Coatings **2014**, *4*, 356-379; doi:10.3390/coatings4020356

OPEN ACCESS

coatings

ISSN 2079-6412

www.mdpi.com/journal/coatings

Article

A Study of the Abrasion of Squeegees Used in Screen Printing and Its Effect on Performance with Application in Printed Electronics

Christopher O. Phillips *, David G. Beynon, Simon M. Hamblyn, Glyn R. Davies, David T. Gethin and Timothy C. Claypole

Welsh Centre for Printing and Coating, College of Engineering, Swansea University, Singleton Park, Swansea SA2 8PP, UK; E-Mails: d.g.beynon@swansea.ac.uk (D.G.B.); s.m.hamblyn@swansea.ac.uk (S.M.H.); g.r.davies@swansea.ac.uk (G.R.D.); d.t.gethin@swansea.ac.uk (D.T.G.); t.c.claypole@swansea.ac.uk (T.C.C.)

* Author to whom correspondence should be addressed; E-Mail: c.o.phillips@swansea.ac.uk; Tel.: +44-1792-295-533; Fax: +44-1792-295-816.

Received: 12 February 2014; in revised form: 3 June 2014 / Accepted: 4 June 2014 / Published: 12 June 2014

Abstract: This article presents a novel method for accelerated wear of squeegees used in screen printing and describes the development of mechanical tests which allow more in-depth measurement of squeegee properties. In this study, squeegees were abraded on the screen press so that they could be used for subsequent print tests to evaluate the effect of wear on the printed product. Squeegee wear was found to vary between different squeegee types and caused increases in ink transfer and wider printed features. In production this will lead to greater ink consumption, cost per unit and a likelihood of product failure. This also has consequences for the production of functional layers, *etc.*, used in the construction of printed electronics. While more wear generally gave greater increases in ink deposition, the effect of wear differed, depending on the squeegee. There was a correlation between the angle of the squeegee wear and ink film thickness from a worn squeegee. An ability to resist flexing gave a high wear angle and presented a sharper edge at the squeegee/screen interface thus mitigating the effect of wear. There was also a good correlation between resistance to flexing and ink film thickness for unworn squeegees, which was more effective than a comparison based on Shore A hardness. Squeegee indentation at different force levels gave more information than a standard Shore A hardness test and the apparatus used was able to reliably measure reductions in surface hardness due to solvent absorption. Increases in ink deposition gave lower resistance in printed silver lines; however, the correlation between the amount of ink deposited and the resistance, remained the same for all levels of wear, suggesting that the wear regime designed for this study did not induce detrimental print defects such as line breakages.

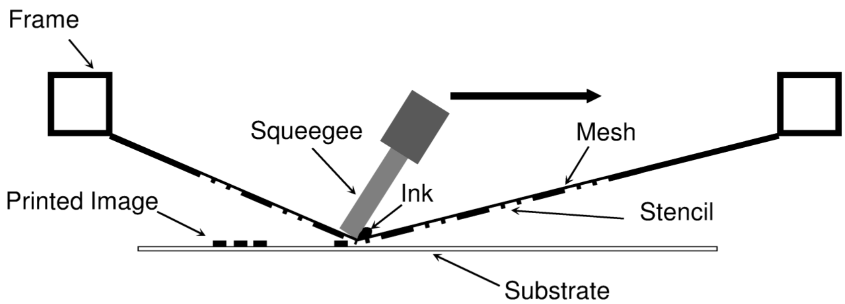
Keywords: screen printing; squeegees; printed electronics; accelerated aging

1. Introduction

As well as conventional graphics printing, screen printing is increasingly being used for a large range of functional devices where thick deposits are required; including but not limited to solar cells [1], fuel cells [2], displays [3], Organic Light Emitting Diodes (OLEDs) [4], transistors [5] as well as sensors for gases [6], humidity [7] and biological materials [8]. There is an increasing requirement for more intricate features, with a high degree of control over their functional properties. The functionality of the various printed layers in terms of conductive, dielectric, insulating and light emitting properties, for example, will vary if the ink deposition is altered. Process consistency is therefore as vital as the understanding of the effect of process parameters when engaging in volume production. Process settings can be used to achieve product quality, but this needs to be maintained over the manufacturing production run. Where volumes are large or the printed inks contain abrasive elements, the squeegee condition will vary over its lifetime and a decision must be made when to replace it. Research to date has focused principally on the effect of process settings [9–12] and no work has been reported to explore squeegee deterioration during printing.

The squeegee (usually polyurethane) is used to transfer ink through the screen mesh onto a substrate (Figure 1) and there are a host of squeegee specific factors which influence the print quality and consistency. These can be categorized as either process setting effects, which are controlled by the selection of the squeegee, or duration effects which will have an impact over the course of the printing run and are less well understood and predictable. Process effects include surface hardness, bulk elastic modulus, mounting angle and edge profile of the squeegee. In the longer term, inks, and in particular functional materials such as conductive metallic particles, will abrade the squeegee over time thus changing its performance. A better understanding of squeegee abrasion and its consequent impact on the printed product are therefore required.

Figure 1. Schematic of screen printing process.



The effect of abrasion on print quality might vary depending on other squeegee factors. For this reason, other factors which influence the contact region between the squeegee and the screen are also investigated. A large range of inks are used in screen printing, and there is a correspondingly large range of solvents used in these inks. There is gradual solvent absorption into the squeegee from the ink which causes swelling of the squeegee during the print run. Solvent absorption is typically evaluated by immersion of small pieces of squeegee [13] with changing mass being the most reliable indicator, rather than volume changes [14]. To assess the comparative uptake of solvent in the different squeegee types, absorption was tested via immersion in solvents used in carbon and silver conductive ink systems used in printed electronics. Solvent absorption has also been previously demonstrated to increase ink transfer by softening the squeegee [14]. However, the Shore A hardness test [15], which is the predominant method for assessing the surface hardness of the squeegee, cannot accurately measure squeegees that have been distorted through contact with ink or solvent as it has an 18 mm wide foot which must remain in contact with the squeegee. This required a method of measuring the resistance to indentation irrespective of the surface form. Furthermore, the Shore A method effectively measures the indentation made by a pin at only one single force or pressure (8.064 N for a 0.79 mm diameter pin). By applying a range of forces, a more comprehensive view of surface hardness should be revealed. Bulk mechanical properties influence how the squeegee bends in response to loading. Depending on the configuration of the screen printer, this will affect the pressure, contact and effective angle that the squeegee forms with the screen; thus affecting deposition. Mechanical properties are typically described according to tensile properties [16]. This is not necessarily representative of the multi-axial strain that occurs during printing. Therefore, the ability of a squeegee to resist flexing in a controlled manner was also investigated. Correlations between these measured parameters and print quality were explored.

Resistance to wear is typically established by controlled abrasion of a small piece of squeegee against a rotating drum mounted with an abrasive sheet [17]. The mass loss due to abrasion is then used to compare the abrasion resistance of the various squeegee materials. This has a number of disadvantages in that it cannot reproduce conditions during printing in terms of pressure, contact angle, resistance to flexing and sample geometry, as well as using a dry contact. However, it is not feasible, or cost effective, to wear squeegees by printing due to the time it would take, the wastage of both ink and substrate and the potentially uncontrolled wear that would result. This necessitated the development of an accelerated wear technique which was rapid and controlled but also allowed the effect on the print to be evaluated. Squeegee wear was then accurately measured using microscopy and image analysis techniques prior to printing in both worn and unworn states using a conductive silver ink. The resulting printed samples were then analyzed to compare the effect of wear on line geometry (ink film thickness, line width, overall deposition) and electrical resistance for printed silver lines. The relationship between the parameters of solvent absorption, surface hardness and resistance to flexing, wear characteristics and print quality were investigated.

2. Experimental Section

2.1. Materials

Six squeegees were obtained from commercial sources for wear testing and an additional squeegee was obtained for set-up tests and to act as a control in order to monitor process drift, during printing, without the influence of wear. All squeegees were obtained from different suppliers and spanned a range of costs. All squeegees had a square edge and most were nominally 70 to 80 Shore A hardness. Squeegee width was approximately 9 mm and height 50 mm. Squeegee 5 differed from the others in that it was composed of three layers, with a central core and two edge layers of nominally 75 Shore A. Shore A hardness [15] was measured for each squeegee, with 10 measurements taken at regular intervals over the length of the squeegee. The average and standard deviation for unused squeegees are presented in Table 1.

Table 1. Squeegees used in the experiments.

Squeegee Number	Measured Shore A Hardness (Standard Deviation)
1	74.2 (0.6)
2	76.0 (0.0)
3	75.8 (0.4)
4	76.9 (1.2)
5	78.7 (0.8)
6	70.0 (0.8)
Control	74.0 (0.0)

Carbon and silver inks were used for wear and printing trials respectively and the solvents used in the manufacture of these inks were therefore used in the solvent absorption tests. Carbon paste screen ink (C2030519P4) was purchased from Gwent Electronic Materials Ltd., UK (GEM). The solvents used in the ink were 4-hydroxy-4-methyl-2-pentanone (diacetone alcohol, CAS: 123-42-2) and 3,3,5-trimethylcyclohex-2-enone (α-Isophorone, CAS: 78-59-1). The solvent blend used in the inks was also provided by GEM for testing the squeegees, in the same ratios used in the ink. A gel type flexible silver paste (C2080415D2) was purchased from GEM. The solvent used in the ink was ethylene glycol diacetate (CAS: 111-55-7). This was purchased in pure form from Sigma Aldrich (525200).

