Chapter 2
Fundamentals of Screen-Printing
Electrochemical Architectures

Abstract This chapter introduces the background theory on the screen-printing process.

2.1 Screen-Printing Process

The technique of screen-printing is described as the production of thick film hybrids, for applications within many areas of the scientific community, such as circuit boards and electrochemical systems to name a few. Due to the nature of screen-printing the creation of mass-produced thick films can be realised, with the utilisation of relatively cheap and simple designs this process possesses excellent scales of economy. Additionally it is noted that due to simplicity of the machinery used throughout, this process can be altered and changed upon a fundamental understanding of screen-printing.

The process of screen-printing typically consists of five prerequisites to ensure identically reproducible thick films, these are as follows:

- Suitable printing medium
- Mesh screen with an embedded stencil design
- Substrate to print upon
- Flexible and resilient squeegee
- Secure base to prevent movement of substrate within the process.

It is important to note that suitable printing machinery is desired to ensure the desired level of reproducibility is achieved with a high throughput. Nevertheless there are situations where the printing machinery can impede and become inauspicious to the overall screen-print, it is with these considerations that it is solely reliant on the methodology.
Upon integration of the above mentioned pre-requisites, a print cycle can occur; Fig. 2.1 represents the process in three simple steps. The first step consists of placement of the printing media (i.e. ink, emulsion or paste) upon the mesh screen, where it is visible that the screen is not in contact with the substrate. Such contact could potentially damage or spoil the print as the substrate would uncontrollably “snap-off” the screen, creating an unclean print. The contact only occurs when the squeegee applies pressure over the screen forcing the printing medium through the stencil design, creating the desired pattern or design in a controlled and efficient manner.

### 2.2 Selection of Screen-Printing Equipment

As mentioned previously the prerequisites are vital for the screen-printing process, it is additionally important the selection of this equipment is crucial for maximising reproducibility and outputs. It is with this section that consideration of the screen, squeegee, flood/distribution bar and printing media are discussed.
2.2.1 The Screen

When utilising and designing the screen there are three factors to consider such as the screen frame, stencil design and the screen-mesh. The screen frame typically is fabricated utilising wood or metal, however due to their similarity in pricing they tend to be made from metal, creating a robust and safe foundation. The material used must be able to withstand the pressure created from the tension of the mesh, which in some cases can exceed values of 80 kg. The frame size can be varied however in all cases the screens tend to be either rectangular or square depending on the size of the machine and design at hand. It is due to this that there is no specific ratio or value that corresponds to the perfect design, however it does refer to the inside dimensions of the screen (as the frame is a support for the open mesh area of the screen, calculated by Eq. 2.1). There are mainly two types of frames for the screen-printing process these are lightweight cast aluminium and extruded aluminium, dependent on the machine of choice the appropriate composition can be selected.

\[
Open \text{ Area} = \frac{(\text{mesh area})^2}{(\text{wire diameter} + \text{mesh opening})^2} \times 100 \% \tag{2.1}
\]

The screen-mesh has many interesting properties that allow for a perfect screen-printed design, as it acts as a support network to hold the stencil-design in place at all times during the print cycle, even after the pressure has been applied by the squeegee. These characteristics originate from its design and manufacture, the choice of an appropriate material for the mesh can be vital for a precise and detailed screen-print. Shown in Fig. 2.2 is an optical image of a screen-mesh showing the woven network of the mesh. In this screen the electrodes will be fabricated; note the distance in the size of the mesh, to allow a certain amount of ink to transfer onto the substrate.

![Fig. 2.2](image-url) Optical image of a stainless steel screen-mesh, for a working electrode (left image) and counter electrode (right image)
A factor that must be considered upon creation of the mesh screen is the mesh count, $M$, i.e. the amount of wires per unit of length as shown in Fig. 2.3.

In conjunction with size of the mesh count and wire diameter, $D$, the mesh opening can be calculated via Eq. 2.2. The mesh opening is a vital measurement that influences the amount and size of the ink that can be passed through the screen.

$$O = \frac{1}{M} - D$$

Many manufacturers prefer to use three types of materials these being nylon, polyester and stainless steel; represented in Table 2.1 are the benefits of utilising each material.

Along with careful consideration of Table 2.1, other vital observations must be carried out. For example, the minimum line width that can be printed must be three times the mesh thread diameter (i.e. large mesh threads cannot print small designs). In addition the mesh diameter must also be three times larger than the particulate size of the printing medium, to allow suitable passage of the media. Furthermore to the above mentioned mesh designs, it is possible to utilise a V-mesh, which consists of a mesh created from Vecry which is a sheathed filament surrounding a liquid crystal based polymer core. This mesh provides the required strength for a screen, the combination of thin, flexible fibres and the weaving process result in flat

![Fig. 2.3 Schematic of a mesh opening](image)

