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Considerations on bulged-out print shoulders due to mesh depression and high 'emulsion over mesh' in screen printing

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Abstract

In screen printing sometimes at the edges of an ink deposit that is wider than a few millimetres a phenomenon occurs, which can be described as an elevated edge or better as bulging-out shoulders. This can be a print quality issue if subsequent overprints need to be carried out. The shoulder bulge-out effect typically occurs if the stencil build-up is not well adapted to the targeted type of print pattern (e.g. fine lines vs. large solid tone areas). The effect is described in screen printing textbooks and some scientific articles but not yet tackled theoretically. As an approach, here a simple model, assuming a quasi-infinite line as the pattern to be printed is used. The model combines the elongation of the mesh caused by the mesh tension and the additional stress applied by the squeegee with material properties and calculates the depression of the mesh towards the substrate during the squeegee movement between the two edges of the stencil opening. The developed relationship ends up in an equation that is solved numerically by means of a look-up-table (LUT) approach. Graphs are derived that show the dependencies on print line width, stencil build-up, stresses applied and materials used.

Keywords: print quality, squeegee pressure, mesh elongation, ink deposition

1. Introduction

During recent years, screen printing is experiencing a kind of renaissance. It is increasingly regarded as a reliable, high-level quality prolific process. The focus is on medium to high volume functional and industrial printing. In industrial printing, the accuracy of the geometrical properties of the prints such as edge definition and surface smoothness is much more important, rather than colour matching as in graphic applications. One effect known in screen printing that will be investigated theoretically in this paper is the case where the bulging-out shoulders occur if the stencil build-up is not well adapted to the targeted feature sizes of the print (e.g. fine lines vs. large solid tone areas). The effect is described in handbooks (SEFAR, 2008), online guidebooks (Hobby, 1997) or scientific articles (Riemer, 1989). The stencil build-up, which is commonly called emulsion over mesh (EOM), can be one of the reasons for the shoulder bulge especially if the EOM is too high. Even though the stencil can be prepared in many different ways, the typical way is coating a liquid photosensitive emulsion onto the mesh or applying a so-called capillary film to the mesh. Both have advantages and disadvantages but with a capillary film, the control on the EOM is easier. Typically, experienced printers know which EOM-values achieve good printing results but theoretical background is missing. Figure 1 shows the situation (not drawn to scale) when the squeegee presses the printing form down onto the substrate. Here, the EOM is quite high and in the vicinity of the stencil-edge, the squeegee is not able to press down the mesh to touch the substrate, at all. Somewhere towards the centre of the print area, however, the squeegee pressure brings the mesh and the substrate into contact. Thus, at the edges, a higher amount of ink is squeezed through the mesh and deposited there in comparison to the centre of the printed area where the threads of the mesh touch the substrate. One of the targeted questions here is how the width of the printed line affects the bulge-out effect. Experienced printers estimate that if the width is about 2 mm or higher the likelihood of shoulder bulging-out significantly increases. This is confirmed by Riemer in his dissertation (Riemer, 1988) but not analysed further. Important to mention is that the snap-off distance does not play a role in this investigation as it is assumed that the squeegee pressure is high enough to press both of the stencil edges tightly down to the substrate.

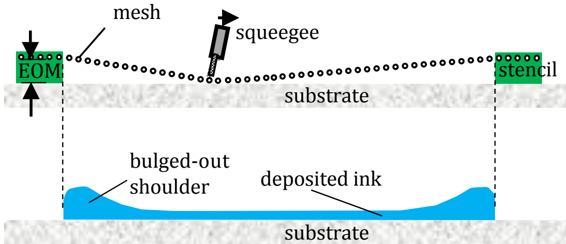

Figure 1: Shoulders bulge-out can occur at the edges of a printing area due to a very high EOM

In a former investigation at the same research institute (Willfahrt, Stephens and Hübner, 2011), the bulge-out effect could be proven quantitatively. According to Figure 2, a pronounced bulging effect can be seen for the 3-mm line (conductive track), whereas the smaller lines have a single peak, only. However, the maximum heights of the smaller lines are significantly larger than that of the 3-mm line.