2.2. Squeegee Characterization

2.2.1. Solvent Absorption by Squeegees

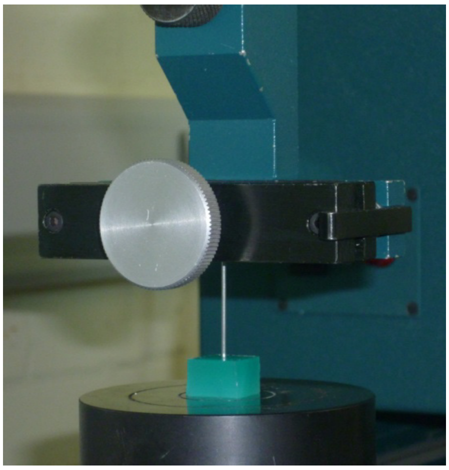
The squeegees were subjected to immersion in the solvents used in the manufacture of the carbon and silver inks used in the wear and print tests. The squeegees were cut into 10 mm by 10 mm by 9 mm (squeegee thickness) pieces using a steel blade. For each squeegee type, five pieces were immersed and all squeegee types were immersed in the same dish at the same time. The squeegee pieces were weighed prior to immersion, using a mass balance accurate to 0.0001 g. The pieces were taken out of the solvent at regular intervals over a five hour period, patted dry, re-weighed and then placed back in the solvent. For each squeegee type, all five pieces were weighed at the same time and the mass was averaged.

2.2.2. Indentation and Deflection Tests

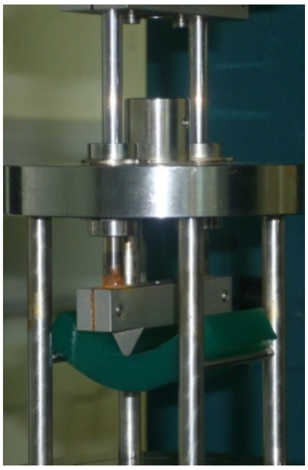
In order to test resistance to indentation, squeegees were cut into 15 mm by 15 mm sections and a Hounsfield HK10S tensile/compressive testing machine was used to indent the squeegee samples. A sample of squeegee was placed on a flat steel platform and a 1.1 mm diameter steel pin was gradually moved in to contact with the squeegee material and the force on the pin and its displacement were measured as indentation proceeded at a speed of 1 mm/min (Figure 2). As the pin engaged with the various squeegees at different points, the indentation was assumed to start once a force of 0.05 N was reached. Five repetitions were performed at different positions on each squeegee sample, with care taken not to indent at the edge of the squeegee. In order to measure the effect of solvent absorption on the hardness of the squeegees, only the squeegee surface subjected to indentation was exposed to the solvent. Squeegees samples were placed in 40 mm diameter watch glasses containing 1 mL of solvent, giving an immersion depth of approximately 2 mm. The reverse surface was undistorted and placed on the steel platform. Squeegee samples were placed in the solvent for 30 min, patted dry then tested immediately.

For deflection testing, squeegees were cut into 30 mm wide strips of 50 mm length (full squeegee strip width). The sample was supported on either end using two steel rods, which were 42 mm apart, and a rounded steel tool was pushed downwards in to the centre of the squeegee at a rate of 10 mm/min using the tensile/compressive testing apparatus. The force required to bring the tool downwards and deflect the squeegee was measured up to a maximum tool displacement of 10 mm (Figure 2). As the tool engaged with the various squeegees at different points, the flexing was assumed to start once a force of 0.1 N was reached. The test was performed six times for each squeegee using the same sample.

Figure 2. (**a**) Indentation and (**b**) deflection test methods for squeegees. Deflection test shows 10 mm tool displacement.



(**a**)



(**b**)

2.3. Squeegee Wear Methodology

In order for the wear to be representative of that achieved through printing, wear was performed using a screen printing press. Squeegees were subjected to controlled accelerated wear using various grades of silicon carbide (“wet and dry”) abrasive papers lubricated with ink. This product was selected as it enabled a controlled and consistent means of wearing the squeegees and it was readily available in a range of standard grades.

The wear apparatus was designed specifically for this experiment and is shown in Figure 3. A stainless steel plate was attached to an aluminium screen printing frame (in place of the screen). Three different grades of silicon carbide abrasives were used; in order of declining roughness these were 1200, 2000 and 2500 grits (the lower the grit number, the higher the roughness—15.3, 10.3 and 8.4 μm average particle sizes respectively. For comparison, the approximate particle size in the silver ink, used in subsequent printing tests, was 2 to 3 μm). The abrasive sheets were cut into strips and placed side by side on the steel plate using a cushioned double sided tape. The full length of the sheets (280 mm) were used and they were cut into widths of 110 mm, for the 1200 and 2500 abrasives located at the sides, and 100 mm for the central strip of 2000 grit abrasive. The squeegees were cut to a length of 340 mm, allowing 10 mm overhang on either side of the abrasive. These dimensions were selected so that the worn squeegees could be used to print three identical test images from the same screen in the ensuing print tests. The parameters are summarized in Table 2.

Figure 3. Controlled wearing of a squeegee, using silicon carbide abrasive, on a screen printing press.

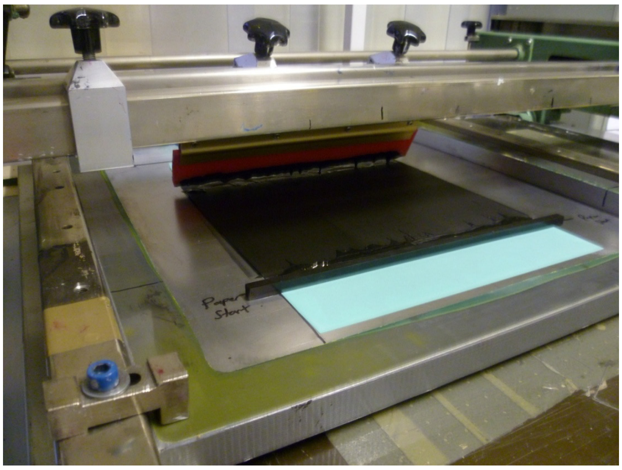


Table 2. Parameters used in wear experiment.

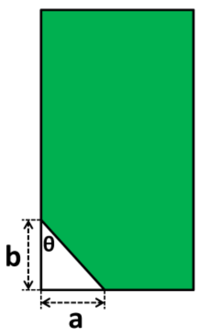
Parameter	Setting
Printing machine	SveciaMatic SM
Abrasive types	1200, 2000 and 2500 grit silicon carbide abrasive paper sheets
Abrasive sheet dimensions	110 mm and 100 mm by 280 mm
Wear length	260 mm per cycle
Number of wear cycles	50 per squeegee
Screen frame	580 mm × 580 mm Aluminium (510 mm × 510 mm internal)
Backing plate	1 mm stainless steel
Backing tape	3M E1715 (381 µm thickness)
Ink used	Carbon graphite paste (C2030519P4, Gwent Electronic Materials Ltd., UK) −40 grams per wear cycle
Squeegee dimensions	9 mm (thickness approx) × 50 mm (height) × 340 mm (length)
Squeegee angle	65°
Squeegee holder	Serilor®MACH straight upper with standard 54.1 mm jaws, Fimor, France.
Squeegee engagement	21 mm (equivalent to kiss contact plus 8 mm)
Speed	2.5 units (equivalent to approximately 0.35 m/s)

In order to help lubricate the contact between the screen and squeegee and assist the transport of abraded particles (of squeegee and silicon carbide) away from contact area, carbon paste screen ink was spread over the abrasive sheet prior to wear. Dry abrasion, or use of a low volatility solvent alone, was found to be much more damaging to the squeegee in preliminary tests. A flow coat was not used as it would most likely damage the abrasive and would suffer abrasion itself. A 10 mm strip of squeegee material was attached to the adhesive tape at the end of the abrasive strips, where the squeegee lifted off after wear. The ink pooled at this point, as it was forced along the abrasive sheet by the squeegee, and the strip allowed a reservoir of ink to form that would recoat the squeegee at the end of each wear cycle. This ensured that a covering of ink remained on the squeegee; rather than having dry contact (Figure 3). This was confirmed upon cleaning the squeegee after wear; where a covering of ink was observed on the printing edge of the squeegee. The use of a lubricating ink also ensured that any solvent related swelling and softening; that would occur during printing, would also be factored in to the wear experiment. The settings used were the same as those used in the later printing trials, with the squeegee angle set to 65°, and are detailed in Table 2.

Each squeegee was reciprocated fifty times over the abrasives to cause it to wear, with bands of different levels of wear across the width from the different abrasive types. Both abrasives and ink were discarded after each cycle of fifty reciprocations to ensure consistency between squeegees. Following wearing, the squeegees were cleaned and left for a minimum of 48 h before wear measurement to allow absorbed solvent to escape and swelling to subside.

