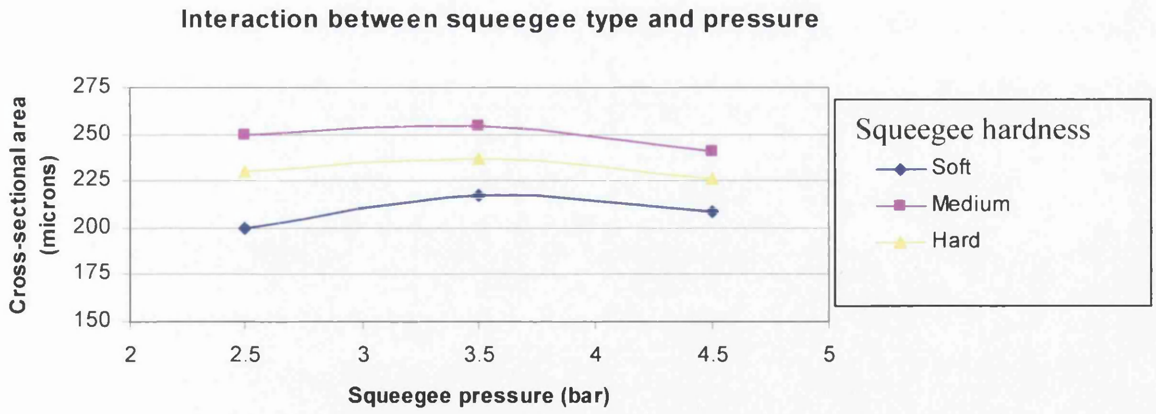
The full results are shown here for the interactions of the squeegee parameters. They are shown for the three lines widths not presented in the main thesis. These were 90μm, 120μm and 280μm wide lines. The line width data is presented first, followed by the cross-sectional area and line width rms.



(a)