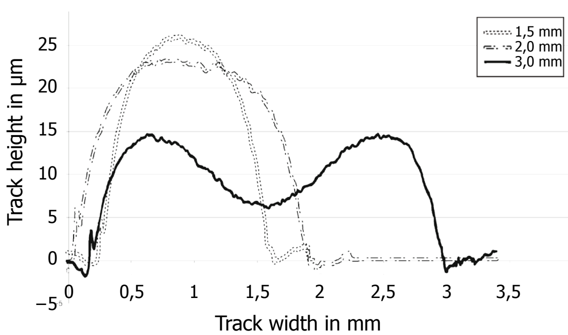

Figure 2: Cross section profile of three printed lines (conductive tracks), from Willfahrt, Stephens and Hübner (2011)

2. Research methods

2.1 Assumptions

During the printing process, the squeegee moves from left to right applying a certain vertical force, the squeegee pressure. The physical and geometrical properties will be idealised (e.g. the squeegee touches the mesh in a single infinitely small contact point) and it is assumed that a line with an infinite length (in squeegee-width direction) is printed. The dimensions in squeegee-width direction are much greater than the width of the printed line. This corresponds well to functional screen printing where mostly lines with conductive inks are printed. The length is up to 100 times the width of the line. The line widths typically are far below 5 mm.

If the printed line stretches in the squeegee movement direction, then it is supported by a high EOM all the time and the squeegee cannot “dive” too much towards the substrate. The investigation here therefore focuses on lines perpendicular to the squeegee movement. If larger solid tone areas are printed, the bulging can occur in both directions depending on the stiffness of the squeegee.

The mesh is regarded as flexible respectively limp. In this first approach, additional horizontal forces that may be caused by friction are neglected. It is obvious that the presence of ink lubricates the contact point.

2.2 Goal of the research

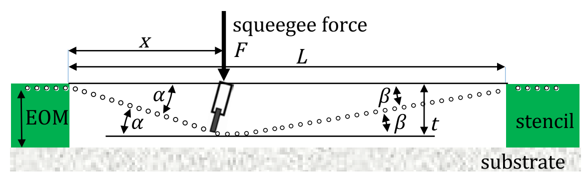

Figure 3: Geometrical dimensions and nomenclature of the problem

Introducing the geometrical properties according to Figure 3, the aim of the study is to find the following dependencies:

$$\alpha = f(F, x, L \text{ and mesh properties}) \qquad [1]$$

and

$$t = f(F, x, L \text{ and mesh properties}) \qquad [2]$$

Where F is the downward force exerted by the squeegee pressure, x the squeegee position, α and β the angles at the stencil edges and L the width of the printed feature. The depression of the mesh is called t.

The relevant mesh properties are the Young’s modulus E in Pa and the specific cross section A_q in mm²/cm.

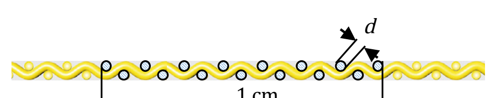

Figure 4: Specific cross section of a screen printing mesh

The specific cross section A_q (aka. SCS) according to Figure 4 is the cumulated area cross section of the threads in between 1 cm and represents a kind of strength parameter of the mesh. The higher the number, the more tension can be applied to the mesh.

$$A_q = n\frac{\pi d^2}{4} \qquad [3]$$

with n = mesh fineness in threads per cm and d = thread diameter. The value of A_q typically is given in mm²/cm.

2.3 Acting forces

The set-up can be regarded as a two dimensional problem in an *x*-*z*-plane. In *y*-direction, the printed feature is assumed to be infinite. The squeegee force F causes forces in the mesh called F_A on the left-hand side and F_B on the right-hand side. Thus, according to Figures 5 and 6, an equilibrium of forces can be found, represented by Equations [4] and [5].

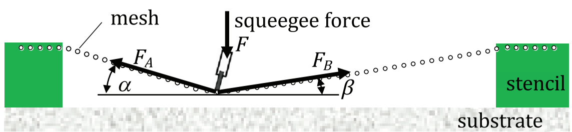

Figure 5: Acting forces

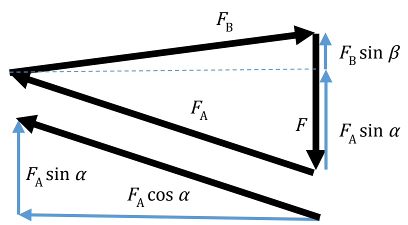

Figure 6: Equilibrium of forces

If the EOM is high enough, the mesh does not touch the substrate. Then the equilibrium of forces in vertical direction yields:

$$F = F_A \sin\alpha + F_B \sin\beta \qquad [4]$$

In addition, with neglected horizontal forces that may be caused by friction:

$$F_A \cos\alpha = F_B \cos\beta \qquad [5]$$

Thus, by combining [4] and [5]

$$F_A = \frac{F}{(\sin\alpha + \cos\alpha \tan\beta)} \qquad [6]$$

2.4 Elongation of the mesh

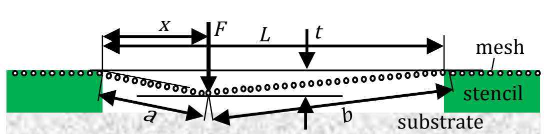

Figure 7: Elongation of the mesh

Due to the forces in the mesh caused by the squeegee force, according to Figure 7 an elongation of the mesh occurs: $a + b > L$. In dimensionless representation the elongation ε caused by the acting squeegee force is

$$\varepsilon = \frac{a + b - L}{L} \qquad [7]$$

Since the forces on the left- and right-hand side from the squeegee position are different, the elongation along the length L comprises of two parts:

$$\varepsilon_A = \frac{a - x}{x} \quad \text{and} \quad \varepsilon_B = \frac{b - (L - x)}{L - x}$$

thus

$$\varepsilon = \frac{\varepsilon_A x + \varepsilon_B (L - x)}{L} \qquad [8]$$

Some geometric considerations help to find relations between the depression of the mesh t and the angles α and β as well as a, b and x. The depression of the mesh t is (depending on the position x of the squeegee):

$$t = x \tan\alpha = (L - x)\tan\beta \quad \text{or} \quad \frac{\tan\alpha}{\tan\beta} = \frac{L - x}{x} \qquad [9]$$

The elongated lengths of the mesh then are $a = x/\cos\alpha$ and $b = (L - x)/\cos\beta$ such that finally:

$$\varepsilon_A = \frac{1}{\cos\alpha} - 1 \quad \text{and} \quad \varepsilon_B = \frac{1}{\cos\beta} - 1 \qquad [10]$$

2.5 Stresses

As long as we are in pure elastic behavior, there is the well-known relation between the stress (tension) and the elongation:

$$\sigma = E \cdot \varepsilon \qquad [11]$$

where E is the Young's Modulus of Elasticity, e.g. in N/mm^2. Thus, the mechanical stress σ = Force/Area in N/mm^2.

In screen printing, however, the mesh tension usually is given as force per unit length, i.e. in N/cm. Thus, let us call the stress per unit length Q in N/cm. According to Figure 8 the indices A and B mean the left- and right-hand side from the squeegee position.

Normally, not only the tension in the mesh due to stretching but also the squeegee line pressure is given in N/cm. Using the specific cross section A_q of a mesh in mm^2/cm (area per unit length), the stress can be written as:

$$\sigma = \frac{Q}{A_q} \quad \text{in} \quad \frac{N/cm}{mm^2/cm} \qquad [12]$$

Thus, left from squeegee position:

$$\varepsilon_A = \frac{\sigma_A}{E} = \frac{Q_A/A_q}{E} \qquad [13a]$$

and right from squeegee:

$$\varepsilon_B = \frac{\sigma_B}{E} = \frac{Q_B/A_q}{E} \qquad [13b]$$

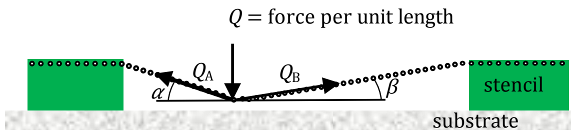

Figure 8: Forces per unit length

Now Equations [10], [13] and [6] can be combined (e.g. for left-hand side):

$$\frac{Q_A/A_q}{E} = \varepsilon_A = \frac{1}{\cos\alpha} - 1 \qquad [14]$$

and with

$$Q_A = \frac{Q}{(\sin\alpha + \cos\alpha \cdot \tan\beta)} \qquad [15]$$

thus yielding

$$\frac{Q}{A_q E} = \left(\frac{1}{\cos\alpha} - 1\right)(\sin\alpha + \cos\alpha \cdot \tan\beta) \qquad [16]$$