2.4. Measurement of Squeegee Wear

Images of squeegee wear were captured using a Leica stereo microscope with a CCD camera. The squeegees were measured from both the side and bottom of the squeegee and for both orientations three images were taken over each wear band. A sample image of a squeegee in both unworn and worn states is shown in Figure 4. Wear was evaluated using image analysis software (Image J 1.46r, U. S. National Institutes of Health). A rectangle was manually selected over the wear region, with the software outputting its dimensions. This was done five times in each image, giving a total of fifteen measurements per orientation per wear band. The microscope was calibrated using a tile with dots of known diameter. The amount of squeegee removed was then calculated as a triangle from the worn width of the squeegee from both orientations using Equation (1). Standard deviation (St. dev) was calculated using Equation (2) and the wear angle, that is the angle between the long side of the squeegee and the wear, calculated using Equation (3).



$$CSA \text{ removed} = \frac{\mathrm{a} \times \mathrm{b}}{2} \quad (1)$$

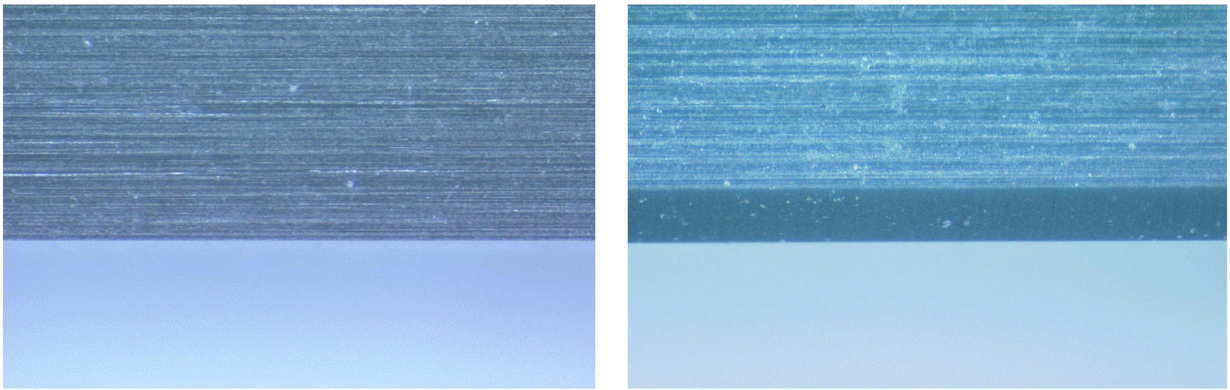
$$\text{St. dev in } CSA \text{ removed} = \frac{\mathrm{a}}{2} \text{St. dev } b \times \frac{\mathrm{b}}{2} \text{St. dev } a \quad (2)$$

$$\theta = \tan^{-1} \frac{a}{b} \quad (3)$$

where *CSA* = cross-sectional area; *a* = wear on bottom of squeegee; *b* = wear on side of squeegee; θ = angle of wear.

The squeegees were used to print in both unworn and worn states using the settings listed in Table 3. Unworn and worn edges of the same squeegee were printed sequentially, before moving on to the next squeegee, with the squeegees printed in the order listed in Table 1 (*i.e.*, 1, 2, 3, 4, 5, 6). To alternate between unworn and worn edges, the squeegee holder was removed, rotated by 180° and replaced in the printing press. In addition to the test squeegees, a series of control prints were made with the unworn control squeegee both prior to and after printing with the other squeegees. This was performed in order to monitor any drifts in the printing process over time so that these could be distinguished from changes due to wear. All prints were performed on the same screen without changing over or cleaning between print cycles. None of the printing parameters were altered and the ink was kept in excess to deter drying in the mesh and replenished when required. A gel type ink (flexible silver paste C2080415D2, Gwent Electronic Materials, Pontypool, UK) was selected as this was stable over time and was not prone to drying in.

Figure 4. Microscope images of squeegee edge (**a**) before and (**b**) after wear. Images 3.84 mm × 2.46 mm.



(**a**) (**b**)

Table 3. Parameters used in printing experiment.

Parameter	Setting
Printing machine	SveciaMatic SM
Substrate	Melinex® 339, DuPont Teijin Films (330 µm thickness, 325 mm × 325 mm) opaque white
Screen frame	800 mm × 800 mm Aluminium (700 mm × 700 mm internal)
Mesh	PET, 68 threads cm^{-1}, 55 µm thread diameter, 45° mesh angle
Ink used	Flexible silver paste C2080415D2 (Gwent Electronic Materials, Pontypool, UK)
Squeegee dimensions	9 mm (thickness approx) × 50 mm (height) × 340 mm (length) (same as wear trial)
Squeegee angle	65° (same as wear trial)
Squeegee engagement	21 mm (equivalent to kiss contact plus 2 mm)
Squeegee holder	Serilor®MACH straight upper with standard 54.1 mm jaws, Fimor, France. (same as wear trial)
Snap off gap	3 mm
Speed	2.5 units (equivalent to approximately 0.35 m/s)
Flowcoat	400 mm width
Flowcoat engagement	6 units
Drying	Belt drying at 120 °C, with two passes at low speed giving approximately 3 min drying time

2.5. Printing of Silver Ink Using Unworn and Worn Squeegees

The screen used for printing consisted of three bands of identical test images whose location coincided with the different wear bands. A range of different line widths in both print direction (perpendicular to the squeegee) and at 90° to the print direction (parallel to the squeegee) were included. A total of ten prints were made for each squeegee configuration, giving a total of 140 prints. Including changeover time, this took less than two hours and the condition of the ink did not change noticeably in that time. The dimensions of the printed features were measured using white light interferometry (Veeco NT9300, Veeco Instruments, Inc., Plainview, NY, USA). This allowed a full three-dimensional surface profile to be captured, so that line width, print thickness and local surface variations could be evaluated. Lines of 400 and 600 μm nominal width were measured both in the print direction and at 90° to the print direction. These lines were 30 mm in length. Measurements were taken on each of the bands for prints with worn and unworn squeegees. Three measurements were taken for each line and three print samples (Repetitions 8, 9 and 10) were measured (nine measurements per line per orientation). The number of samples was based on an analysis of the variation in control prints and there was not found to be any benefit in accuracy in using five prints instead of three. Measurement was performed using an automated method in which the measurement locations were the same for all sets of measurements. Five times magnification was used, giving a measurement area of 1.25 mm by 0.94 mm (a resolution of 640 × 480 pixels with sampling at 1.9 μm intervals).

Average line width and ink film thickness across the measured profiles (1.25 mm or 0.94 mm depending on the orientation) were evaluated using "WCPCLine" software written by WCPC. The software aligned the data, to account for any tilt in the substrate, and used substrate roughness data to precisely differentiate between ink and substrate. Standard deviations were calculated over the nine readings taken per line type (three readings per individual line × three sheets) to indicate variability between the measured lines (not variability within the lines).

The resistance of the lines was measured with a Keithley 2400 multimeter using the two point probe technique. Probes were applied to the contact pads at each end of the 30 mm long tracks and the resistance recorded. The reported resistance is the average of measurements over three samples with the probe contact resistance subtracted.

3. Results and Discussion

3.1. Solvent Absorption by Squeegees

The solvent absorption of the squeegee materials is shown in terms of the percentage change in mass [100 × (Mass−Original mass)/Original mass] for carbon ink and silver ink solvents in Figures 5 and 6 respectively.

For all squeegees, there was a substantial difference in solvent absorption between the different solvents; overall there was on average 3.4 times more mass of ethylene glycol diacetate absorbed than the solvent blend used in the carbon ink over a given time period. The rate of solvent uptake was fastest at the onset of immersion but remained reasonably stable between one and five hours after immersion. The squeegees kept absorbing solvent throughout the duration of the experiment, even when quite substantial amounts of solvent (up to 17% mass increase) were absorbed. Squeegee 2 gave the lowest amount of solvent absorption of all the squeegees and was particularly resistant to absorption of the solvent blend used in the carbon ink; increasing in mass by less than 1% after five hours immersion. The greatest solvent uptake was observed in Squeegees 1 and 6, followed by the control squeegee. The remaining squeegees (3, 4 and 5) were broadly similar and displayed intermediate absorption levels between those of the control squeegee and Squeegee 2. The levels of solvent uptake were higher than what would be observed during printing due to the immersive nature of the test, use of neat solvent, test duration and small specimen size. However, the test illustrates the wide range of responses of the different squeegees as well as the continual absorption of solvent over time.

For most of the squeegees there appeared to be a trend of increasing solvent uptake as the Shore A hardness decreased. However, Squeegee 1 showed higher levels of solvent absorption compared with squeegees of the same hardness while Squeegee 2 showed lower levels of absorption.

Figure 5. Percentage change in squeegee mass during immersion in solvent blend used in carbon (wear) ink.

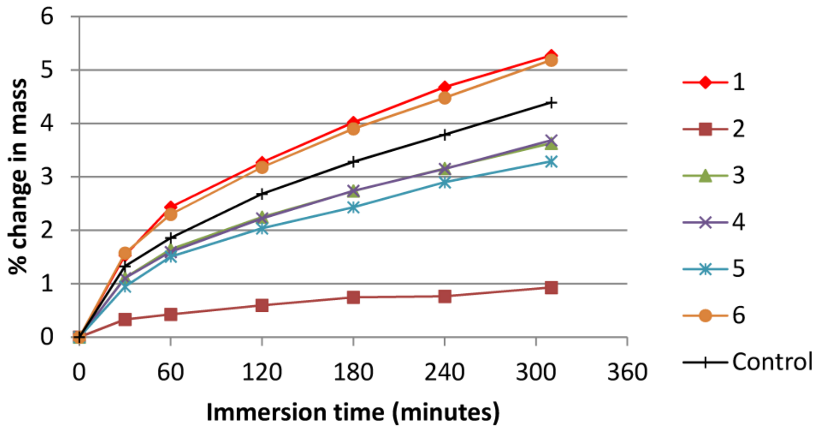
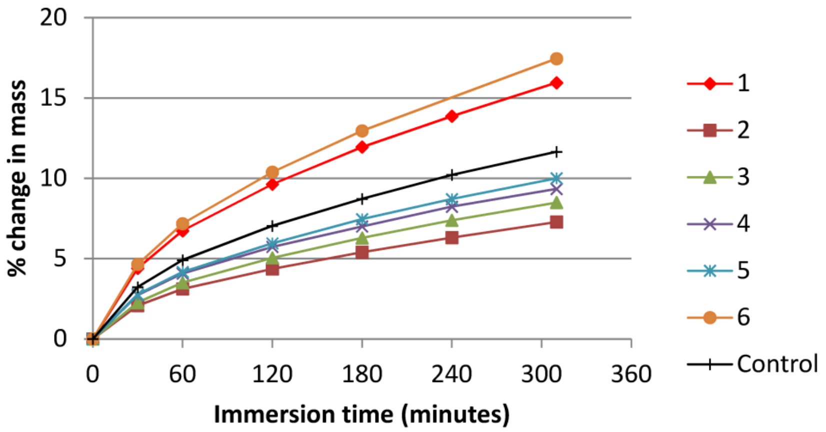


Figure 6. Percentage change in squeegee mass during immersion in ethylene glycol diacetate used in silver (print) ink.

