Improving the Speed and Resolution of Screen-Printing for Industrial Applications

I. J. Fox [*], M. F. J. Bohan, T. C. Claypole, and D. T. Gethin

Keywords: High-speed, screen-printing, roller squeegee, numerical simulation

Abstract

Screen-printing is frequently used to print inks containing complex materials, such as those found in biomedical sensors, low density semi conductors and smart packaging. Screen-printing has the advantage of being able to print inks that frequently contain large functional particulates, while enjoying exceptional product consistency. The variation for print to print is the smallest of any volume printing process. However, the print speed that can be achieved by the screen-printing process is lower than other volume processes, such as flexo or litho. Thus, it is difficult to integrate screen directly with packaging lines. As part of screen-printing press development, fundamental issues relating to the fluid dynamics and mechanics of the process have been examined. This has led to the development of a novel squeegee system that enables the printing of high resolution through fine meshes at high speed.

This paper first reviews the current performance of screen for industrial printing applications. Based on this review, a new design of roller squeegee was developed that reduces friction. The performance of the squeegee has been evaluated both experimentally and theoretically using numerical modelling. The new design allows higher speeds without loss of quality and paves the way for the improved productivity of existing screen-printing and for the long term integration of screen with other volume print processes.

---

[*] Email; i.j.fox@swansea.ac.uk

Welsh Centre for Printing and Coating, School of Engineering, University of
Wales Swansea, Singleton Park, Swansea, SA2 8PP, U.K.

1 Introduction

Screen-printing holds a unique position in the printing industry in that it is capable of printing almost any ink onto practically any surface. Screen-printing is used as a manufacturing process for the production of biomedical sensors, circuit boards, trim finishing as well as smart packaging and semi-conductors. It also has its advantages in that it is one of the most consistent, reproducible and predictable printing processes available. This results in minimal product to product variation, which is critical in industrial printing applications. However, the main disadvantage of screen-printing is the relatively slow speeds, thus preventing its benefits from being applied in conjunction with the high volume printing processes. To increase the speed of screen-printing, rotary screen-printing presses have been developed where speeds up to 125m/min are achievable (Hunt, 1999). The process works by having a rotary screen to form a drum. This is commonly constructed from elecro-deposited nickel, with the chosen printing design stencilled onto the screen to create the open printing area. The process is capable of printing heavy ink deposits, but at relatively low resolution.

The aim of this work is to demonstrate the ability to screen print at increased speeds with a novel design of squeegee. Firstly, the paper briefly reviews the screen-printing process. It then examines the science of the process and through this it leads to the development of a roller squeegee that is capable of high-speed printing without the loss of resolution.

2 High-Speed Industrial Screen-Printing

High-speed screen-printing can be achieved with rotary screen-printing presses. However, the increased speeds and the continuous motion of such presses result in an increase in wear when blade squeegees are used. For this reason, roller squeegees are often employed to reduce the friction, where the diameter is usually small enough to allow the ink to flow over the squeegee. The parameters of such a press, incorporating a roller squeegee, have been investigated (Hawkyard and Miah, 1987), where it was suggested that there is significant hydrodynamic pressure within the paste wedge and that it is closely connected with the effective squeegee angle. This can be seen to increase as the angle between the squeegee and the screen decreases. It is also highlighted that a roller squeegee will produce a greater hydrodynamic pressure than that of a squeegee blade, due to the roller squeegee system having two moving surfaces as oppose to one moving surface acting on the ink. Amongst the results that were discovered, it was found that a higher volume of ink penetrated the fabric when a larger squeegee diameter was used. This was postulated to be caused by the larger diameter squeegees increasing the contact time and contact width, resulting in greater ink deposits. It was shown experimentally that the volume of ink applied decreases sharply with an increase in printing speed when using smaller diameter squeegees. Whereas when using a larger diameter squeegee there is very little decrease in the volume of ink applied.

Using the theory that a roller squeegee has an increase in contact area and a reduced squeegee angle, which gives an increased ink deposit, blunt or rounded squeegee blades can be used where higher ink coverage is required. This is largely been attributed to the squeegee failing to remove all of the ink from the screen and the remaining ink on the screen surface is then drawn through the mesh open area, immediately after snap-off, and onto the substrate producing the increase in ink deposit (Sefar, 1999) (Screen Process, 1991).

Although it has been shown that printing can be achieved using roller squeegees, this has previously been in applications where the resolution has not been of particular importance. The work reported in this paper is the development of a high-speed roller squeegee design capable of high-resolution based on a scientific understanding of the process. This will lead to further advantages such as reduced stencil and screen wear and the increased speeds will allow screen-printing to become integrated with the higher speed printing processes. Ultimately this will allow advantages such as screen-printing of smart packaging applications to be incorporated within gravure, flexo and offset process lines.

3 Roller Squeegee Design

The roller squeegee comprised of an aluminium core covered with a deformable elastomer coating of approximately 6mm thickness and a hardness of 70 Shore A hardness. Preliminary work into high-resolution screen-printing using a roller squeegee has shown that successful printing depends upon the complete rolling action of the squeegee (Anderson, 1997). For this reason, a small motor was mounted near to the squeegee to positively drive it. To study the impact of different squeegee diameters, two diameters were manufactured, notably 30mm and 50mm. The roller squeegee and drive mechanism were mounted onto a flat-bed, single station screen-printing press, where the press can be seen in Figure 1 with the squeegee mechanism in Figure 2.