2.6 Non-dimensional representation

It is now helpful to introduce the relative position ξ of the squeegee:

$$\xi = \frac{x}{L} \;;\text{ with } 0 < \xi < 1 \qquad [17]$$

The final step is replacing $\tan\beta$ by a function of ξ and α. See Figure 7 for the geometric relations:

$$\frac{\tan\alpha}{\tan\beta} = \frac{1-\xi}{\xi} \quad \text{or} \quad \tan\beta = \frac{\xi}{1-\xi}\tan\alpha \qquad [18]$$

At last, the final formula can be derived by entering [15] into [13] and after some rearranging:

$$\frac{Q}{A_q E} = \frac{\tan\alpha - \sin\alpha}{1-\xi} \qquad [19]$$

2.7 Numerical approach – solving with a look-up table (LUT)

It is – at least to the knowledge of the author – impossible to solve the right hand side of the Equation [19] for α, which would be the aim of the calculations. The left-hand side, however, contains all well-known parameters that are preset and remain constant.

The squeegee pressure Q is ranging somewhere from 0.5 to 10 N/cm. For the Young's modulus values are e.g. E_{PET} = 4 500 N/mm^2 = 4.5 GPa and $E_{stainless}$ = 180 GPa. The specific cross section A_q is equal mesh count times single thread cross section, e.g. A_q = 0.058 mm^2/cm for a 380–14 mesh and A_q = 0.185 mm^2/cm for a 48–70 mesh. Since these three parameters are given machine settings or material properties, they can be regarded as constants. Therefore, a single, dimensionless constant K is introduced:

$$K = \frac{Q}{A_q E} \qquad [20]$$

On the contrary, the right-hand side of Equation [19] is a function of α and ξ only, so it can be written:

$$(\alpha, \xi) = \frac{\tan\alpha - \sin\alpha}{1-\xi} = K \qquad [21]$$

This function of α can be analysed using numerical methods. Thus, in an Excel-worksheet a table has been created for the function where in appropriate fine steps the values for α and ξ vary in ranges of $0 < \alpha < 90°$ and $0 < \xi < 1$, respectively.

This table can be used as a look-up table (LUT), in which for a given K and ξ the value for α is picked out easily. Interpolation techniques are used if the appropriate α-values cannot be read-out directly.

In Figure 9, the way to look up for α is shown. The value for $K = (Q/A_q E)$ is searched on the y-axis and on the x-axis the angle α can be looked up according to the relative position ξ in the set of curves in the plot.

As mentioned above, the actual value of K can vary in a quite large range. Besides the material (stainless steel or PET), the main influence comes from the mesh geometry.

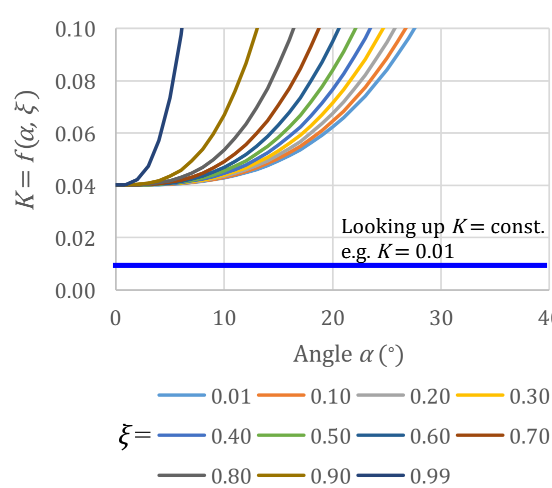

Figure 9: Set of curves for $K = f(\alpha, \xi)$

Table 1 shows some values for A_q (earlier in 2.7). The figures in the table are calculated from specifications found for PET-meshes from vendor SEFAR. Especially comparing the PET-meshes with the same n (e.g. 120 threads per cm) but with different thread diameters is interesting, since this lets one vary the A_q value by at least of a factor of 1.6.