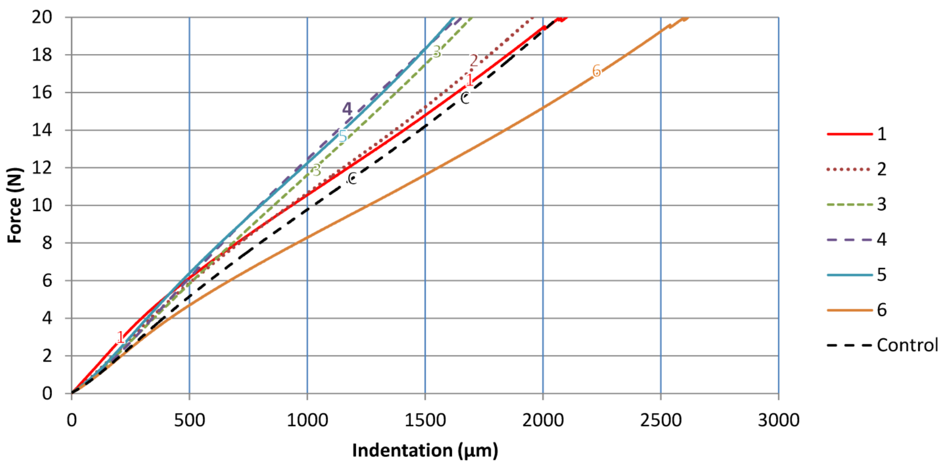


3.2. Surface Hardness of Squeegees

3.2.1. Untreated Squeegees

The force required for different levels of indentation is compared for all squeegees in Figure 7. The curves shown for each squeegee are the mean of five measurements. For the majority of the force-indentation curve, Squeegee 6 was the softest squeegee. The next softest was the control squeegee, followed by Squeegees 1 and 2. The remaining squeegees (3, 4 and 5) were the hardest and were fairly similar to one another. Plotting indentation *versus* Shore A hardness gave a linear relationship for a 10 N indentation force. However, in the low force part of the curve, Squeegee 1 was noticeably more resistant to indentation than the other squeegees and did not fit the trend. The Shore A hardness test will only cover a single force and does not give any information where low forces are concerned. As the indentation increases, the force-indentation curve for Squeegee 1 crosses over those of most of the other squeegees, so that at mid to high force levels, it appears to be one of the softer squeegees.

Figure 7. Force *vs.* indentation for untreated squeegees.



3.2.2. Solvent Treated Squeegees

The force required for different levels of indentation is compared for all squeegees when treated with the carbon ink and silver ink solvents in Table 4. In order to compare the squeegees more readily, indentation levels are shown for all squeegees before and after solvent treatment at 5 N indentation force.

Table 4. Indentation levels of squeegees at 5 N indentation force with and without solvent treatment.

Squeegee	Untreated	Carbon Ink Solvent		Ethylene Glycol Diacetate	
	Indentation (µm)	Indentation (µm)	Change (%)	Indentation (µm)	Change (%)
1	386.8	444.2	14.8	501.0	29.5
2	421.5	416.0	−1.3	500.6	18.8
3	430.6	456.2	5.9	467.4	8.5
4	432.6	432.8	0.0	481.0	11.2
5	393.8	422.2	7.2	490.0	24.4
6	538.6	579.6	7.6	631.4	17.2
Control	484.8	514.0	6.0	544.8	12.4

Solvent ingress softened the squeegees and the solvent used in the silver ink had a greater effect as it was absorbed by the squeegees in greater amounts. Squeegee 1, which absorbed solvent more readily than most of the other squeegees, showed the greatest percentage reduction in surface hardness as a result of solvent ingress. Squeegee 2 showed very little ingress of carbon ink solvent and no noticeable change in surface hardness resulted. When the absolute levels of indentation are compared, Squeegee 1 was found to be the hardest squeegee at a low indentation force of 3 N in both untreated and solvent treated states. This was not observed when force levels were increased as Squeegee 1 became softer in comparison with the other squeegees. This is similar to the observations made with the untreated squeegees.

In general, a greater reduction in hardness was associated with greater solvent ingress. However, there was not a straight-forward relationship between solvent uptake and loss in surface hardness. Squeegee 6, for example, absorbed more solvent than most of the other squeegees but this was not reflected in the changes in surface hardness, which were comparable to the changes seen in squeegees which absorbed less solvent. However, Squeegee 6 was already substantially softer than the others prior to solvent addition. Squeegee 2 showed very little mechanical response to carbon ink solvent but responded much more strongly to the silver ink solvent, despite absorbing less of this than any of the other squeegees.

3.3. Deflection of Squeegees

The relationship between squeegee deflection and force is shown in Figure 8. The data shown is the average of five measurements (reading one was discarded). As the squeegee is deflected, progressively more force is required to increase the bending angle. The force response was not smooth due to occasional slip at the contact between the squeegee and the supporting rods. The data suggests that at large amounts of deflection, Squeegee 5 was the most resilient to bending, followed by 4, 2, 1 and 3, the control squeegee and finally Squeegee 6. However, when looking at smaller levels of deflection, which are more representative of screen printing, Squeegee 1 appeared to be the most resistant to bending. This has parallels with the observations made in the indentation testing, and there is a good correlation between the indentation produced at 5 N with the force required to deflect the squeegee to 3 mm (approximately 8°). Likewise there is a correlation at higher forces; and the correlation between Shore A hardness and deflection improves at higher amounts of deflection. This suggests that Shore A hardness is a more suitable indicator for squeegee behavior when under high deflection. However, behavior under low deflection, or indentation force, cannot always be inferred from Shore A hardness data. This is particularly true of Squeegee 1, which shows higher comparative hardness at low indentation than at higher indentations.

The data from squeegee testing was compared with ink film thickness data from the print tests for unworn squeegees (print methods detailed in Table 3, ink film thickness data in Table 6). The optimum predictor of ink thickness was found to be the force measured at 3 mm squeegee deflection. With the exception of Squeegee 6, there was a general pattern of increasing ink deposition with decreasing resistance to deflection (Figure 9). This is due to the squeegee exerting a greater pressure on the screen and being forced in to the open areas of the mesh. Excluding Squeegee 6 there was an R^2 value of 0.92, indicating a good correlation. When considering indentation force, again with the exception of Squeegee 6, there was a general pattern of increasing ink deposition with decreasing resistance to indentation. The correlation was less effective with an R^2 value of 0.77 at an indentation force of 5 N. Finally, Shore A hardness gave the worst correlation with ink film thickness with an R^2 value of 0.47. Squeegee 1 did not fit the pattern when Shore A was used, for reasons outlined previously, which further demonstrates that Shore A hardness cannot necessarily reflect the behavior of a squeegee during printing. Analogous to selecting a softer squeegee, the softening of squeegees by solvent absorption has been shown to cause increased ink deposition [14]. This should increase over time as the squeegee progressively absorbs solvent.

Figure 8. Force *vs*. deflection tool displacement for squeegees.

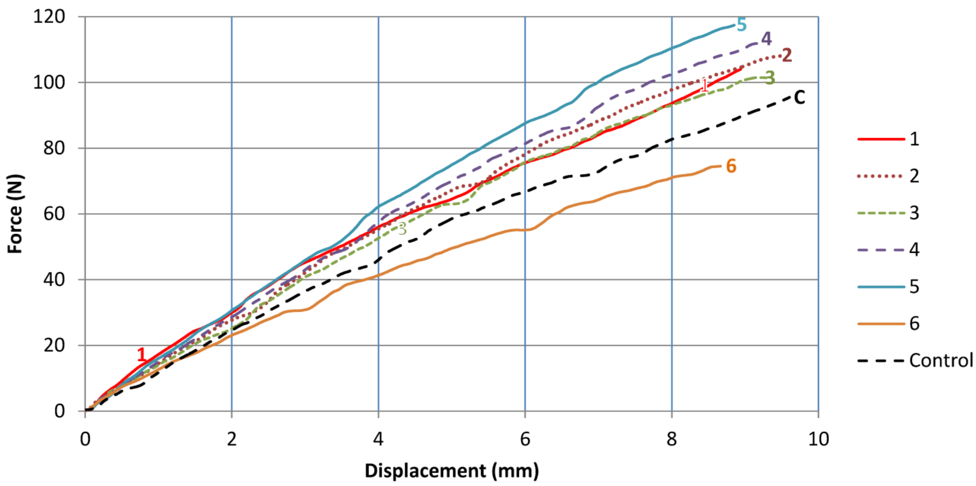
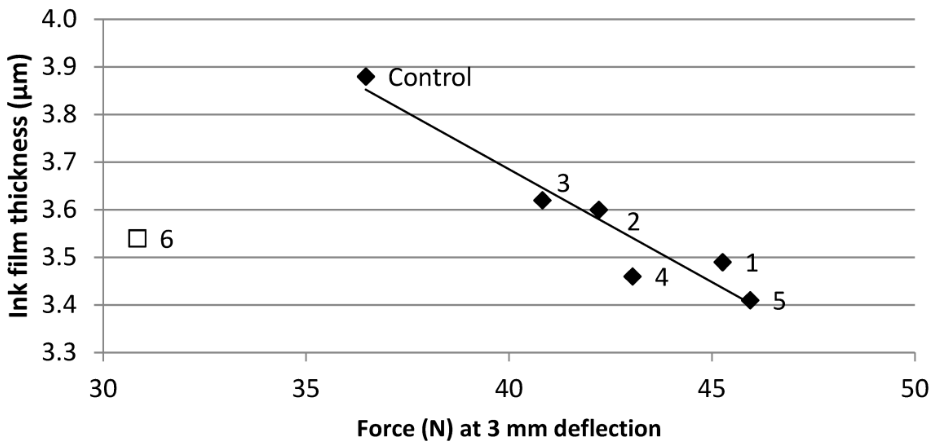


Figure 9. Ink film thickness *vs*. force required to deflect squeegee (R^2 0.92 when Squeegee 6 not included).