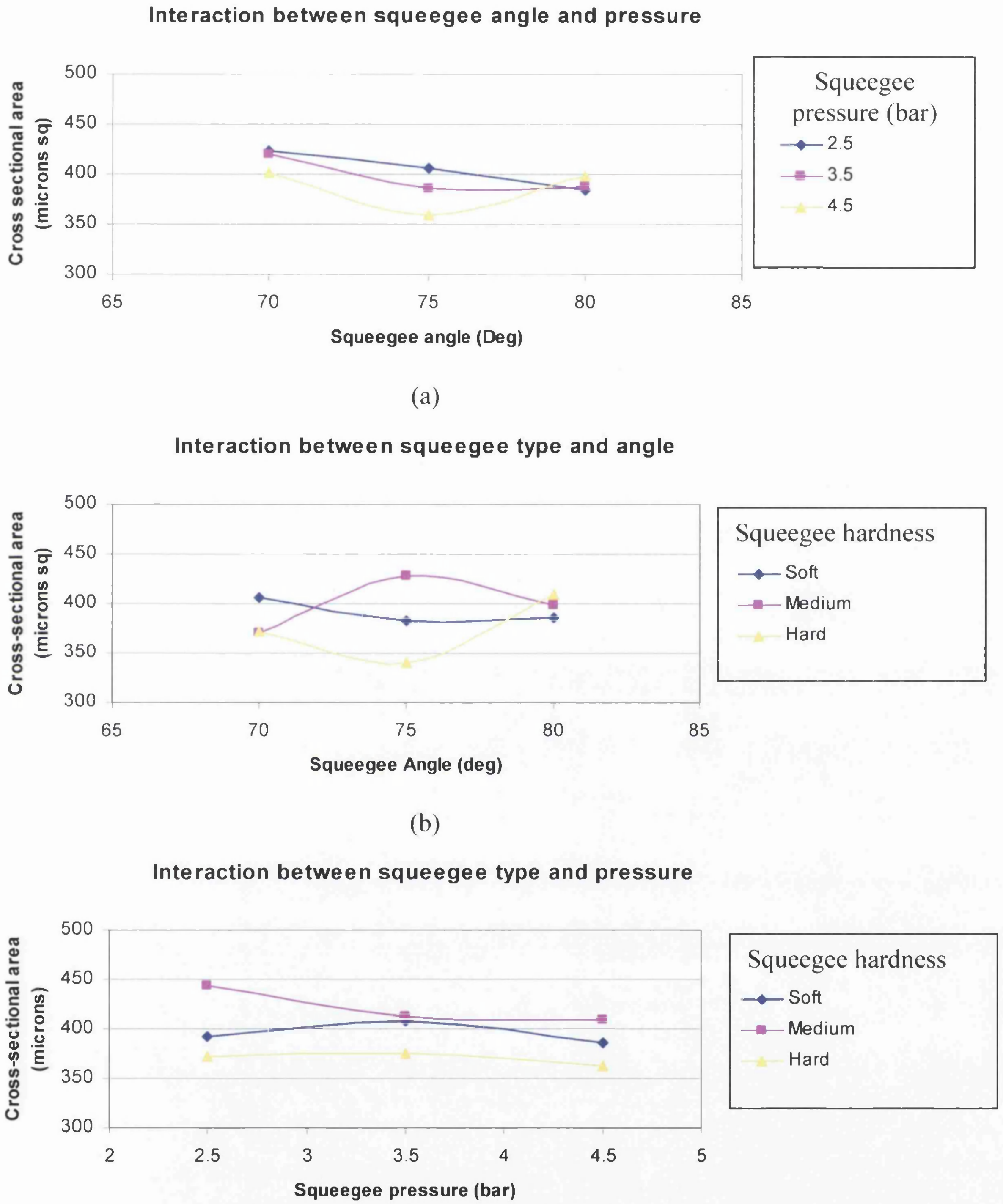


(b)



(c)

Figure D.1 : The effect of parameter interactions on the cross-sectional area for 90µm wide lines

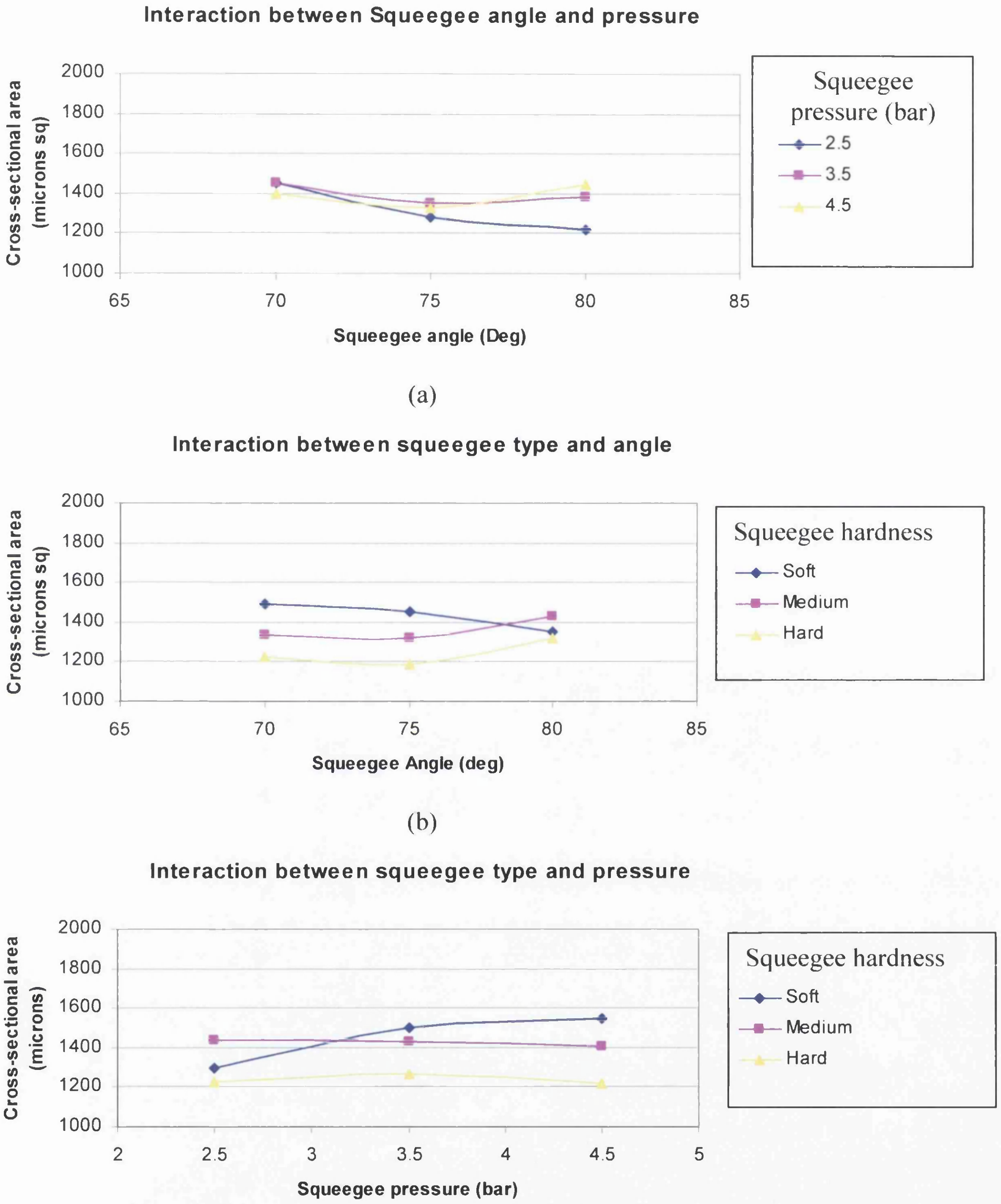


(a)