Table 1: Specific cross section of the mesh regarding the fineness and diameter of the thread

Mesh *n–d*	A_q (mm²/cm)
48–70	0.185
110–34	0.099
110–40	0.138
120–31	0.091
120–34	0.109
120–40	0.151
150–27	0.086
150–34	0.136

2.8 First conclusions

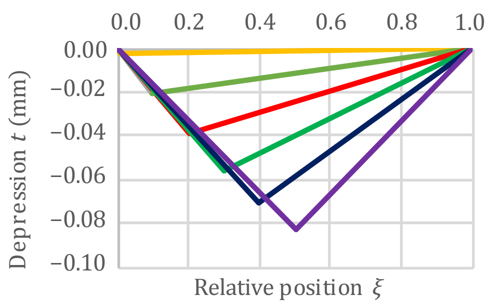

Figure 10: Depression t as function of ξ for different squeegee positions (setting: K = 0.044)

Using the appropriate values for K, Equation [21] can be evaluated using the LUT-method. Instead of having a single result for the depression e.g. as drawn in a kind of snapshot in Figure 3, Figure 10 shows a plot of subsequent snapshots during the squeegee movement from left to right.

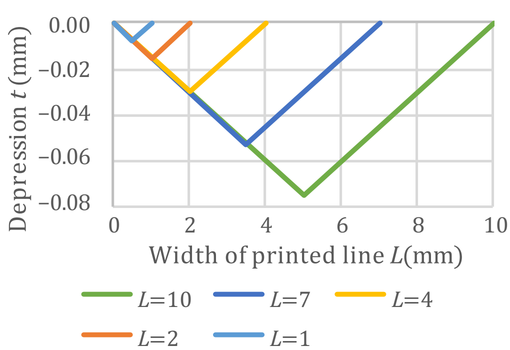

Figure 11: Dependence of t on line width L (mm) for ξ = 0.5

In the case of Figure 11 the influence of the width L of the printed feature is shown.

A typical value of the EOM is around 10 µm. In the case of Figure 11 at L > 1.6 mm the depression is large enough so that the mesh will touch the substrate. This theoretical finding corresponds with the observations described in the handbooks (SEFAR, 2008).

2.9 Influence of the mesh tension

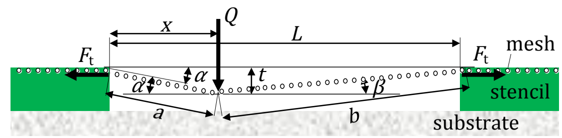

Figure 12: Forces overlaid by the tensioning of the mesh

For a good screen printing operation, the mesh must have an appropriate tension, typically applied in a mesh-stretching device. Thus, the length L is already a stretched length. The stress applied by the squeegee pressure described in the previous chapter is on top of that. If the mesh has an appropriate tension, represented in the drawing in Figure 12 by F_t (index t stands for tensioning), the elongation ε or the depression t is much less than without.

Thus, introducing the mesh tension per unit length $Q_t = F_t/L$ in N/cm and the stress $\sigma_t = Q_t/A_q$ it can be written – particularly for the left part (left from ξ):

$$\varepsilon_A = \frac{1}{\cos\alpha} - 1 = \frac{Q_A/A_q}{E} - \frac{Q_t/A_q}{E} \qquad [22]$$

and again, after some rearranging:

$$\frac{Q}{A_q E} = \frac{\tan\alpha - (Q_t/A_q)\sin\alpha}{1-\xi} \qquad [23]$$

Since the term $(Q_t/A_q)/E$ represents the elongation caused by the mesh tensioning it could be abbreviated with $\varepsilon_t = (Q_t/A_q)/E$

and finally:

$$K = \frac{Q}{A_q E} = \frac{\tan\alpha - (1-\varepsilon_t)\sin\alpha}{1-\xi} \qquad [24]$$

Using Equation [24], the given and constant value of ε_t can be introduced into the look-up table and with the procedure according to Figure 9, the angle α can be read out.

3. Results

The following result plots depict the depression t as a function of ξ where the lowermost points of the squeegee depression are interconnected in one single curve representing the lowermost point of the squeegee tip while passing over the distance L. Since the look-up still bears some impreciseness, interpolation methods had to be used. According to the geometric properties shown in Figure 12, the depression t is calculated with the modified Heron/Pythagoras relation according to

Equation [27] known from basic triangle calculations that can be found in formularies (e.g. Wikipedia, 2017). The needed distance a was calculated from the left-hand side of the squeegee position with

$$a = \frac{\xi\, L}{\cos\alpha} \qquad [25]$$

and the distance b from the right-hand side position respectively.

$$b = \frac{(1-\xi)\,L}{\cos\beta} \qquad [26]$$

$$t = \frac{1}{2L}\sqrt{2(a^2b^2 + a^2L^2 + b^2L^2) - (a^4 + b^4 + L^4)} \qquad [27]$$

The depression t is determined for 11 discrete values of ξ in steps of 0.1. The resulting curves are symmetric and reach a maximum in the middle position.