Figure 1 Single Station Flat-bed Press

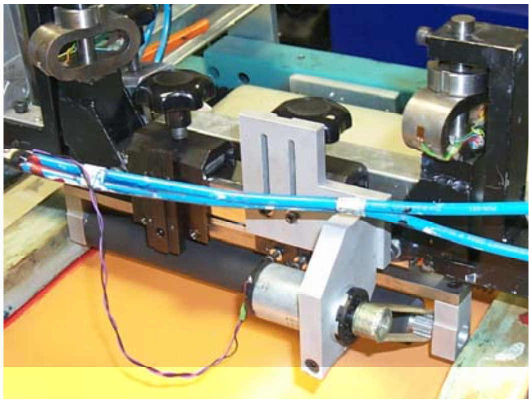

Figure 2 Roller Squeegee Mechanism

4 Experimental Study

Initial Experimental Study

The initial experimental trials used a solvent-based ink so that the viscosity of the ink could be readily adjusted with the addition of the appropriate solution. The manufacturers recommend that the highest resolution of mesh used with this ink contains no more than 120 threads per cm. A higher mesh count than this will reduce the effective ink volume within the screen, which will result in a decrease in the drying time of the ink where it may then dry in the open areas of the screen, thus preventing it from being printed. To reduce the viscosity of the ink and to delay the drying time of the ink, 15% thinners and 15% retarder were added to the ink. The printed image areas were created with a capillary stencil containing gradations ranging from 3% to 100% in line rulings of 85lpi, 100lpi and 120lpi.

A blade squeegee of medium hardness was used to produce an image using the aforementioned screen to enable the experimental programme to be cross-referenced to conventional screen prints. The squeegee speed and pressure were set to 0.4ms^{-1} and 3.0b respectively, with a snap-off gap set to 4.5mm. this produced a well defined, sharp image, indicating appropriate settings for successful screen-printing using a blade squeegee, Figure 3.

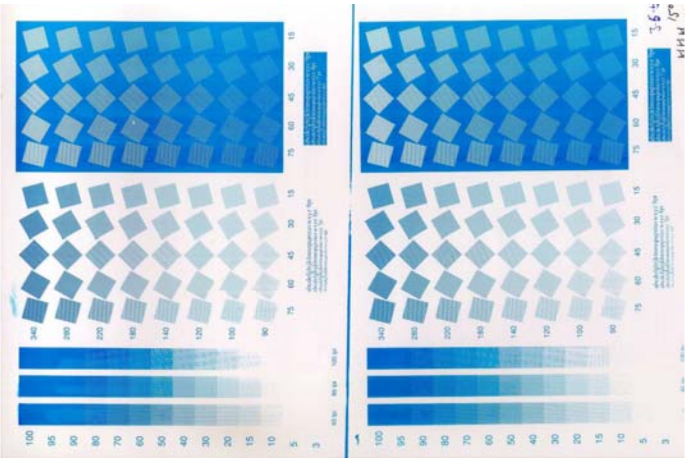

Figure 3 Blade Squeegee Printed Sample Using 120-34 Screen

A series of experiments were then carried out where the blade squeegee was replaced with a roller squeegee whilst keeping the same settings as used with the blade squeegee tests. Initial results with the 50mm diameter squeegee resulted in a considerable amount of ink remaining on the screen after the print stroke. Additionally, the image areas of more than 30% open area were flooded with ink and produced rivulets of ink on the substrate, Figure 4. The ink remaining on the screen after the printing stroke appeared to be drawn through the screen and onto the substrate at the point of the snap-off. This would then produce excessive ink transfer as observed.

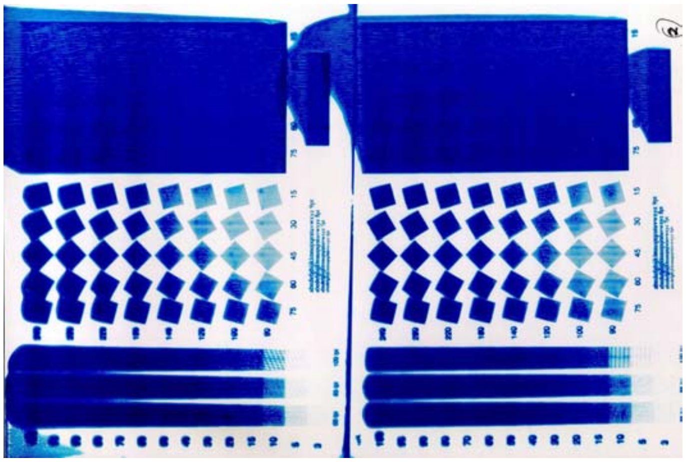

Figure 4 Roller Squeegee Printed Sample Using 120-34 Screen

In an attempt to remove the ink from the screen surface after the print stroke, the squeegee pressure was increased to a maximum of 4.5b. This was then repeated with the 30mm diameter squeegee. This produced no obvious improvement in image quality. The reduction of the viscosity of the ink also had a minimal effect on reducing the tone gain where formulations from 10% to 70% of thinners and retarder were investigated.

The roller squeegee produced a significant increase in the ink transfer compared to that of the blade squeegee. Four reasons were postulated for this occurrence;

- The ink not being removed from the screen after the printing stroke. This ink is then drawn through the screen and onto the substrate during the snap-off phase.
- The increased contact width, and therefore an increase in contact duration, of the roller squeegee upon the screen and the substrate compared to that of the blade squeegee. This will then allow more ink to be transferred through the screen and onto the substrate.
- The rotational effect of the squeegee could be inducing an increase in pressure within the bow wave of the ink. This pressure could be sufficient as to cause ink to be forced through the screen before contact is made with the screen and the substrate, effectively pre-printing in the bow wave
- The rotational effect of the squeegee could be increasing the hydrodynamic pressure distribution within the nip contact region of the squeegee, forcing more ink onto the substrate at the point of squeegee contact.