<table>
<thead>
<tr>
<th>Screen requirements</th>
<th>Polyester</th>
<th>Stainless steel</th>
<th>Nylon</th>
</tr>
</thead>
<tbody>
<tr>
<td>Flexibility</td>
<td>1</td>
<td>2</td>
<td>3</td>
</tr>
<tr>
<td>Resilience</td>
<td>1</td>
<td>2</td>
<td>3</td>
</tr>
<tr>
<td>Percentage of open area</td>
<td>2</td>
<td>1</td>
<td>2</td>
</tr>
<tr>
<td>Stability of print size</td>
<td>2</td>
<td>1</td>
<td>3</td>
</tr>
<tr>
<td>Damage from squeegee</td>
<td>2</td>
<td>3</td>
<td>1</td>
</tr>
<tr>
<td>Accidental damage</td>
<td>2</td>
<td>3</td>
<td>1</td>
</tr>
<tr>
<td>Cost</td>
<td>1</td>
<td>3</td>
<td>1</td>
</tr>
<tr>
<td>Minimal snap-off from large areas</td>
<td>2</td>
<td>1</td>
<td>3</td>
</tr>
</tbody>
</table>

Ranked 1–3 which corresponds to the worst (3) and best (1) in its category.
filament intersections. Additionally, the smoother thread surfaces further enhance paste release. Such screens can exhibit higher levels of tension allowing a less-snap off, thus reducing the risk of faulty screen-prints. The thickness of the screen is additionally vital for the printing process, in most cases the overall screen-mesh thickness will be double that of the wire diameter. Typically within the fabrication process of the polyester and nylon mesh screens the mesh is woven and then passed through heat rollers which weld the wires together creating a bound matrix of mesh wires. In the case of stainless steel meshes the metallic properties of the steel allows for instant mesh strength upon weaving of the wires, therefore this additional heating step is no longer required. Represented within Fig. 2.4 are the resulting wire mesh thicknesses upon utilisation of the two fabrication methods. It is noticeable that a distortion of the wire mesh occurs upon utilisation of the heat rollers, therefore reducing the wire diameter from 3 to 2 mm. It is important to note that the stainless steel mesh thicknesses can vary an extraordinary amount due to the nature of the stiffness and hardness of the steel wires.

As mentioned previously the amount of printing medium that can be transferred relies on the opening in the screen and the thickness, the volume of paste (V) can be calculated using Eq. 2.3. Assuming the screen thickness is double that of the wire diameter:

\[ V = (2D) \left( \frac{1}{M} - D \right)^2 \]  

(2.3)

In order for a successful print with a minimal snap-off the screen-mesh must be held at a specific tension which must be sufficient to allow the screen to peel away
from the substrate in a controlled and reproducible fashion. Nonetheless excessive tension upon the mesh can cause detrimental and costly damage. It is with manipulation of these tensile qualities that a perfect mesh can be created. It is duly noted that screens that are highly taught will give the best control of the snap-off and therefore reproducibility of the print. On the other hand, highly taught screens are more likely to be susceptible to unwanted or accidental damage due to their excessive tension. Therefore when utilising stainless steel screens, elongation of 0.9 % will allow the screen to revert back to its original state, with an additional 0.1 % as leverage. It is possible for a mesh screen to give a perfectly defined and reproducible print at values of half that of the elongation limit, considering that an alteration to the print-gap between the screen and substrate is incurred, for the perfect snap-off.

2.2.2 The Squeegee

During a screen-print cycle a highly important factor is the constant movement of the printing media towards the substrate, at a sufficient speed and pressure, this is accomplished by the utilisation of a squeegee. As described in Sect. 2.1 the squeegee applies pressure to forcing the ink through the stencil design, creating an even print upon the substrate in a controlled manner.

For the squeegee to complete its necessary tasks, it must be fabricated with materials that are flexible and resilient. The most common material used throughout industry is Polyurethane, it is general practise that squeegees possess an extremely long life and on average can achieve prints of 20,000 before any visible damage occurs. However utilising stainless steel meshes will decrease this as the surface friction applied during cycle will eventually damage the point of contact. During the fabrication of the squeegees many grades of softness are created, it is generally accepted that the softest material creates a larger contact with the screen; therefore this is the more efficient grade to use. Depicted in Fig. 2.5 is the potential effect of squeegee damage towards the coverage of printing media during the print cycle, it is clear that upon the snap-off from the substrate the print is incomplete and irregular. Additionally the squeegee must be at least 10 mm wider than that of the print area, it is apparent that a larger squeegee will create a smaller the natural print gap, as there is more pressure applied on the screen-mesh potentially damaging the screen irrevocably (shown in Fig. 2.6).

The angle at which the squeegee applies its pressure is also a vital condition for the successful transfer of print media through the stencil design. If the angle is too high the transfer of the printing medium will not be sufficient to fill the print area, therefore creating a thinner application of ink/paste to the substrate below. Additionally if the squeegee is at a much shallower angle the hydrodynamic pressure increases, therefore transferring too much of the ink/paste onto the substrate and potentially blocking and hindering the controlled snap-off. Figure 2.7 exhibits a selection of angles and their advantages/disadvantages, to the screen-printing process.
Fig. 2.5 Schematics of the effect of a damaged squeegee during the print cycle, upon the transfer of ink to the substrate; not that the ink has been pushed through the screen correctly and the deposited ink does not reflect the original defined image.