3.1 Varying the line width *L*

The most important parameter for this investigation is the width of the printed line (with infinite length).

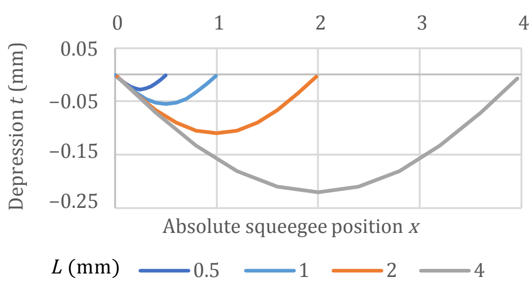

Figure 13: Depression t as a function of the squeegee position x for different line widths L; with settings: PET, squeegee pressure Q = 5 N/cm, mesh tension Q_t = 20 N/cm

Figures 13 and 14 show in different representations that the depression is strongly dependent on the length L of the printed feature. It is very likely that with typical values of the EOM, the mesh starts touching the substrate if the printed feature is wider than 1 mm.

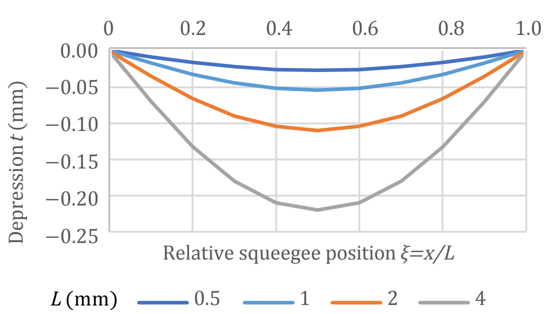

Figure 14: Depression t as a function of the relative squeegee position ξ for different line widths L; with settings: PET, squeegee pressure Q = 5 N/cm, mesh tension Q_t = 20 N/cm

3.2 Varying the mesh tension

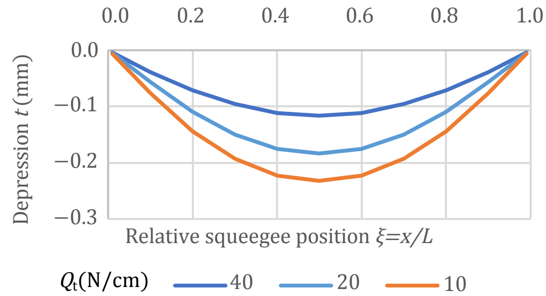

Figure 15: Depression t as a function of the relative squeegee position ξ, by varying the mesh tension with settings: PET, L = 2 mm, squeegee pressure Q = 10 N/cm

In Figure 15 the result plot is shown when varying the mesh tension Q_t. It is obvious that with higher mesh tension the depression decreases. Thus, in practical observations the bulging-out effect can be minimised if screens with high mesh tension are used.

Another way of avoiding the bulging-out effect is using stainless steel instead of PET. Figure 16 depicts the result with exactly the same settings as in Figure 15 except using stainless steel mesh instead of PET.

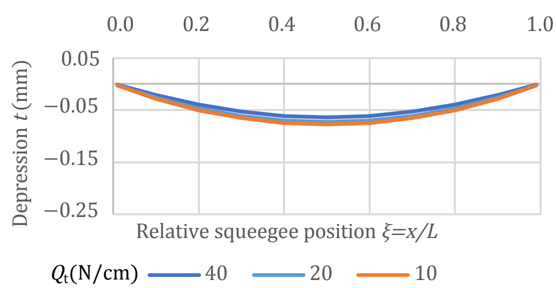

Figure 16: Depression t as a function of the relative squeegee position ξ; with the same parameter settings, as in Figure 15 except stainless steel instead of PET

3.3 Varying the squeegee pressure

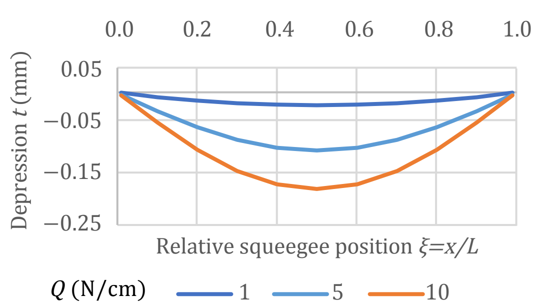

Figure 17: Depression t as a function of the relative squeegee position ξ, by varying the squeegee pressure Q; with settings: PET, L = 2 mm, mesh tension Q_t = 20 N/cm

The graphs in Figures 17 and 18 show the influence of the squeegee pressure Q on the depression t, again the first plot for PET, the latter for stainless steel (same scale of the y axis). Since the effect of Q and Q_t superimpose each other, the plots look very similar.