Although the highest resolution screen should be approximately 120 threads per cm when using solvent-based inks, it was decided to investigate a 150-34 screen. This would lead to a reduction in the ink volume within the screen and would also mean an increase in the flow resistance through the screen, thus a reduction in ink deposit should be observed. It was believed that the ink would not dry in the open areas of a 150-34 screen, as occurs with blade squeegees, as the quantity of ink left on the screen after the printing stroke would be sufficient as to prevent it from drying before it had been transferred to the substrate. However, as a precautionary measure to further prevent the ink from drying in the screen, the volume of thinners and retarder added to the ink was increased to 20%. Additionally, to provide a comparison between inks of different viscosity levels, a conventional UV ink was also investigated. Using the 150-34 screen, the two different ink types and the same press settings that were used in the previous trials, the resultant prints were clear, sharp and absent from excessive tone gain and rivulets, Figure 5.

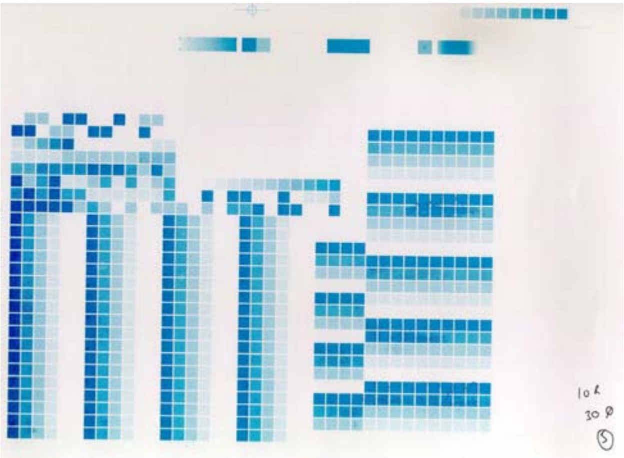

Figure 5 Roller Squeegee Printed Sample Using 150-34 Screen

As satisfactory printing was now possible, a parametric study was conducted to fully explore the process parameters and to develop a clear understanding of the criteria of roller squeegee screen-printing.

Parametric Study

Within the experimental programme, a number of parameters were maintained constant (Table 1). These were fixed as it was decided that the investigation of these particular parameters was not warranted until the effect of the other parameters had been established.

Parameter	Mesh tension	Snap-off gap	Flow-coat speed	Flow-coat gap
Setting	15Ncm^{-1}	4.5mm	0.4ms^{-1}	0.5mm

Table 1 Fixed Press Settings

Using the 150-34 screen and the squeegee pressure set to 4.5b, the two roller squeegees were used to print samples at 0.4 ms^{-1} and 0.8 ms^{-1}, using both the solvent-based and the conventional UV ink. To establish the effect of the squeegee rotation, experiments were carried out with the squeegee rotating and also with a lock applied to prevent the squeegee from rotating. This allows a direct comparison to be made between prints produced with two moving surfaces (where the squeegee is free to rotate) and one moving surface (where the squeegee was locked into position). In a full factorial analysis this will lead to 16 individual experiments, Table 2. In addition to the roller squeegee experiments, the blade squeegee used in the initial trials was also used to produce printed samples using identical settings to the roller squeegee experiments. This then allowed a direct comparison to be made between the roller squeegee printed samples and the blade squeegee printed samples. To minimise error five samples were produced at each experimental setting.

Speed (status)	Ink type		Squeegee diameter	
0.4ms^{-1} (Rotate)	Solvent-based	Conventional UV	30mm	50mm
0.8ms^{-1} (Rotate)	Solvent-based	Conventional UV	30mm	50mm
0.4ms^{-1} (Locked)	Solvent-based	Conventional UV	30mm	50mm
0.8ms^{-1} (Locked)	Solvent-based	Conventional UV	30mm	50mm

Table 2 Parametric Study Experimental Programme

The density of the tonal gradation, situated in the centre of the image area containing open areas ranging from 3% to 100%, were then measured for each test condition, where the five prints from each setting were averaged together to minimise error. These measurements were taken with a spectrophotometer, configured to measure the density, from which the tone gain characteristics can be calculated via the Murray Davies equation (Field, 1999).

Experimental Results

The tone gain plots for the UV ink, produced with the 30mm and 50mm diameter squeegees are shown in Figure 6 to Figure 9, with the results from the blade squeegee experiments also incorporated. In each case, there is a considerable amount of tone loss, with no tone gain occurring until printing above an open area of 80%. The curves show a higher tone gain for the roller squeegee than that of the blade squeegee, although this difference is not excessive and is never more than 8%. This increase in tone gain for the roller squeegee compared to the blade squeegee can be largely attributed to the increase in contact area of the squeegee point upon the print bed. Where the larger the contact area, such as when the roller squeegee is employed, then the longer the contact duration will become, thus enabling an increase in ink transfer rate onto the substrate. This contact duration phenomenon is then further supported where the larger diameter squeegee has produced a higher tone gain than the smaller diameter squeegee. An additional reason for the blade squeegee producing lower tone gain is the release rate of the printing screen from the substrate immediately after the printing stroke. This is commonly referred to the snap-off rate and the slower the screen releases from the substrate, then the more ink can be transferred through to the substrate. Hence, a point contact such as a blade squeegee will result in a much faster snap-off rate than a roller squeegee and should therefore produce a lower tone gain. The increase in speed produces a reduction in the tone gain, due to a reduced contact duration of the squeegee upon the screen and the substrate and an increased snap-off rate, thus limiting the ink transfer. The tone gain for the rotating roller squeegee can be seen to be slightly higher than that created with the locked roller squeegee. This is believed to be resulting from the increase in hydrodynamic pressure created by the two moving surfaces.