(b)

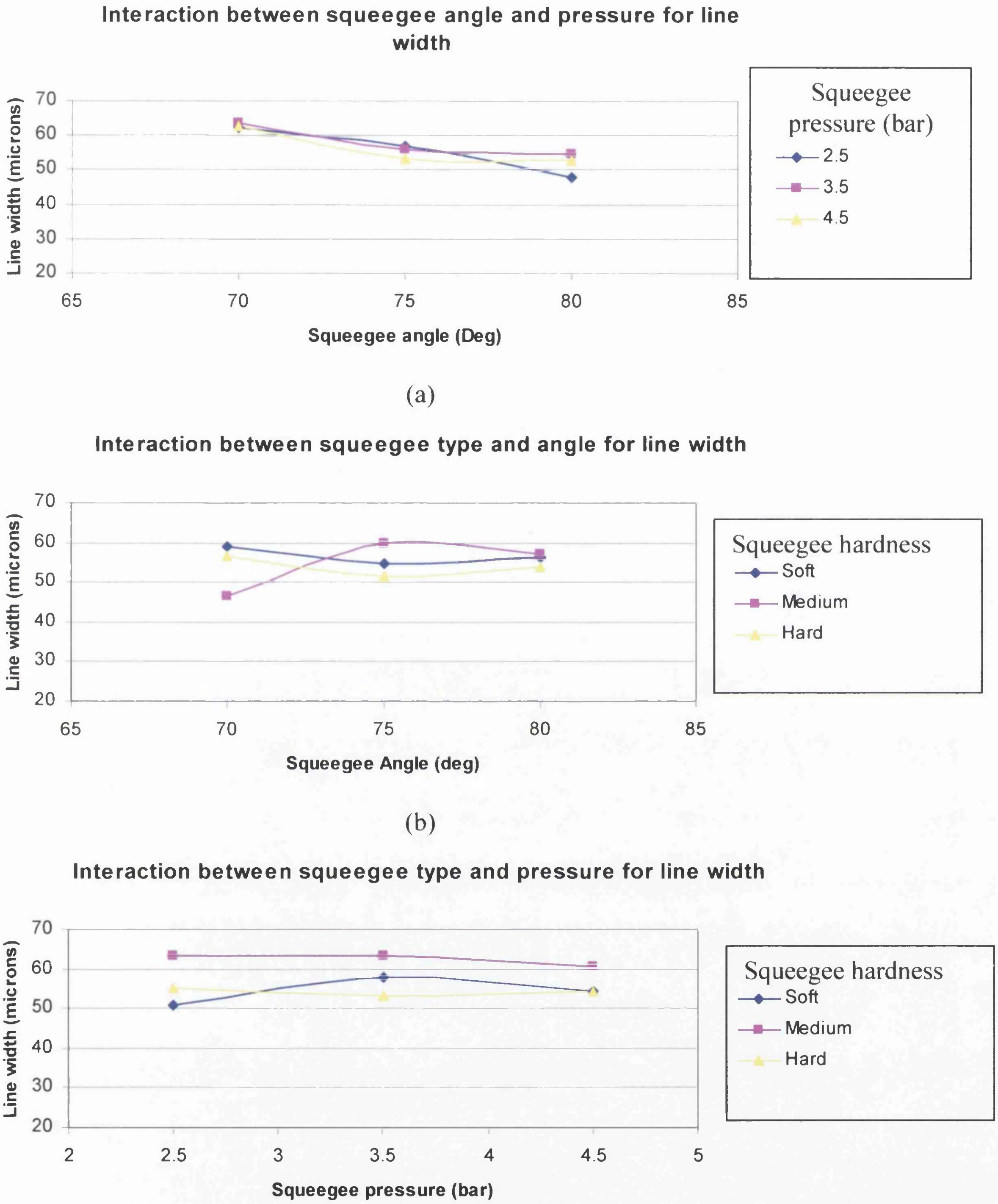
(c)

Figure D.2 : The effect of parameter interactions on the cross-sectional area for 120µm wide lines



(c)

Figure D.3 : The effect of parameter interactions on the cross-sectional area 280μm wide lines