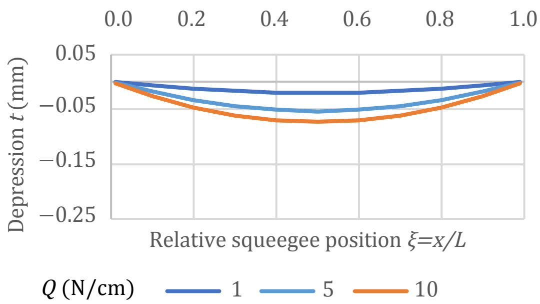

Figure 18: Depression t as a function of the relative squeegee position ξ, by varying the squeegee pressure Q (1, 5 or 10 N/cm); with same parameter settings, as in Figure 17 except stainless steel instead of PET

4. Conclusions

It could be shown that with some simple assumptions the depression that a screen printing mesh is undergoing during the squeegee movement over the given width of an infinite printing line under the impact of the squeegee pressure can be calculated theoretically. The theoretical results correspond to measurements done in previous projects (Willfahrt, Stephens and Hübner, 2011). In other experiments, where it was tried to provoke the bulging-out effect it was almost impossible to observe elevated edges.

It seemed that the ink showed thixotropic behavior and levelled quite well after printing and before drying. These experiments should be repeated with an ink showing no thixotropy at all.

In future, the simple theory might be broadened by introducing influences of horizontal forces (friction between squeegee and mesh). Furthermore, a certain bending stiffness (especially for stainless steel) may be assumed, but it would complicate the calculations significantly.

In the calculations done here, the approach in which the x-z-plane provides the image feature width and depth having infinite length in the y-direction parallel to the squeegee extension represents the worst case with maximum depression of the mesh. Any stencil material before or behind the observed x-z-plane would support the squeegee and decrease the depression.

Table of symbols

α, β = squeegee deflection angles at edges (left and right hand side of squeegee)

t = mesh depression in mm

L = width of the printed feature in mm

E = Young's modulus of elasticity in N/mm^2 or in Pa

A_q = specific cross section of the mesh in mm^2/cm

x = squeegee position ($0 < x < L$)

$\xi = \frac{x}{L}$ = relative squeegee position in dimensionless representation with $0 < \xi < 1$

F = vertical squeegee force in N

F_A, F_B = forces in mesh in N (A = left and B = right hand side of squeegee)

a, b = elongated lengths of the mesh (left and right hand side of squeegee) in mm

ε = relative elongation, ε_A left and ε_B right hand side of the squeegee

ε_t = mesh elongation caused by the stretching in %

ε_q = mesh elongation caused by the squeegee pressure in %

$K = \frac{F_q}{A_q E}$ = dimensionless constant

Q = squeegee pressure in N/cm

Q_t = mesh tension in N/cm

References

Hobby, A., 1997. *Printing thick film hybrids*. [online] Pontypool: The Gwent Group. Available at: < http://www.gwent.org/gem_thick_film.html> [Accessed October 2017].

Riemer, D.E., 1988. *Ein Beitrag zur Untersuchung der physikalisch-technischen Grundlagen des Siebdruckverfahrens*. Doctoral thesis. Technische Universität Berlin.

Riemer, D.E., 1989. The theoretical fundamentals of the screen printing process. *Microelectronics International*, 6(1), pp. 8–17.

SEFAR, 2008. *Siebdruckhandbuch*. Thal, Switzerland: Sefar AG.

Wikipedia, 2017. *Triangle*. [online] Available at: <https://en.wikipedia.org/wiki/Triangle> [Accessed October 2017].

Willfahrt, A., Stephens, J. and Hübner, G., 2011. Optimising stencil thickness and ink film deposit. *International Circular of Graphic Education and Research*, 04, pp. 6–17.