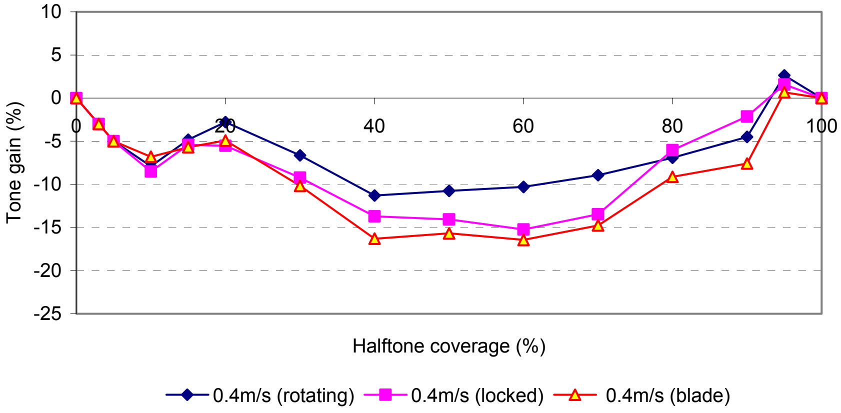

Figure 6 Tone Gain For 30mm Squeegee at 0.4ms^{-1} Using UV Ink

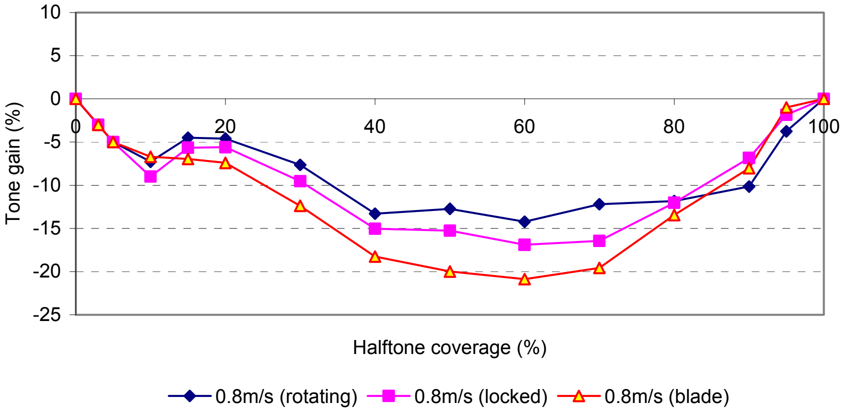

Figure 7 Tone Gain For 30mm Squeegee at $0.8ms^{-1}$ Using UV Ink

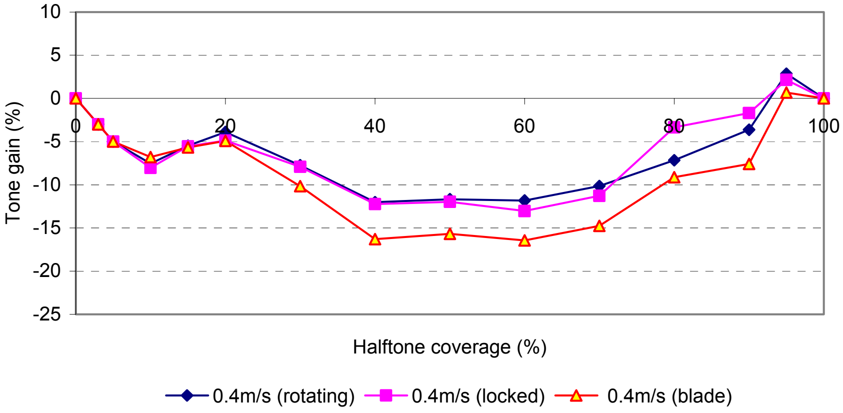

Figure 8 Tone Gain For 50mm Squeegee at $0.4ms^{-1}$ Using UV Ink

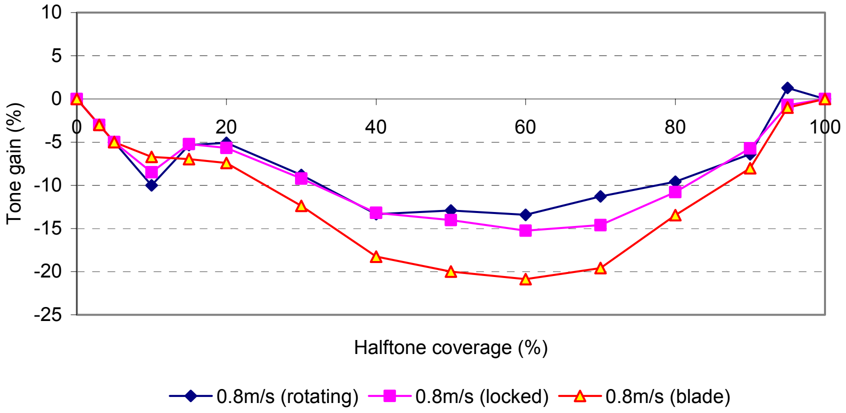

Figure 9 Tone Gain For 50mm Squeegee at 0.8ms^{-1} Using UV Ink

Figure 10 to Figure 13 depict the tone gain curves for the solvent-based inks produced with the two roller squeegees. The blade squeegee was not able to print this ink type through the 150-34 screen as the ink dried in the screen open areas before printing could be achieved. There is tone loss in the highlight region and tone gain in the shadow regions with the tone gain increasing as the diameter is increased. However, the difference in the tone gain between the two roller squeegees is considerably greater than that observed with the UV ink. This can be attributed to the different ink characteristics.