Interaction between squeegee angle and pressure for line width

(a)

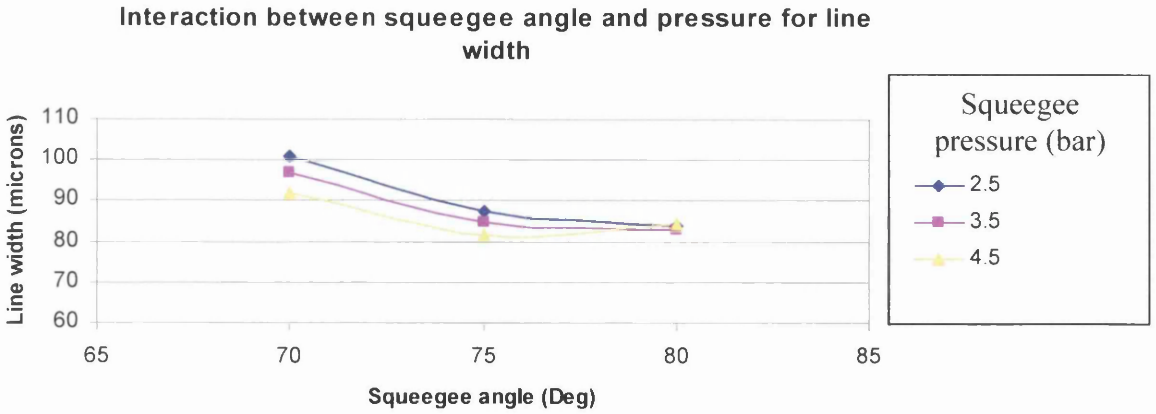
Interaction between squeegee type and angle for line width

(b)

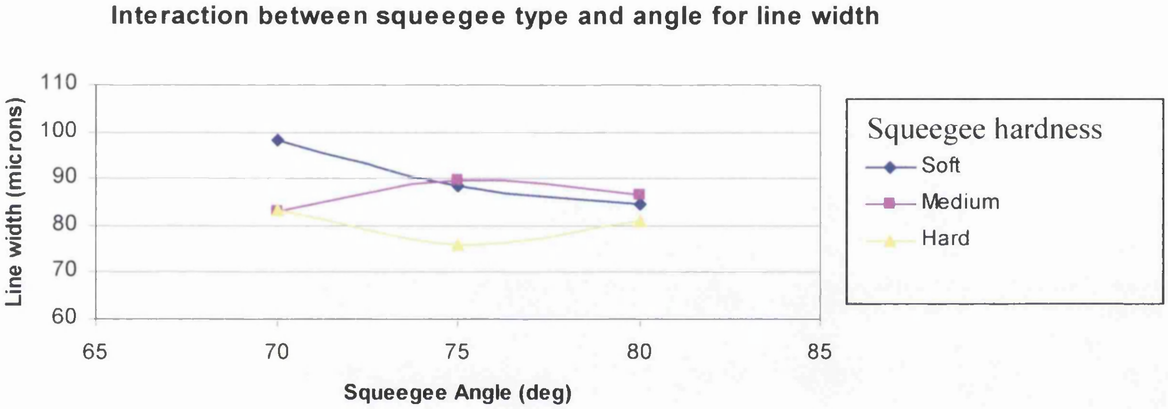
Interaction between squeegee type and pressure for line width

(c)

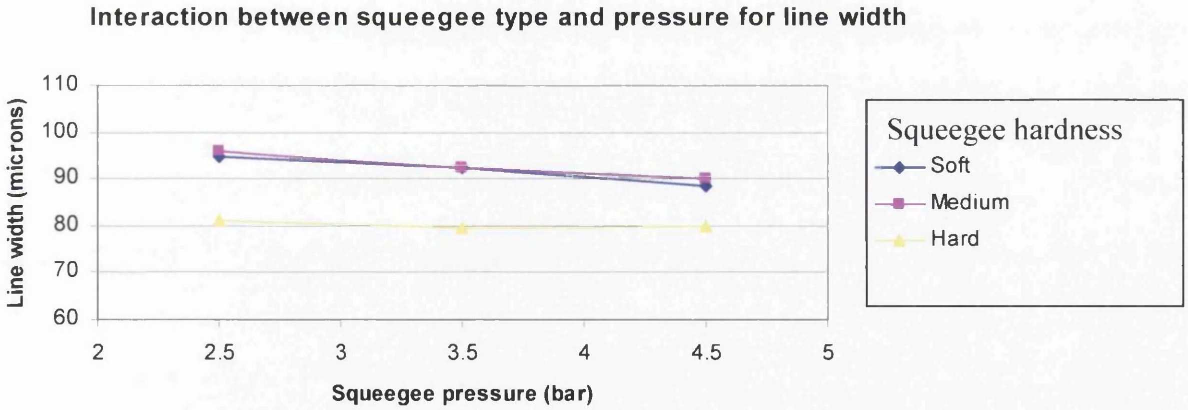
Figure D.4 : The effect of parameter interactions on the line width for 90μm wide lines