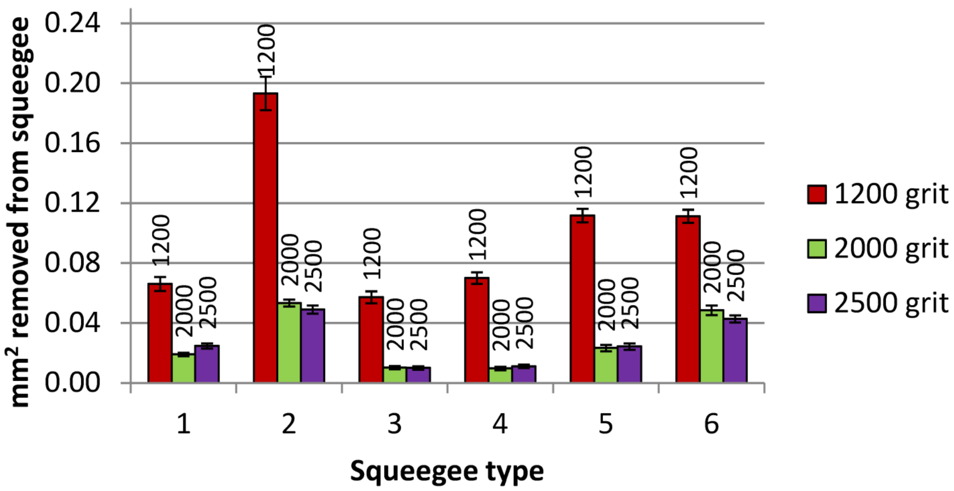
3.4. Squeegee Wear

The amount of wear, in terms of cross-sectional area removed from the squeegee and wear angle, is shown for the three wear bands (1200, 2000 and 2500) and for each squeegee in Table 5. The squeegee removal is also shown graphically in Figure 10. The roughest abrasive (1200 grit) gave the highest amount of wear, while the less rough papers (2000 and 2500 grit) gave less wear but were fairly similar to each other. For the roughest abrasive (1200 grit), the lowest amount of wear was observed in Squeegee 3, followed by 1 and 4, though all three were broadly similar with between 0.057 and 0.070 mm^2 removed. Squeegees 6 and 5 gave more wear than 1, 3 and 4, and performed similarly with 0.111 and 0.112 mm^2 removed. The most wear was observed in Squeegee 2 with 0.193 mm^2 removed; significantly more than any of the other squeegees. For the 2000 grit abrasive, Squeegees 3 and 4 gave the least wear, followed by 1, 5, 6 and finally 2. For the 2500 grit abrasive, Squeegee 3 gave the least wear, followed by 4, 5, 1, 6 and finally 2. For both 2000 and 2500 abrasives, Squeegees 2 and 6 gave substantially more wear than Squeegees 1, 3, 4 and 5. Overall, across all the abrasive types, the least wear was observed in Squeegee 3. Squeegees 2 and 6 were inferior to the other squeegees in terms of their resistance to wear.

Table 5. Squeegee cross-sectional area removed and wear angle after 50 wear cycles with different silicon carbide abrasives. Standard deviation shown in parentheses.

Squeegee Number	Removal (mm^2)	Wear Angle (°)	Removal (mm^2)	Wear Angle (°)	Removal (mm^2)	Wear Angle (°)
	1200 grit		2000 grit		2500 grit	
1	0.066 (0.005)	49.3	0.019 (0.001)	51.9	0.025 (0.002)	53.7
2	0.193 (0.011)	44.4	0.053 (0.002)	43.2	0.049 (0.003)	43.8
3	0.057 (0.004)	46.2	0.010 (0.001)	46.4	0.010 (0.001)	46.2
4	0.070 (0.004)	48.3	0.010 (0.001)	49.0	0.011 (0.001)	48.1
5	0.112 (0.005)	46.3	0.023 (0.002)	49.7	0.024 (0.002)	47.9
6	0.111 (0.004)	45.5	0.048 (0.003)	47.8	0.043 (0.002)	47.0

Figure 10. Squeegee cross-sectional area removed after 50 wear cycles with different silicon carbide abrasives. Error bars show standard deviations.



The angle of wear differed depending on the squeegee type. Squeegee 1 had the highest wear angle, with more wear apparent from the bottom of the squeegee than from the face. The lowest wear angles were observed on Squeegee 2, with the other squeegees showing intermediate wear angles. There appeared to be a rough correlation between the ability of a squeegee to flex and the wear angle; the squeegees most resistant to bending tended to give the highest wear angles. The ratios of wear for the roughest abrasive to wear with the other abrasive materials was not consistent. So for example, Squeegee 4 showed seven times more wear with 1200 grit abrasive than for 2000 grit abrasive but Squeegee 6 showed only 2.3 times more wear with 1200 grit abrasive than for 2000 grit abrasive. The other squeegees showed intermediate wear ratios for the different abrasives.

3.5. Geometry and Electrical Resistance of Printed Silver Lines Using Unworn Squeegees

The geometry of the printed lines is described in terms of the average ink film thickness over the width of the line and the average line width over the measured length of the line. The dry ink contained in that line is thus ink film thickness multiplied by line width. This can be used as an indicator of ink consumption.

For prints made on the unworn squeegees, the ink film thickness varied between the different line orientations and widths, the different positions along the squeegee and between the different squeegees. The average data for all measurements on each unworn squeegee is shown in Table 6. The average film thicknesses ranged from 3.41 to 3.62 µm (*i.e.*, a 6% increase from thinnest to thickest ink film) for the test squeegees, and were higher for the prints made with the control squeegee. The correlations with squeegee flexure, hardness, *etc.,* are detailed previously. There was a general decline in line width over the course of the experiment as demonstrated by the lower line widths recorded in the Control end when compared with Control start. Ink film thickness was also lower in the final control prints than in the starting control prints (by 3%). This suggested that there was some drying in the mesh during the printing that reduced ink transfer. However, the effect should be minimal between prints made with unworn and worn edges of the same squeegee.

Table 6. Ink film thickness, line width and line resistance for unworn squeegees. Averaged over all measurements.

Squeegee Number	Ink Film Thickness (µm)	400 µm Line Width (µm)	600 µm Line Width (µm)	400 µm Line Resistance (Ω)	600 µm Line Resistance (Ω)
1	3.49	346.9	541.8	7.93	4.72
2	3.60	334.5	531.5	8.24	4.65
3	3.62	338.6	534.1	8.17	4.79
4	3.46	323.5	525.0	8.80	5.00
5	3.41	316.9	513.3	9.38	5.41
6	3.54	313.2	510.2	9.33	5.40
Control start	3.88	380.5	577.1	5.87	3.74
Control end	3.76	326.8	524.4	8.17	4.66
Percentage drift	−3.1%	−14.1%	−9.1%	+39.2%	+24.6%

The mean standard deviation in ink film thickness over all sets of nine measured lines (for the various squeegee type, line width and orientation combinations) was 0.12 µm which is 3.3% of the mean ink film thickness. For line width this was 9.5 and 7.6 µm for 400 and 600 µm lines respectively (2.9% and 1.4% of the mean line widths). For line resistance this was 0.22 and 0.17 Ω for 400 and 600 µm lines respectively (2.6% and 3.4% of the mean resistances). The orientation of the printed lines affected the ink film thickness. Lines produced in the print direction (perpendicular to the squeegee) tended to have a greater amount of ink deposition than those printed at 90° to the print direction. This is described in more detail in the following section.

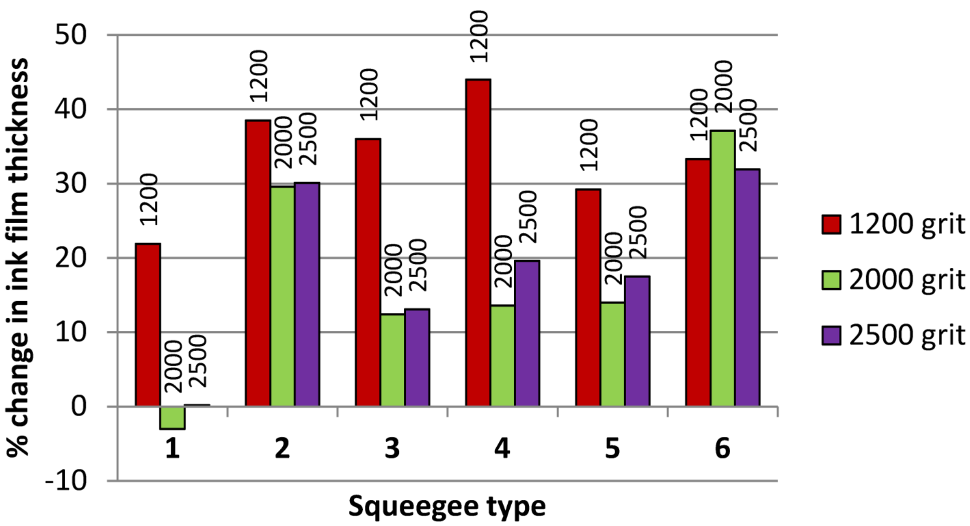
3.6. Geometry and Electrical Resistance of Printed Silver Lines Using Worn Squeegees

The effect of wear on print geometry is shown in terms of the percentage change in printed line thickness and line width when moving from unworn to worn squeegees [*i.e.*, 100 × (thickness worn−thickness unworn)/thickness unworn]. The average effect of wear on the ink film thickness, width, overall ink deposition (cross-sectional area) and resistance of printed lines are shown for each squeegee and abrasive type in Table 7. The change in ink film thickness is illustrated graphically in Figure 11.