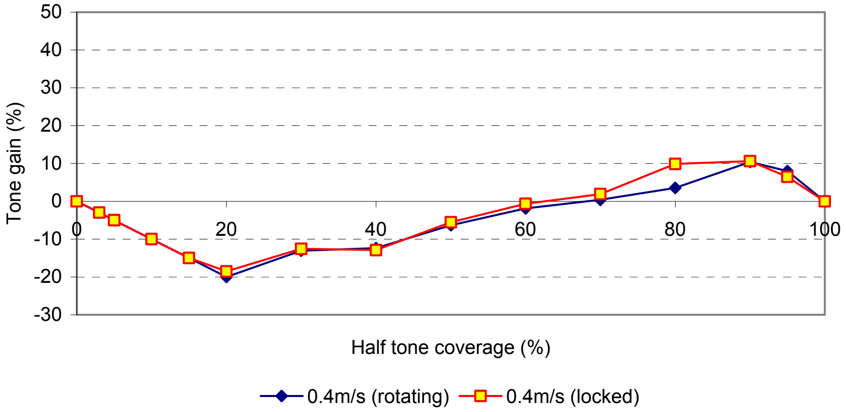

Figure 10 Tone Gain For 30mm Squeegee at 0.4ms^{-1} Using Solvent-Based Ink

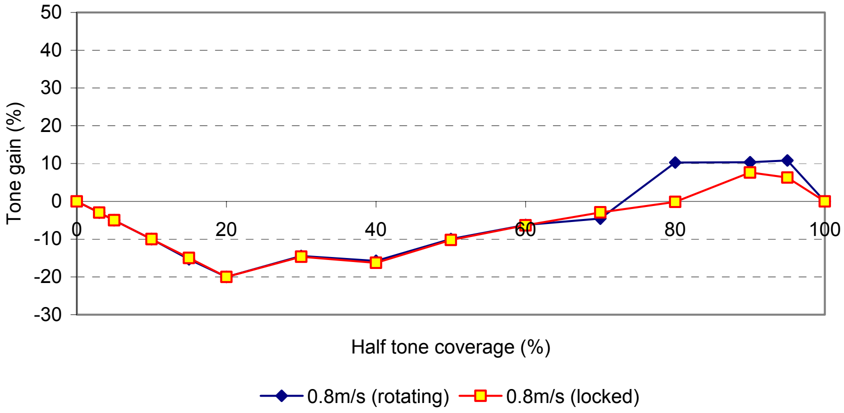

Figure 11 Tone Gain For 30mm Squeegee at $0.8ms^{-1}$ Using Solvent-Based Ink

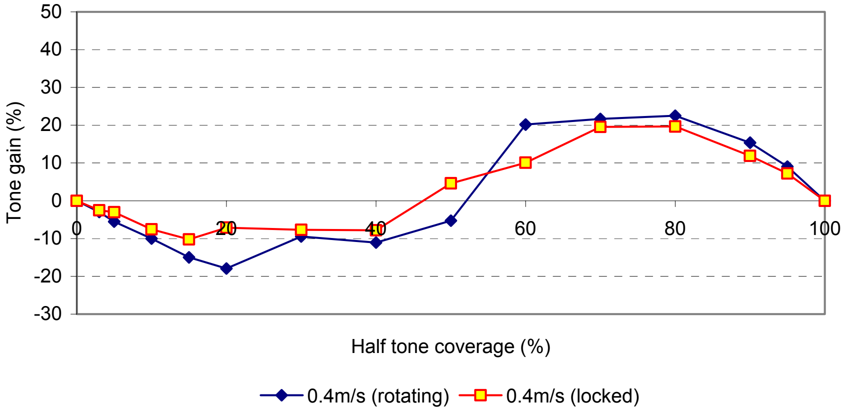

Figure 12 Tone Gain For 50mm Squeegee at $0.4ms^{-1}$ Using Solvent-Based Ink

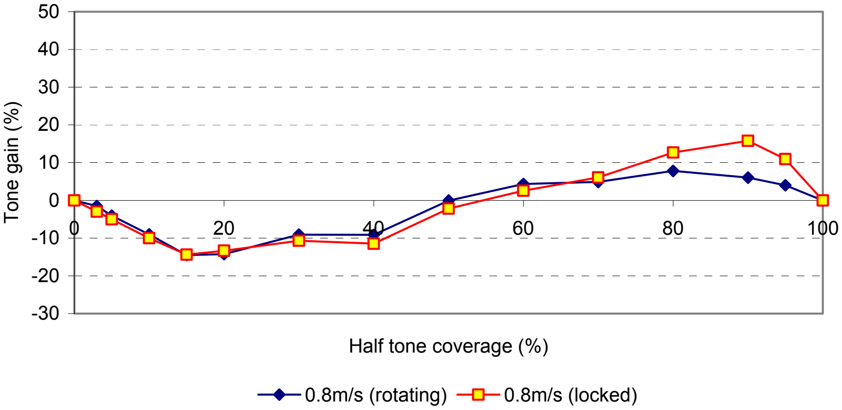

Figure 13 Tone Gain For 50mm Squeegee at 0.8ms^{-1} Using Solvent-Based Ink

Discussion

The tone gain curves for the roller squeegees are comparable to those produced with the blade squeegee, when using the conventional UV ink. The prints produced with a rotating or a locked roller squeegee are of similar quality to those produced with a traditional blade squeegee, although the friction of the screen upon the roller squeegee will be eliminated when it is rotating. However, the screen resolution must be at least 150-34 as to prevent excessive ink coverage. The blade squeegee failed to print with the solvent-based ink due to the ink drying in the open areas of the screen. Where as the roller squeegee did not remove the ink from the top surface of the screen after the printing stroke, thus the ink did not dry in the screen and successful printing was achieved. Therefore, using the roller squeegee, screen resolutions of 150 threads per cm can be used with solvent-based ink, thus creating a new niche market for high-speed, high resolution screen-printing with a roller squeegee, which is not achievable with conventional squeegee systems.