(a)

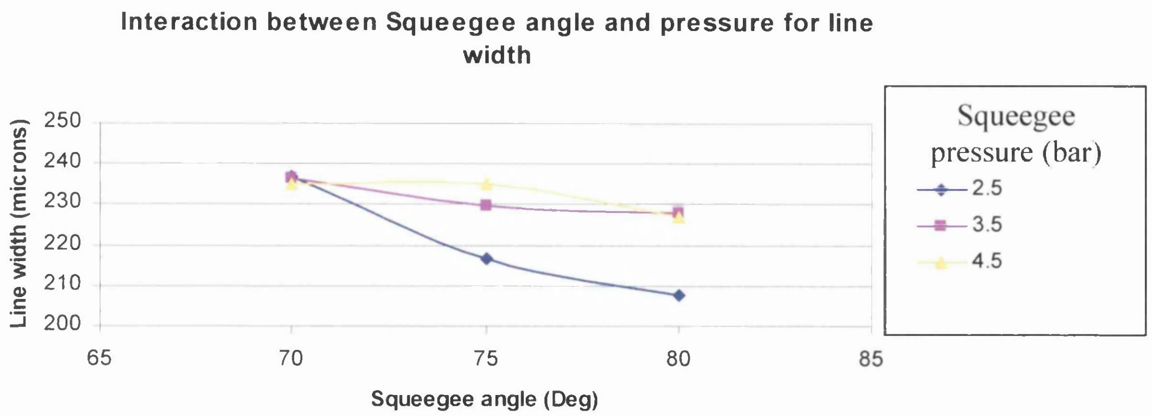


(b)

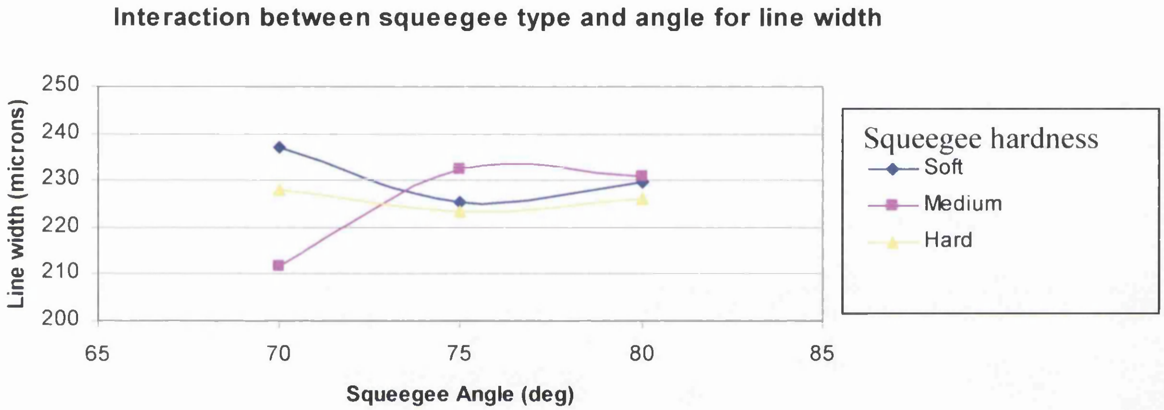


(c)

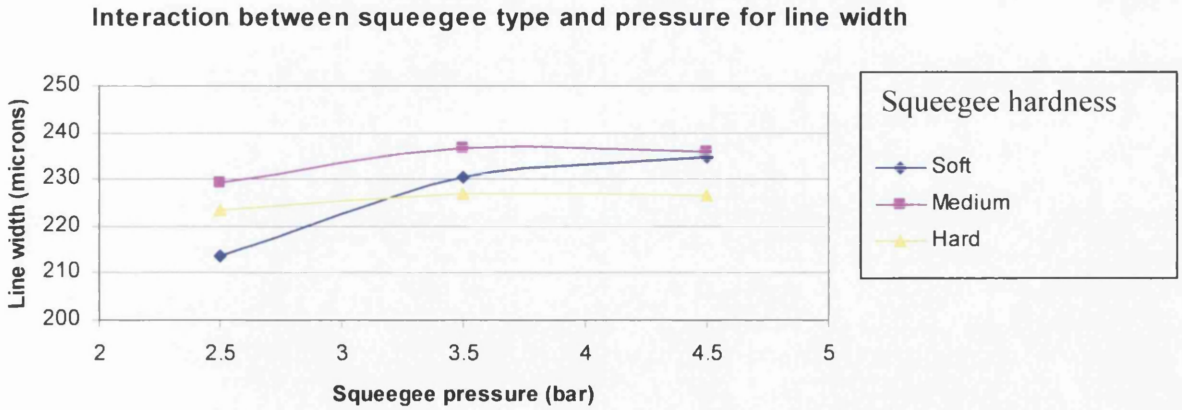
Figure D.5 : The effect of parameter interactions on the line width for the 120μm wide lines