Table 7. Percentage change in printed ink film thickness, line width, ink deposition and line resistance as a result of squeegee wear. Data as average for all measured lines.

Squeegee	Change in Ink Film Thickness (%)			Change in Line Width (%)		
	1200 grit	2000 grit	2500 grit	1200 grit	2000 grit	2500 grit
1	21.9	−3.0	0.2	3.0	−0.2	0.5
2	38.5	29.6	30.1	7.9	5.4	6.7
3	36.0	12.4	13.1	5.9	0.6	1.1
4	44.0	13.6	19.6	6.9	0.7	1.9
5	29.2	14.0	17.5	5.9	−0.3	1.9
6	33.3	37.1	31.9	4.7	5.4	7.6
Squeegee	**Change in Deposition (%)**			**Change in Line Resistance (%)**		
	1200 grit	**2000 grit**	**2500 grit**	**1200 grit**	**2000 grit**	**2500 grit**
1	25.5	−3.1	0.8	−21.1	3.1	1.5
2	49.5	36.6	38.8	−33.2	−29.8	−27.8
3	44.0	13.0	14.5	−34.1	−33.2	−17.8
4	53.9	14.4	21.9	−37.0	−12.7	−19.1
5	36.8	13.7	19.7	−29.3	−17.4	−22.4
6	39.5	44.6	41.9	−30.3	−37.8	−32.3

Figure 11. Percentage change in printed ink film thickness as a result of squeegee wear (average for all measured lines).



Worn squeegees, for the most part, gave greater ink film thickness than unworn squeegees. This was most severe in the higher levels of wear given by the roughest, 1200 grit abrasive, with Squeegee 1 showing the lowest increase in ink film thickness due to wear (average 21.9% increase overall). This was followed by Squeegees 5, 6, 3, 2 and 4 with overall increases up to 44%. For the mid roughness abrasive, Squeegee 1 showed a small decrease of 3% in ink film thickness due to wear while the other squeegees all increased their ink film thickness, in varying amounts, between 12.4% and 37.1%. For the smoothest abrasive, Squeegee 1 showed only a negligible increase in average ink film thickness of 0.2% while the other squeegees all increased their ink film thickness, in varying amounts, between 13.1% and 31.9%. There was a print defect in Squeegee 3 for the mid wear range lines at 90° to the print direction. This caused break-up in the lines and the formation of satellite drops of ink around the line but was not observed with any of the other squeegees, in either worn or unworn states, or for lines printed in the print direction. Squeegee 1 was the best performing in terms of maintaining consistency in the print as a result of wear and there was a marked contrast between its performance and that of the other squeegees. Of the remaining squeegees, 3, 4 and 5 were substantially better than 2 and 6 when using the 2000 and 2500 abrasives but this was not the case for the roughest 1200 abrasive. The wear levels for the roughest abrasive would be unlikely to be tolerated in practice. Variability within the individual sets of measurements was similar to that measured for the unworn squeegees (standard deviation of 0.13 µm, 3.0% of the mean).

Squeegee wear tended to influence line width in a similar way to ink film thickness but the effect on overall deposition was generally lower. Squeegee wear also tended, for the most part, to increase the width of the printed lines up to a maximum of around 8%, depending on the squeegee and abrasive type, but showed decreased line width in some instances. Squeegee 1 showed the least variation in line width between worn and unworn squeegees. Overall, Squeegees 3, 4 and 5 gave intermediate behavior, while 2 and 6 generally gave the greatest increase in printed line width. The 2000 and 2500 abrasives gave only marginal changes in line width for Squeegees 1, 3, 4 and 5, while Squeegees 2 and 6 showed more substantial changes for these abrasives. Variability within the individual sets of measurements was similar to that measured for the unworn squeegees (standard deviation of 9.7 µm and 8.9 µm for 400 and 600 µm lines respectively: 2.8% and 1.7% of the mean line widths respectively).

Ink film thickness, line width, and hence ink deposition generally increased with the amount of wear on the squeegee. However, the dominant factor in the deposition was the change in ink film thickness rather than the width of the line. In line with the trends for ink film thickness and line width, Squeegee 1 gave the smallest changes in ink deposition between worn and unworn states. For, the roughest abrasive, an increase in ink deposition of 25.5% was recorded for Squeegee 1, while the other squeegees showed increases between 36.8% and 53.9%. For the mid roughness abrasive, Squeegee 1 showed a small decrease of 3% in ink deposition due to wear while the other squeegees all increased deposition, in varying amounts, between 13% and 44.6%. For the smoothest abrasive, Squeegee 1 showed only a negligible change in deposition (+0.8%) while the other squeegees all increased deposition, in varying amounts, between 14.5% and 41.9%. The small reduction in deposition observed in Squeegee 1 for the 2000 abrasive was most likely within the inherent variability in the process and the gradual drying in the mesh (demonstrated by the change in the control prints). There was not an intermediate increase in ink deposition for the 2000 grit abrasive. However, this abrasive did not produce intermediate wear levels (Figure 10).

For squeegees worn with the roughest, 1200, abrasive, there was a reduction in electrical resistance for all printed lines. The average reduction was between 21% (Squeegee 1) and 37% of the initial values, depending on the squeegee type. This was due to the increase in ink deposition from the worn squeegees, primarily due to the increased ink film thickness but also increased line width, as described previously. Reductions in ink film deposition gave the higher resistances noted for Squeegee 1 when using the 2000 and 2500 abrasives. For the mid roughness abrasive, Squeegee 1 showed a small increase of 3% in line resistance due to wear while the other squeegees all showed a reduction in resistance, in varying amounts between 12.7% and 37.8%. For the smoothest abrasive, Squeegee 1 showed only a very small increase in resistance of 1.5% while the other squeegees all gave reduced resistances, in varying amounts between 17.8% and 32.3%. For worn squeegees mean standard deviations in resistance were 0.13 Ω (2% of mean) and 0.20 Ω (5.2% of mean) for 400 and 600 μm lines respectively.

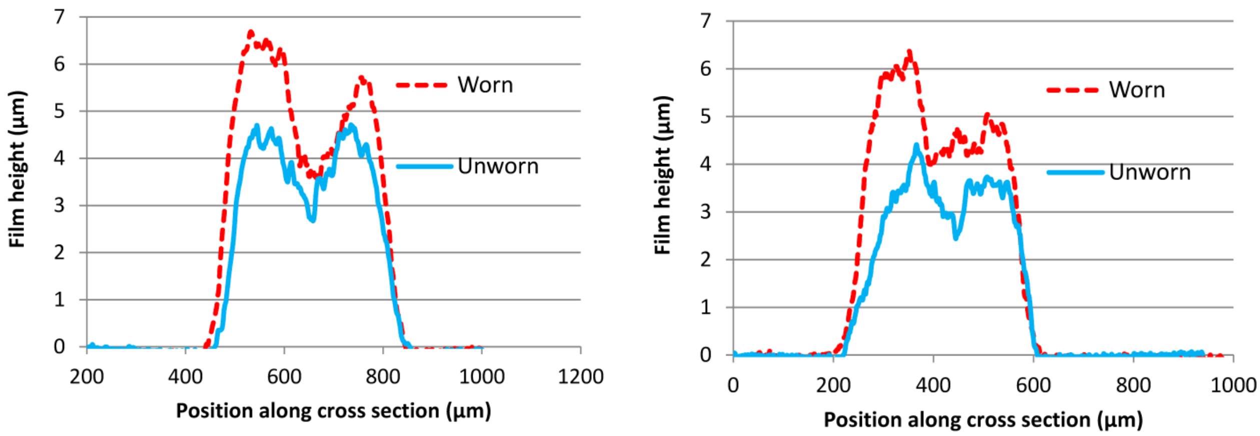
The effect of wear on the print varied depending on the orientation of the printed lines. Ink film thickness in unworn and worn states, as well as the percentage change in printed ink film thickness resulting from squeegee wear, is shown both in the print direction and at 90° to the print (parallel to the squeegee) in Table 8.

Table 8. Printed ink film thickness (μm) in unworn and worn states and percentage change in ink film thickness as a result of squeegee wear for lines printed in the print direction and at 90° (parallel to squeegee).