Fig. 2.6 Representation of the squeegee size and its effect upon the screen-mesh, where it can be seen that upon utilisation of a larger/heavier squeegee a naturally smaller print gap is created.
2.2.3 The Flood Bar/Distributor

The distribution of ink/paste is another vital process of the print cycle for a successful print. Typically flood bars are designed from stainless steel and will be slightly longer than the squeegee being utilised, it is then fixed behind the squeegee and upon the first transition of the print cycle the flood bar will transport the ink/paste over the print area. It is vital that the flood bar is slightly above or touching the screen-mesh, so that it is constantly in touching distance of the ink. In many printing situations the squeegee will remove the excess ink/paste back to the starting position, and the process can be repeated.

2.2.4 Printing Medium

The screen-printed process allows the user to fabricate a variety of geometric designs and shapes; such ability requires the utilisation of a durable, compatible printing medium. Terminology of such media can range from a dye to a simple ink.
or paste, but in most cases they all will possess the same composition. The viscosity of these ‘inks’ will determine how successful the print is, as due to the nature of screen-printing the ink must be passed through a specific shape (stencil) keeping its geometric design. The formulation of the specialist inks tend to consist of two components: suitable pigments for the application at hand and an appropriate amount of solvent/binder ratio creating the perfect transport of the pigment.

Upon application of screen-printing some designs or screen-prints may require viscosities that are higher than the ideal, as the majority of quality control issues arise when the ink is more viscous, therefore it is important to ensure that the operation procedure should be modified via optimising each step of the manufacture. The ideal screen-printing ink should require no forcing into the open area of the screen, flow readily when moved by the flood bar and not dry within the screen-mesh during the operation. To achieve this perfect consistency, prior mixing of the ink must occur until a smooth fluidic composition is achieved.

In general examination of the composition is performed by utilising a fineness of grind (FOG) gauge (shown in Fig. 2.8) for the determination of dispersion, particle size, and fineness of many materials like inks, lacquers, pigments, filler, chocolate to name a few. In this situation, the materials being tested are inks. The gauge may also be used to indicate the presence of undesired large particles in these materials. Such tool has an attached scrapper, which pulls the material along the sloping groove machined onto the top surface of the gauge. The value for fineness of grind is obtained directly from a scale engraved into the gauge.

Fig. 2.8 Optical images of fineness of grind gauge. Reproduced from Ref. [1]
**Standard Operating Procedures for the Fineness of Grind Gauge**

1. Place the gauge on a flat, horizontal and non-slip surface, with the zero mark on the scale closest to the user.
2. Place a considerable amount of material (ink) in the deep end of each groove.
3. Place the scrapper on the surface of the gauge behind the material (ink), which is at the deepest groove.
4. Use both hands to hold the scrapper and pull along the length of the gauge at a constant speed apply sufficient pressure to clean the excess material (ink) from the edge of the gauge.
5. Stop at a point beyond the zero depth and assess the drawn out material within the next 3 s.
6. Note: This avoids inaccurate testing due to evaporation of solvents from materials.
7. The material (ink) should be viewed at right angles to the length of the groove and at an angle of 20–30° with the surface of the gauge.
8. Find the first position across the groove 3 mm wide which contains 3–10 particles/streaks/scratches of material (ink).
9. Read the position on the scale and record this value.
10. Perform the test three times; afterwards calculate the average value of the result. The average value is the fineness of grind of the material (ink).

The FOG test can be used as a QA/QC measurement for inks used in the screen-printing process.

### 2.2.5 Curing of the Ink

The nature of the printing media requires a curing step within the fabrication of the design. Generally many failures in the fabrication of conductive inks are reliant upon the poor selection of solvents. It is with this in mind that consideration of the solvents utilised within the ‘ink’ allow for an ideal curing time and temperature to envisage a situation depicted within Fig. 2.9; where it is clear that upon the curing step of the ink the volume starts to decrease, leaving behind a fully conductive ‘stack’ upon the substrate where the polymer in the ink formulation holds the structure of the electrode surface.

In many cases the manufacturer of the ink will provide the solvents that are the best ratio for working and curing properties, therefore if an amendment is requested consideration of the curing procedure must be endured. Note that an ink has a range of solvents varying from slow and fast evaporation time, to ensure a controlled
drying process resulting in a reproducible electrode surface. It is important to note that the solvent is duly there to create a fluidic support for the conductive paste and thus in most cases a solvent with a lower boiling point would be ideal.

**Reference**

Screen-Printing Electrochemical Architectures
Banks, C.E.; Foster, C.W.; Kadara, R.O.
2016, VII, 56 p. 48 illus., 17 illus. in color., Softcover
ISBN: 978-3-319-25191-2