(a)



(b)



(c)

Figure D.6 : The effect of parameter interactions on the line width for the 280μm wide lines

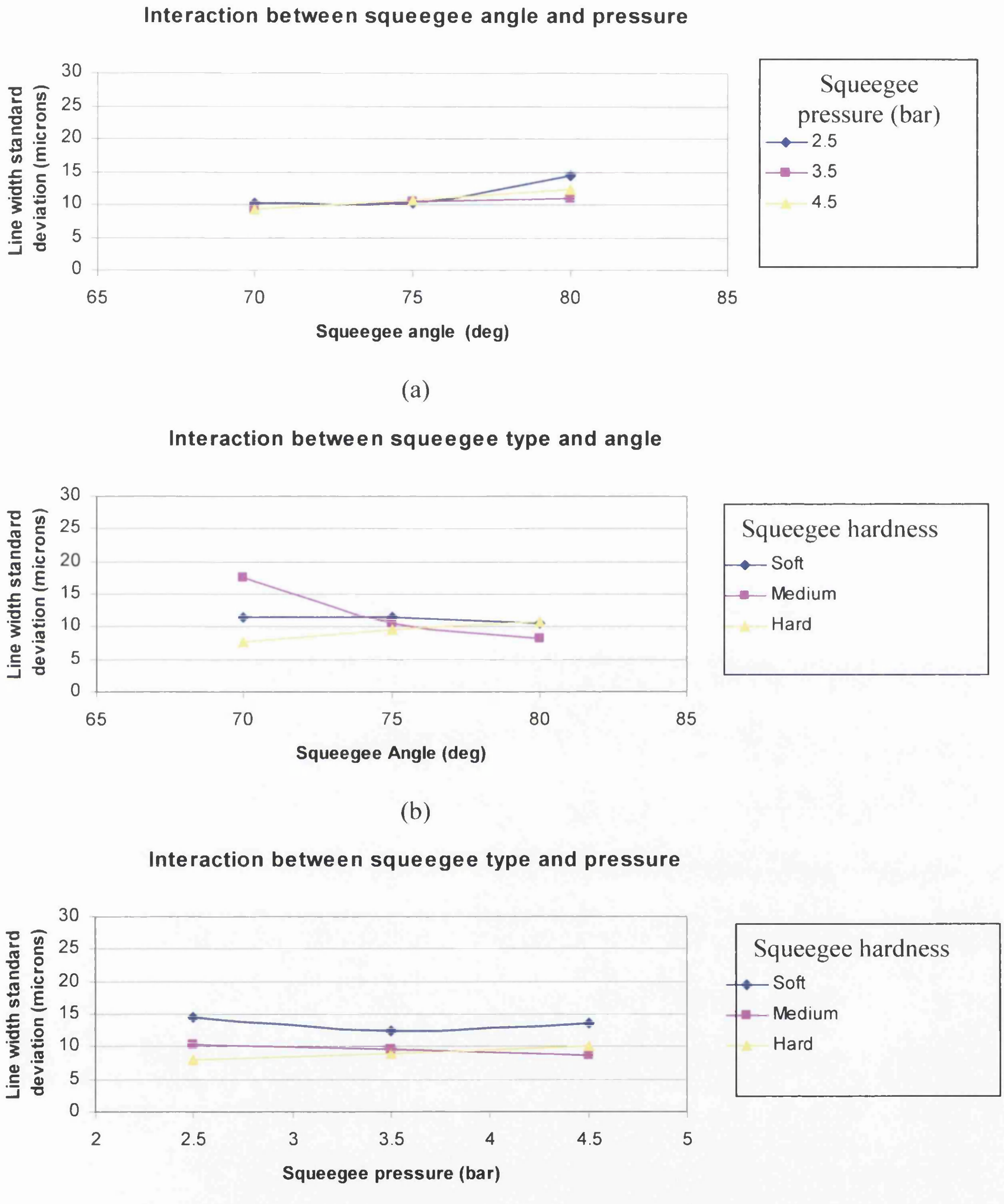
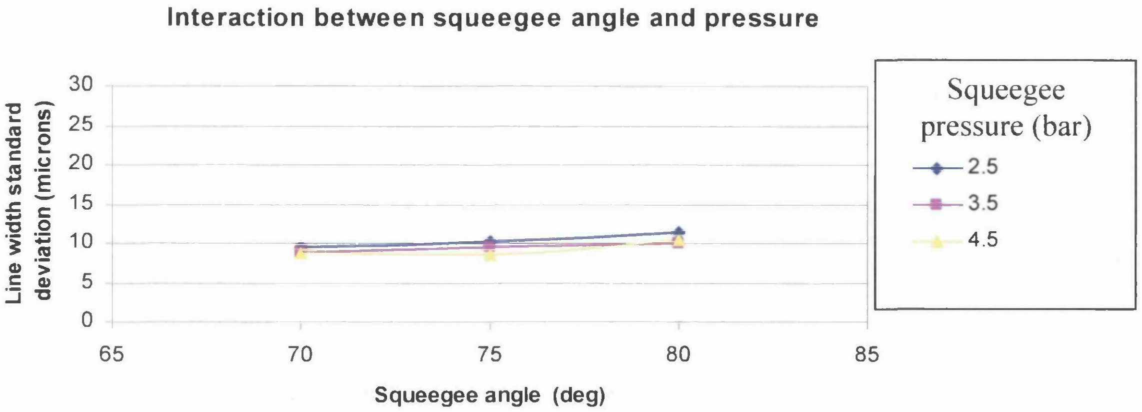
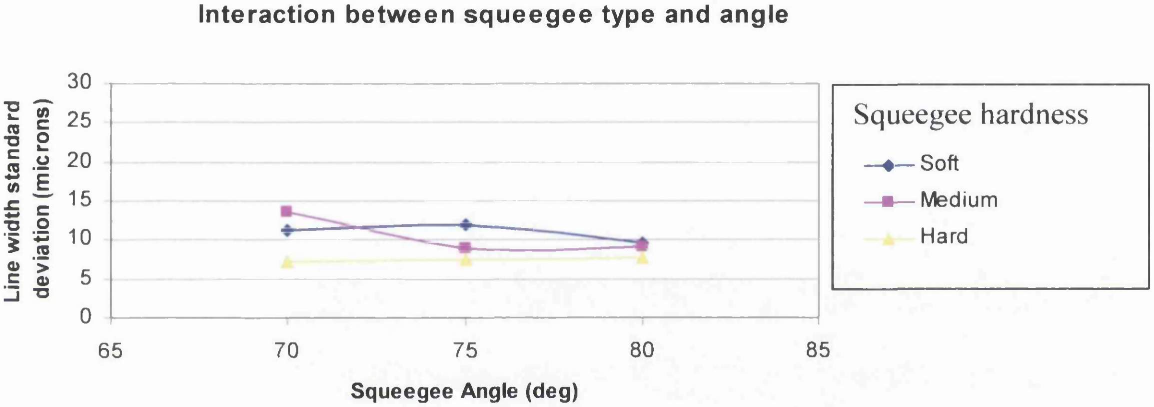