Squeegee		Printed Ink Film Thickness (μm)											
		1200 grit				2000 grit				2500 grit			
		Line Width 400 μm		Line Width 600 μm		Line Width 400 μm		Line Width 600 μm		Line Width 400 μm		Line Width 600 μm	
		Print	90°	Print	90°	Print	90°	Print	90°	Print	90°	Print	90°
1	Unworn	3.69	3.11	3.91	3.47	3.58	3.15	3.62	3.45	3.55	3.14	3.65	3.57
	Worn	4.26	3.98	4.72	4.27	3.36	3.13	3.47	3.42	3.46	3.24	3.54	3.69
	Change (%)	15.4	28.2	20.8	23.1	−6.1	−0.5	−4.3	−1.0	−2.6	3.4	−3.1	3.2
2	Unworn	4.02	3.12	4.21	3.60	3.51	3.26	3.69	3.62	3.58	3.08	3.93	3.62
	Worn	5.00	4.69	5.68	5.21	4.49	4.24	4.90	4.62	4.45	4.29	4.94	4.76
	Change (%)	24.2	50.1	34.9	44.6	27.9	30.2	32.8	27.4	24.3	39.0	25.5	31.5
3	Unworn	3.61	3.39	4.13	3.56	3.74	3.26	3.83	3.59	3.64	3.17	4.07	3.45
	Worn	5.05	4.46	5.48	4.98	4.16	N/A	4.35	N/A	3.97	3.76	4.21	4.18
	Change (%)	39.9	31.4	32.7	40.0	11.1	N/A	13.7	N/A	9.1	18.6	3.5	21.1
4	Unworn	3.75	2.98	3.80	3.38	3.56	3.44	3.57	3.61	3.41	2.98	3.71	3.35
	Worn	5.01	4.46	5.59	4.94	4.05	3.64	4.25	4.17	3.86	3.70	4.21	4.27
	Change (%)	33.5	49.4	47.1	46.1	14.0	5.9	19.1	15.5	13.2	24.2	13.5	27.4
5	Unworn	3.69	3.35	3.81	3.73	3.45	3.10	3.39	3.39	3.33	2.91	3.37	3.40
	Worn	4.76	4.23	5.23	4.63	3.96	3.54	4.07	3.63	3.62	3.53	4.04	4.09
	Change (%)	29.0	26.4	37.3	24.1	15.0	14.1	20.0	6.9	8.7	21.2	19.9	20.2
6	Unworn	3.97	3.37	4.30	3.57	3.71	3.07	3.50	3.17	3.37	3.21	3.71	3.60
	Worn	4.97	4.61	5.40	5.18	4.49	4.43	4.83	4.60	4.35	4.30	4.87	4.78
	Change (%)	25.4	36.8	25.7	45.2	21.0	44.4	38.1	44.9	29.3	34.0	31.3	32.8

For lines printed at 90°, there tended to be a greater increase in ink deposition (as a proportion of unworn ink film thickness) as a result of wear than for lines produced in the print direction. However, it should be noted that ink film thicknesses in both unworn and worn states were lower for lines printed at 90°. In this orientation, it is postulated that there is greater "scooping-out" as the squeegee is less restricted by the stencil after travelling over the edge of the stencil. For lines printed at 90°, there was also a greater increase in ink film thickness on the leading edge of the line when compared with that on the trailing edge. However, for lines deposited in the print direction, wear related increases in ink film thickness were observed more equally on both edges of the lines. Regardless of line orientation, the middle of the line was lower than the edges. This is illustrated in Figure 12, sample graphs of the cross-sectional profiles of different orientation lines before and after wear. It is postulated that this greater ink deposition after wear is due to the worn edge of the squeegee no longer being able to deform into the mesh to the same extent as the unworn squeegee. This effect varied depending on the squeegee type, the amount of wear and the orientation of the lines.

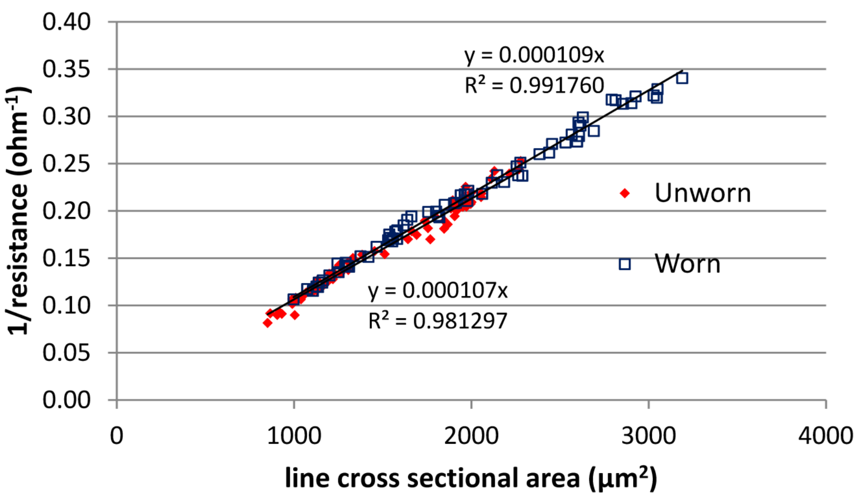
Figure 12. Sample images of variation in ink deposition (cross-section) as a result of squeegee wear at different orientations: (**a**) Parallel to print direction (90° to squeegee); (**b**) 90° to print direction (parallel to squeegee); using 1200 grit abrasive, Squeegee 4. Note this effect varies depending on squeegee/abrasive types.



(**a**) (**b**)

The relationship between the ink deposition (cross-sectional area of the printed lines—ink film thickness × line width) and the reciprocal of the measured line resistance is shown in Figure 13. The relationship was very similar regardless of whether the lines were printed with the worn or unworn squeegees. There was a linear relationship with high R^2 values. While the worn squeegees gave a general increase in ink deposition, which gave a reduction in line resistance, there was no deviation from the relationship which would suggest print defects, such as broken lines, which would lead to higher than expected resistances. The data confirms that resistance measurements are sufficient to accurately characterize the amount of ink deposition for silver prints made with unworn and worn squeegees.

Figure 13. Correlations between ink deposition (line cross-sectional area) and line resistance.



3.7. Discussion

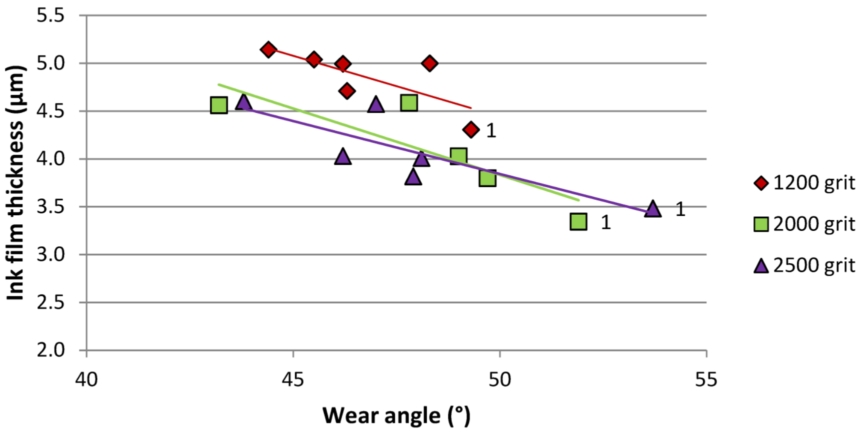
The indentation and bending tests described in this report have been able to characterize the squeegees in a more effective manner than traditional Shore A hardness measurement. Measuring indentation at a lower pressure than a Shore A hardness meter gives data which is more representative of what occurs during printing, while squeegee deflection tests offered an even better correlation with ink film thickness. However different values will be obtained if any of the settings such as pin or deflection tool geometry are altered. The method of immersing only one surface of the squeegee in solvent, coupled with the indentation method, allowed solvent related softening of the squeegees to be reliably measured. Solvent absorption softens the squeegee which should lead to an increase in ink transfer as indicated both by the correlation between hardness and ink transfer and by previous work [14]. Squeegee hardness after exposure to solvent could also be linked with wear characteristics and there appeared to be a correlation between squeegee hardness and the amount of wear, with harder squeegees wearing more. However, this was only observed at a 5 N indentation force and did not apply at higher forces, or indeed when using Shore A hardness. It was also only apparent when solvent treated indentation data was used and this observation should therefore be treated with caution. Both squeegee hardness and pressure should influence the amount of wear but these factors will interact, with a harder squeegee having a higher pressure. The squeegee contact needs to be better understood so that wear can be anticipated from measurable squeegee parameters. Furthermore, each squeegee responded differently to the various abrasives. The amount of wear from one abrasive could not be used to anticipate the wear from another and there was not a consistent ratio of wear for a certain abrasive against wear for another.

There were distinct differences in the amount of wear observed in the different squeegees and a large range in the effects of this wear on the printed lines. There was a general trend of increasing wear levels giving greater levels of ink film thickness and line width and hence reduced line resistance for silver lines. The effect of wear on ink film thickness was more significant than the effect on line width. During production, such an increase in ink transfer would lead to an increase in ink consumption as well as a variation in the quality of the printed features. In the case of functional screen printing for electronics or sensors, this would have an effect on the functional of the end product, while for graphics the appearance of the product would be affected. This would have cost implications in terms of ink consumption but would also lead to greater product failure and rejection.

White *et al.* [9] state that ink flux through the screen is proportional to the square root of the squeegee tip curvature; provided other factors remain unchanged. Although this is based on modeling using a Newtonian fluid, when screen printing inks are usually shear thinning, worn squeegees should give greater ink transfer as their sharp edges are gradually rounded. It is proposed that the change in line geometry is due to a reduced ability for the squeegee to deform into the mesh and displace the ink from the mesh. However, the relationship between the amount of wear and ink deposition was not straightforward and depended on the squeegee. Squeegee 1 suffered similar levels of wear to other squeegees yet it was much more effective at maintaining consistency in the print. Even with the wear suffered in 2000 and 2500 abrasives, the squeegee remained usable. The others squeegees all showed substantial increases in ink deposition (up to 44%) indicating that they would not be useable at this point and would consume much higher amounts of ink in the printing process.

The higher comparative resistance to both indentation and flexing at lower forces, previously noted, suggested that Squeegee 1 would print with a high pressure which would give a reduced ink film thickness. This also influences the angle of wear, which changes the effective squeegee angle during printing and in turn also affects the ink film thickness. The influence of wear angles on ink film thickness is shown in Figure 14. The ink film thickness appears to be affected by a combination of squeegee wear angle and the amount of squeegee removed during wear. Squeegee 1 had both the highest wear angles and the lowest ink film thickness after wear, despite other squeegees having lower levels of wear. The combination of resistance to bending and a high wear angle presents a sharper edge and higher pressure at the squeegee/screen interface. This reduces the ink film thickness.

Figure 14. Ink film thickness *vs*. wear angle in worn squeegees.