5 Numerical Study

A numerical procedure has been developed to simulate the ink flow through the nip contact region of a deformable roller squeegee. This enabled process simulations to be carried out to provide further understandings of the ink flow in the screen-printing process. This allowed the ink film thickness and the hydrodynamic pressure distribution within the nip junction to be calculated.

The work is an extension of previous work into the study of flow coats within roller trains in the coating industry (Carvalho and Scriven, 1997) (Lim et al, 1997), although the shear thinning effect of the squeegee upon the ink film and the local squeegee deformation will be demonstrated, as seen in similar work into this field (Bohan et al, 2002) (Fox, 2002). As the ink flows through the nip contact region, pressure is generated within the ink film. This pressure then deforms the squeegee, which then influences the ink film thickness in the nip contact region. The change in ink film thickness will then further affect the pressure distribution within the ink film. This type of problem is referred to as Soft Elasto Hydrodynamic Lubrication (SEHL) in a line contact and is likely to have a considerable effect on the ink transfer mechanism. To solve this solution numerically requires an iterative approach. This combines the pressure within the fluid, calculated through the Finite Difference Method, and the deformation of the squeegee, calculated using the Boundary Element Analysis. The governing equations of which have been derived in detail by Fox (2002) and Fox (2003)

Figure 14 shows an idealised section through the fluid domain in the nip junction and the analysis is subjected to the normal thin film lubrication assumptions and the governing equation reduces to a balance between pressure gradients and viscous stresses.

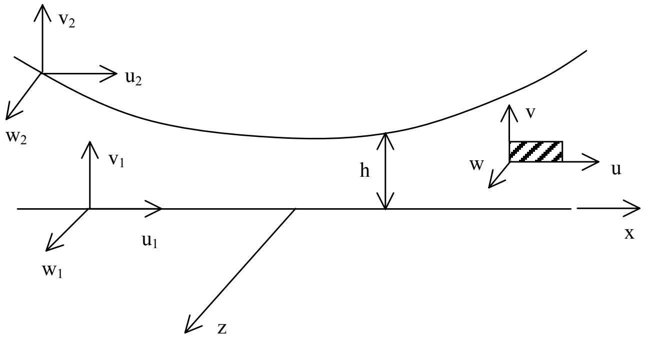

Figure 14 A Section through the Nip Junction

The ink film pressure profiles and the corresponding ink film thickness profiles, for the conventional UV ink, modelled with the rotating and the locked roller squeegee can be seen in Figure 15 and Figure 16 respectively. An increase in print speed with the rotating squeegee has a slight effect of moving the pressure profile towards the inlet region of the contact, with minimal effect on the overall pressure distribution, in accordance with previously published data (Bohan et al, 1997). The pressure profiles for the 50mm diameter squeegee have exhibited a greater contact width than the smaller squeegee, due to the difference in geometry. Overall, the 50mm diameter squeegee has produced a higher ink film thickness than the 30mm diameter squeegee, which has the effect of an increased pumping capacity. This will result in the ability of a higher quantity of ink to be transferred through the screen and onto the substrate, thus increasing the ink coverage, as observed in the experimental trials. Additionally, to promote an increase in flow through the junction, the ink film thickness increases as the speed increases. This will then have the effect of further increasing the pumping capacity of the squeegee. However, the increase in speed reduces the contact duration of the squeegee, which will result in a reduction in the ink deposit. Therefore, the pumping capacity of the squeegee and the squeegee contact duration both have a significant impact on the ink transfer rate.

When the squeegee is prevented from rotating, the pressure distribution profiles are almost identical to those produced by the rotating squeegee. However, compared to the rotating squeegee, locking the squeegee has resulted in a reduction in the ink film thickness. This can be attributed to a reduction in the viscosity of the ink, created by the increase in shear from the locking of the squeegee. The result of this is a reduction in the pumping capacity of the squeegee and will therefore produce printed images of a reduced ink coverage, which was again seen in the experimental trails.

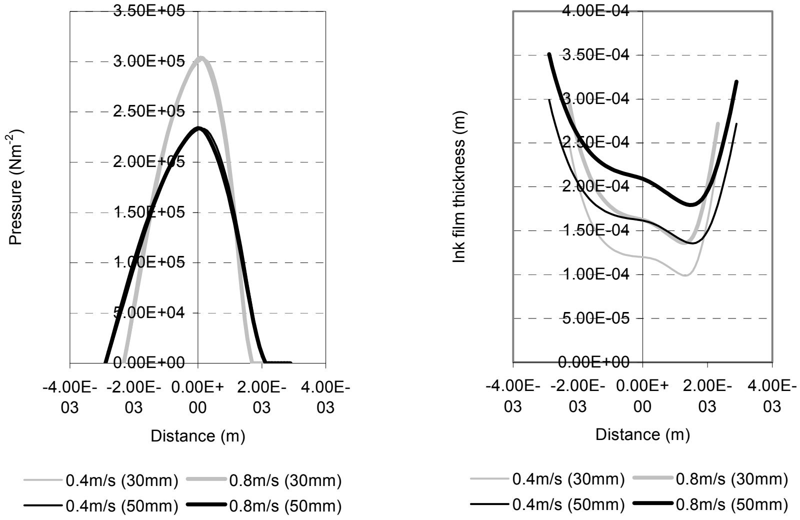

Figure 15 Film Pressure and Respective Ink Film Thickness for Rotating Roller Squeegee, Conventional UV Ink