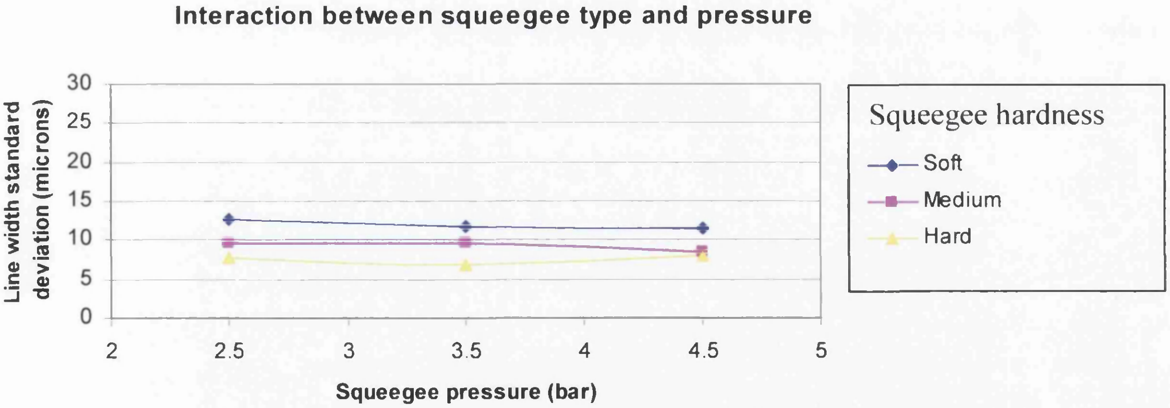
Figure D.7 : The effect of parameter interactions on the line width rms for the 90µm wide lines