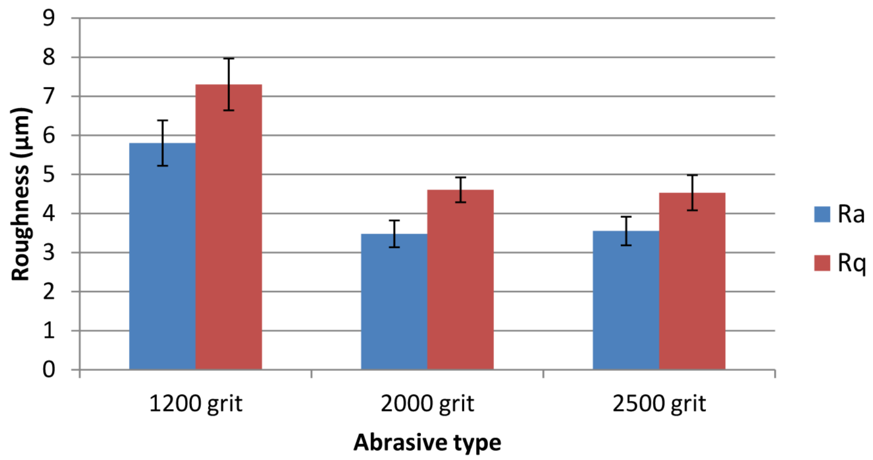
The controlled wear did not, apart from one line orientation for Squeegee 3, cause any print defects, such as breakages, pinholes in the lines, or satellite drops of ink around lines that would be detrimental to their electrical performance. This highlights the benefit of a controlled wear methodology rather than testing squeegees worn through printing which might suffer nicks or other uneven damage and cause broken lines. Wear trials performed using both silver and carbon inks on a screen with a blocked mesh, did not show such levels of wear, even after thousands of cycles.

The roughest abrasive material gave very high levels of wear which would not be tolerated in practice. This was reduced when using smoother abrasives but still gave substantial increases in ink consumption for most squeegees. There was a drift in the print characteristics over the duration of the printing experiment with a small reduction in ink film thickness was observed but a more noticeable reduction in line width. This also gave an increase in line resistance. Assuming this is a gradual effect related to ink build-up in the mesh, the drift anticipated between the sequential prints of an unworn and worn state of a given squeegee is only a small pro-rata proportion of this. Averaged over all features this would be of the order of 0.25% for ink film thickness and less than 1% for line width. This would not be significant for most of the observations, where large changes in deposition were observed.

The 2000 and 2500 grit abrasives did not appear to differ substantially from one another, either in their ability to abrade the squeegee or change the ink deposition after wear. The particle size of the intermediate 2000 grit abrasive was closer to that of the 2500 grit than the 1200 grit abrasive. There might also be some variations in pressure due to the positions of the different bands which will affect wear. Preliminary analysis of the surface topography of the abrasives using white light interferometry

[Veeco NT2000 (Veeco Instruments, Inc., Plainview, NY, USA) with array size 305 µm × 232 µm] suggested that roughness characteristics, in terms of average and root mean squared roughness surface roughness (R_a and R_q respectively) were very similar for 2000 and 2500 grit abrasives (Figure 15). An alternative intermediate 1500 grit abrasive has a particle size profile much closer to the 1200 grit abrasive and hence would be expected to give wear results more similar to that.

Figure 15. Surface roughness data for abrasives obtained using white light interferometry. Five measurements per abrasive type with error bars showing standard deviations.



The ink used in the wear testing can be selected to match a particular application. The various inks use different solvents which will affect how the squeegee abrades. This is particularly relevant for novel formulations whose effect on squeegee material is unknown.

During printing, squeegee wear would be expected to be inconsistent and localized, due to varying topography from the patterning in the screen and possible build-up of material in certain areas over time. This would then give rise to localized variations in ink film thickness within the printed sheet. Although these experiments do not simulate the localized defects that would occur during printing, the findings are applicable in terms of the consequences of wear on the print.

4. Conclusions

A reliable accelerated wear test has been developed for squeegees used in screen printing. Mechanical tests have also been developed which allow more in-depth measurement of squeegee properties than currently used tests. These measurements have subsequently been used to establish correlations with print quality both before and after wear. Squeegee wear differed between different squeegee types and caused increases in ink transfer and wider printed lines. This will lead to greater ink consumption and therefore cost per unit and an increasing likelihood of product failure or rejection, particularly for functional layers used in printed electronics. While more wear generally gave greater increases in ink deposition, the effect of wear differed, depending on the squeegee and the orientation of the line. There was a correlation between the angle of the squeegee wear and ink film thickness from a worn squeegee. A higher ability to resist flexing gave a higher wear angle. This in turn presented a sharper edge at the squeegee/screen interface thus mitigating the effect of wear.

Increases in ink deposition gave lower electrical resistance in printed silver lines; however, the correlation between the amount of ink deposit and the resistance remained the same, for all levels of wear. This suggested that the wear regime designed for this study did not induce detrimental print defects such as line breakages. Therefore resistance can be used as a rapid indicator of changes in conductive ink transfer.

Squeegee indentation at different force levels gave more information than a standard Shore A hardness test and the apparatus used was able to reliably measure reductions in surface hardness due to solvent ingress. Indentation data obtained at low forces was a better indicator of the likely effect of squeegee hardness on ink deposition than Shore A. However, the mechanical resistance of the squeegee to deflection was found to be the most effective predictor of ink film thickness as it indicates the pressure at the squeegee-screen interface.

Acknowledgments

This work was part funded by Trelleborg Applied Technology. The authors wish to thank Paul Habberfield from Trelleborg and Eifion Jewell from SPECIFIC, Swansea University for their help and advice with this work.

Author Contributions

Christopher Phillips prepared the manuscript, performed wear and print tests, measured and assessed squeegee characteristics. David Beynon worked on print tests, surface profiling and electrical measurement of print samples. Simon Hamblyn worked on wear tests and wear method development. Glyn Davies, David Gethin and Timothy Claypole contributed towards development of the squeegee wear and characterization methods.

Conflicts of Interest

The authors declare no conflict of interest.

References

1. Krebs, F.C.; Jørgensen, M.; Norrman, K.; Hagemann, O.; Alstrup, J.; Nielsen, T.D.; Fyenbo, J.; Larsen, K.; Kristensen, J. A complete process for production of flexible large area polymer solar cells entirely using screen printing—First public demonstration. *Sol. Energy Mater. Sol. Cells* **2009**, *93*, 422–441.
2. Rotureau, D.; Viricelle, J.-P.; Pijolat, C.; Caillol, N; Pijolat, M. Development of a planar SOFC device using screen-printing technology. *J. Eur. Ceram. Soc.* **2005**, *25*, 2633–2636.
3. Shi, Y.S.; Zhu, C.-C.; Wang, Q.; Li, X. Large area screen-printing cathode of CNT for FED. *Diam. Relat. Mater.* **2003**, *12*, 1449–1452.
4. Pardo, D.A.; Jabbour, G.E.; Peyghambarian, N. Application of screen printing in the fabrication of organic light-emitting devices. *Adv. Mater.* **2000**, *12*, 1249–1252.

5. Lee, M.-Y.; Lee, M.-W.; Park, J.-E.; Park, J.-S.; Song, C.-K. A printing technology combining screen-printing with a wet-etching process for the gate electrodes of organic thin film transistors on a plastic substrate. *Microelectron. Eng.* **2010**, *87*, 1922–1926.
6. Viricelle, J.-P.; Riviere, B.; Pijolat, C. Optimization of SnO_2 screen-printing inks for gas sensor applications. *J. Eur. Ceram. Soc.* **2005**, *25*, 2137–2140.
7. Qi, Q.; Zhang, T.; Yu, Q.J.; Wang, R.; Zeng, Y.; Liu, L.; Yang, H.B. Properties of humidity sensing ZnO nanorods-base sensor fabricated by screen-printing. *Sens. Actuators B Chem.* **2008**, *133*, 638–643.
8. Crouch, E.; Cowell, D.C.; Hoskins, S.; Pittson, R.W.; Hart, J.P. Amperometric, screen-printed, glucose biosensor for analysis of human plasma samples using a biocomposite water-based carbon ink incorporating glucose oxidase. *Anal. Biochem.* **2005**, *347*, 17–23.
9. White, G.S.; Breward, C.J.W.; Howell, P.D.; Young, R.J.S. A model for the screen-printing of Newtonian fluids. *J. Eng. Math.* **2006**, *54*, 49–70.
10. Fox, I.J.; Bohan, M.F.J.; Claypole, T.C.; Gethin, D.T. Film thickness prediction in halftone screen-printing. *Proc. Inst. Mech. Eng. E* **2003**, *217*, 345–359.
11. Owczarek, J.A.; Howland, F.L. A study of the off-contact screen printing process. II. Analysis of the model of the printing process. *IEEE Trans. Compon. Hybrids Manuf. Technol.* **1990**, *13*, 368–375.
12. Pan, J.; Tonkay, G.L.; Quintero, A. Screen printing process design of experiments for fine line printing of thick film ceramic substrates. *J. Electron. Manuf.* **1999**, *9*, 203–213.
13. *BS ISO 1817:2011 Rubber, vulcanized or thermoplastic—Determination of the effect of liquids*; British Standards Institution: London, UK, 2011.
14. Jewell, E.H.; Claypole, T.C.; Gethin, D.T. The effect of exposure to inks and solvents on squeegee performance. *Surf. Coat. Int. B* **2004**, *87*, 253–260.
15. *BS ISO 7619–1:2010 Rubber, vulcanized or thermoplastic—Determination of indentation hardness. Part 1: Durometer method (Shore hardness)*; British Standards Institution: London, UK, 2010.
16. *BS ISO 37:2011 Rubber, vulcanized or thermoplastic—Determination of tensile stress-strain properties*; British Standards Institution: London, UK, 2011.
17. *BS ISO 4649:2010 Rubber, vulcanized or thermoplastic—Determination of abrasion resistance using a rotating cylindrical drum device*; British Standards Institution: London, UK, 2010.