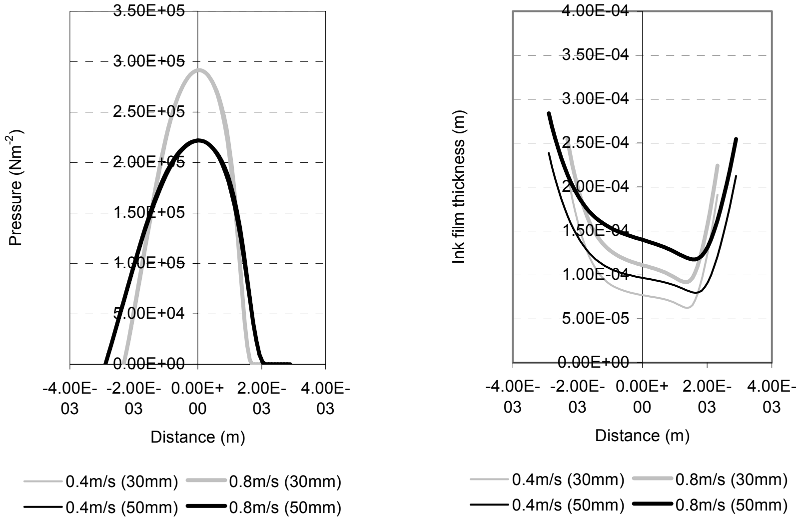

Figure 16 Film Pressure and Respective Ink Film Thickness for Locked Roller Squeegee, Conventional UV Ink

Figure 17 and Figure 18 show the ink film pressure profiles and the corresponding ink film thickness profiles for the solvent-based ink, modelled with the rotating and the locked roller squeegee. The pressure profiles and the contact widths are similar to those observed with the conventional UV ink, as the squeegee pressure and dimensions remain the same. However, the difference in viscosity of this ink compared to the conventional UV ink has resulted in a significant decrease in the ink film thickness. This has resulted in a much lower pumping capacity of the squeegee and the different viscosity ink has also resulted in the ink film thickness being less affected by a change in print speed.

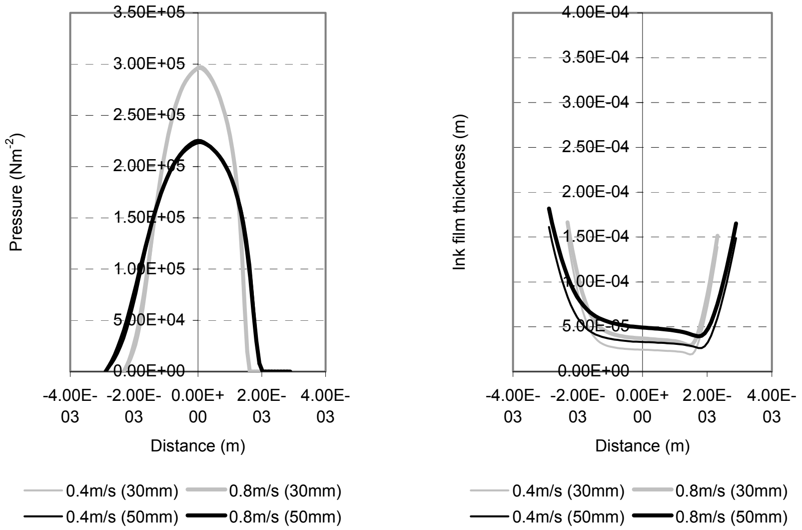

Figure 17 Film Pressure and Respective Ink Film Thickness for Rotating Roller Squeegee, Solvent-based Ink

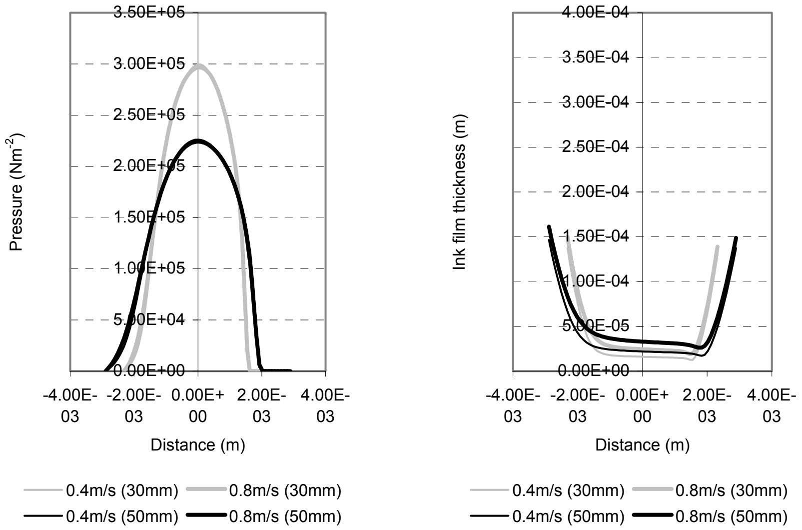

Figure 18 Film Pressure and Respective Ink Film Thickness for Locked Roller Squeegee, Solvent-based Ink

Discussion

The larger squeegee diameter generally produces a higher ink deposit than the smaller diameter squeegee. Previously, this was believed to be resulting from an increase in the contact duration and a decrease in snap-off speed. However, the numerical model has shown that a larger diameter roller squeegee produces a higher ink film thickness on the squeegee as well as an increased contact width. The numerical model also produced results where the ink film thickness increased with the print speed, which has resulted in a higher pumping capacity of the squeegee. This would then be expected to produce a higher ink coverage. However, the experimental studies showed that an increase in speed decreased the ink deposit and is believed to be as a result of a reduced contact duration and an increase in snap-off speed. Therefore, the ink film thickness on the squeegee and the contact duration of the squeegee upon the screen have a considerable effect upon the ink deposit that is generated.