(a)

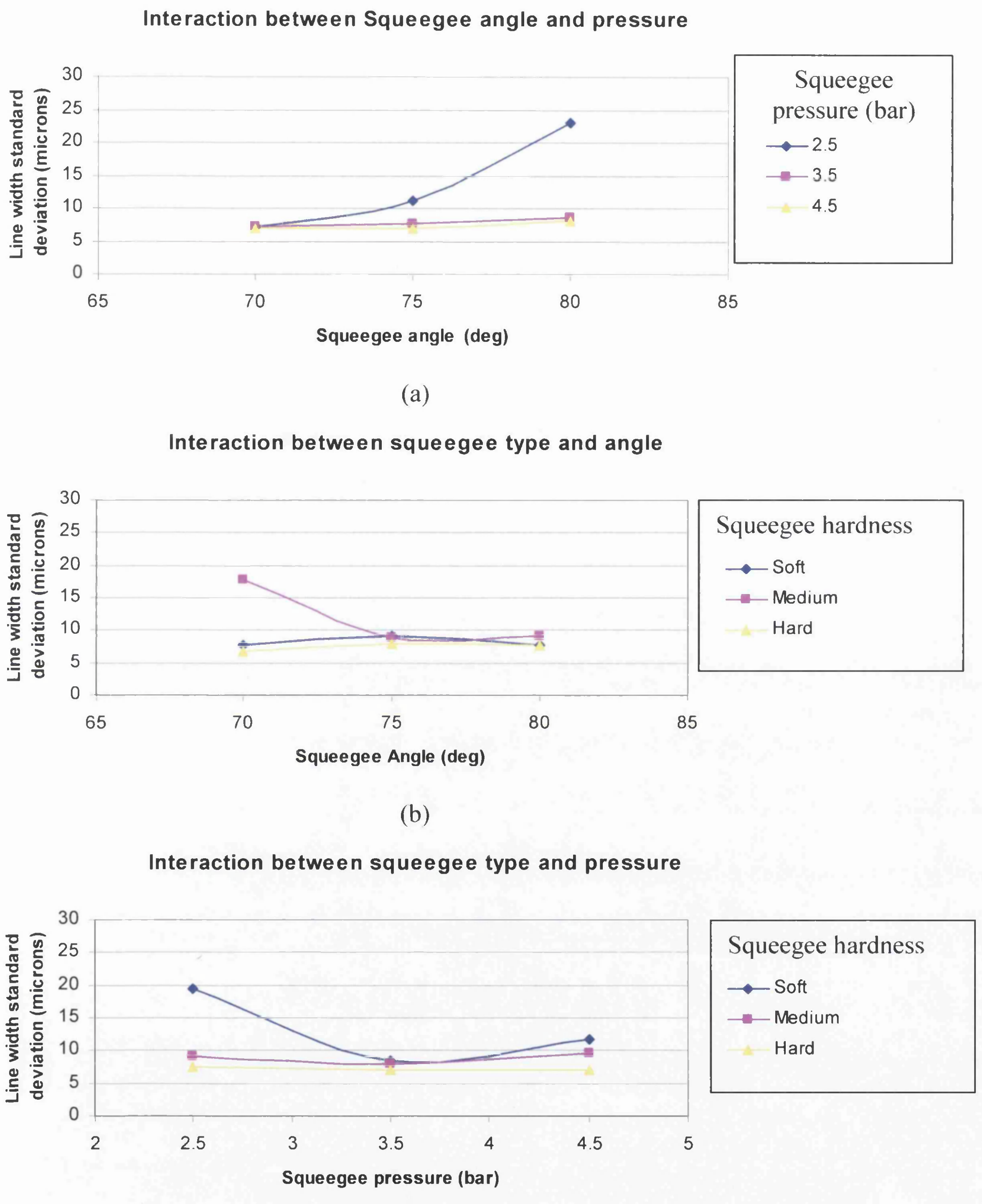


(b)



(c)

Figure D.8 : The effect of parameter interactions on the line width rms for the 120μm wide lines



Interaction between Squeegee angle and pressure

(a)

Interaction between squeegee type and angle

(b)

Interaction between squeegee type and pressure

(c)

Figure D.9 : The effect of parameter interactions on the line width continuity for the 280μm wide lines

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