With the squeegee locked, the experimental results produced lower ink deposits than if the squeegee were free to rotate. This was postulated to be as a result of the increase in the pressure generated by two moving surfaces. However, in the numerical model, there was a minimal difference in the pressure profiles when the squeegee was free to rotate or when it was locked. This occurrence of a lower ink coverage for the locked squeegee can be explained by the reduction in the ink film thickness, which has resulted in a reduction in the pumping capacity of the squeegee, thus allowing less ink to be transferred through the printing screen.

6 Conclusion

Printing with a roller squeegee proved to be successful and could be achieved with the squeegee rotating at the printing speed or locked, preventing rotation. The printed images were crisp, sharp and were absent from excessive ink coverage. These prints were comparable to those produced with a blade squeegee in terms of visual quality and tone gain.

The numerical investigations demonstrate that the larger the squeegee diameter, the higher the ink film thickness is on the roller squeegee. This will have the effect of increasing the pumping capacity of the squeegee, resulting in an increase in ink supply to the screen. Additionally, the increase in squeegee diameter will also increase the contact width, thus increasing the contact time of the screen upon the substrate, therefore further increasing the ink deposit.

When the roller squeegee was used, it failed to remove all of the ink from the top surface of the printing screen. This gives the advantage of when using solvent-based inks, the ink that remains on the screen after the printing stroke increases the drying time of the ink within the screen open areas. The result of this is a squeegee system that not only prints with a significant reduction in friction, but it also allows printing of solvent-based inks through high resolution screens. Previously, this has created problems with traditional squeegee systems as the ink dries in the open areas of the screen and prevents printing.

This work has shown both experimentally and numerically, that roller squeegee screen-printing can be achieved to the same resolution as seen with traditional blade squeegees. Ultimately, the rotating action of the roller squeegee will pave the way to new technologies with advantages such as reduced screen and squeegee wear, which will then lead to increased printing speeds being achievable and will therefore allow future screen-printing systems to be incorporated within other high volume printing systems.

Literature Cited:

Anderson J. T. *"An Investigation into the Physical Aspects of the Screen-printing Process."* Ph.D. Thesis, University of Wales Swansea, 1997.

Banerjee P. K., Butterfield R. *"Boundary Element Method in Engineering Science."* McGraw Hill, 1981.

Bohan M. F. J., Claypole T. C., Gethin D. T., Basri S. B. *"Application of BoundaryElement Modelling to Soft Nips in Rolling Contact."* 49th Annual TAGA Tech. Conf., Quebec City, Canada, May 1997.

Bohan M. F. J., Fox I. J., Claypole T. C., Gethin T. D. *"Numerical Modelling of Elastohydrodynamic Lubrication in Soft Contacts Using Non-Newtonian Fluids."* International Journal of Numerical Methods for Heat and Fluid Flow. Volume 12, Number 4, 2002.

Brebbia C. A., Dominguez J. *"Boundary Elements: An Introductory Course."* McGraw Hill, 1989.

Brebbia C. A., Walker S. *"Boundary Element Techniques in Engineering."* Newnes-Butterworths, 1980.

Carvalho, M.S. and Scriven, L.E. *"Deformable Roller Coating Flows: Steady State and Linear Perturbation Analysis"*, Journal of Fluid Mechanics, 339, 1997, p143-172.

Dowson D; *"A Generalized Reynolds Equation for Fluid Film Lubrication."* Int. J. Mech. Sci. Vol. 4, pp159-pp170, 1962.

Field G. G. *"Color and its Reproduction."* Second Edition, GATF Press, 1999.

Fox I. J. *"Ink Flow Within the Screen-Printing Process."* Ph.D. Thesis, Mechanical Engineering, University of Wales Swansea, 2002.

Fox I. J., Claypole T. C., Bohan M. F. J., Jewell E. H., Gethin D. T.,*"Ink Film Thickness Prediction in Half Tone Screen-Printing."* Submitted, Proceedings of the Institute of Mechanical Engineers. Part E, 2003.

Hawkyard C. J., Miah A. S. *"The Parameters of Rotary Screen-printing."* Journal of the Society of Dyers and Colourists. Vol. 103, January 1987.

Hunt B; *"Rotary Screen's Flexible Face for Labels,"* Screen and Digital Printer, pp48-pp50, Nov/Dec 1999.

Lim, C.H., Bohan, M.F.J., Claypole, T.C., Gethin, D.T. and Roylance, B.J. *"A Finite Element Investigation Into a Soft Rolling Contact Supplied by a Non-Newtonian ink"*, J. Phys. D: Appl. Phys, vol. 29, pp 1894-1903, 1996.

Miles LWC; *"Textile Printing."* Bradford Dyers Company Publications Trust, 1981.

Scott GE; *Rotary Screen-printing: A Revolution in Wallcovering Production;* Journal of the Oil and Colour Chemists Association. Vol. 72, No. 9, September 1989.

"Handbook for Screen Printers." Published by Sefar AG Printing Division, Sefar Mesh and Technology, February 1999.

"What Every Printer Should Know About Squeegees." Screen Process, Novenber1991, pp27-pp29.