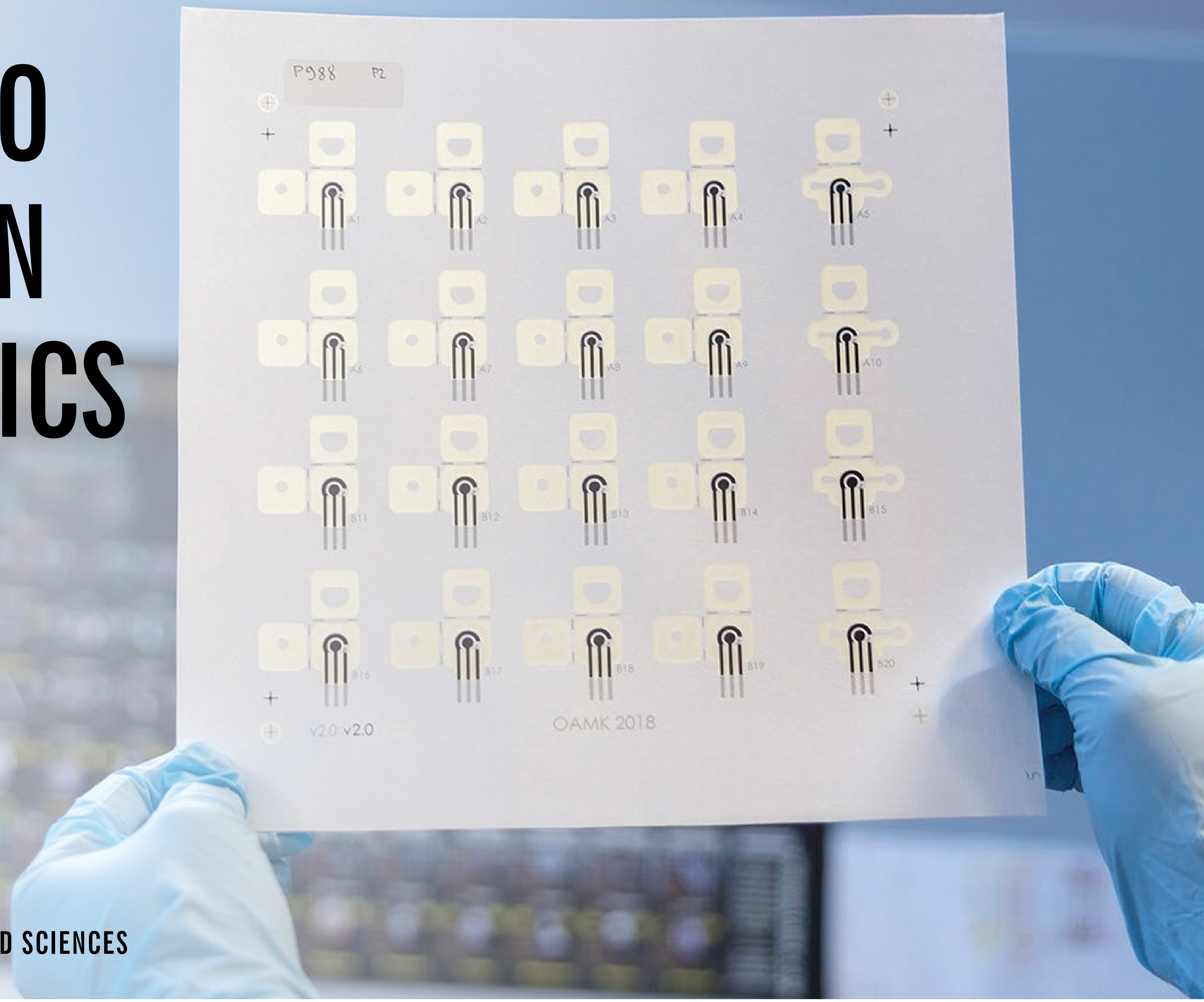
PRACTICAL GUIDE TO SCREEN PRINTING IN PRINTED ELECTRONICS

Teija Tuhkala, Tomi Tuomaala and Harri Määttä (eds.)



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Please feel free to learn about PrinLab at **oamk.fi/prinlab**.

PrintoCent Pilot Factory – Open access environment for scale up

In PrintoCent, the pilot factory environment enables companies easy access to new business development and pilot manufacturing resources for the introduction of printed intelligence components, systems and products, from pilot production to early market trials.

Application focus areas range from rapid disposable diagnostics, smart flexible lighting and wearables to Internet-of-Things with sensors and energy harvesting. PrintoCent has wide global reach with its international member companies and partners. In Oulu region more than 450 experts are available in research and in industry. Step by step the value chains of printed intelligence covering the printing, component assembly, integration to structures like laminated glass, over moulded plastics and high pressure laminates (HPL) will reach the maturity for commercial manufacturing. There will be a growing need to enlarge the hard printed circuit board approach to the flex printed circuit foil approach and most of the printing will be screen printing in sheet-to-sheet or roll-to-roll way of working.

The growth of an efficient ecosystem around printed intelligence includes also education. Universities based in Oulu universities offer a range of graduate courses and education programmes around printed intelligence. Understanding the process and hands on experience of silk screen printing is essential both to engineers designing products, process and related testing and operators running the machinery and performing the process steps. We hope that this Practical Guide to Screen Printing will pave the way to companies towards a wider use of printed intelligence in their next generation products.

VTT
Ilkka Kaisto
Director of PrintoCent

Contents

1. About this guide

TEIJA TUHKALA

Photo credit: Jussi Tuokkola

1. About this guide

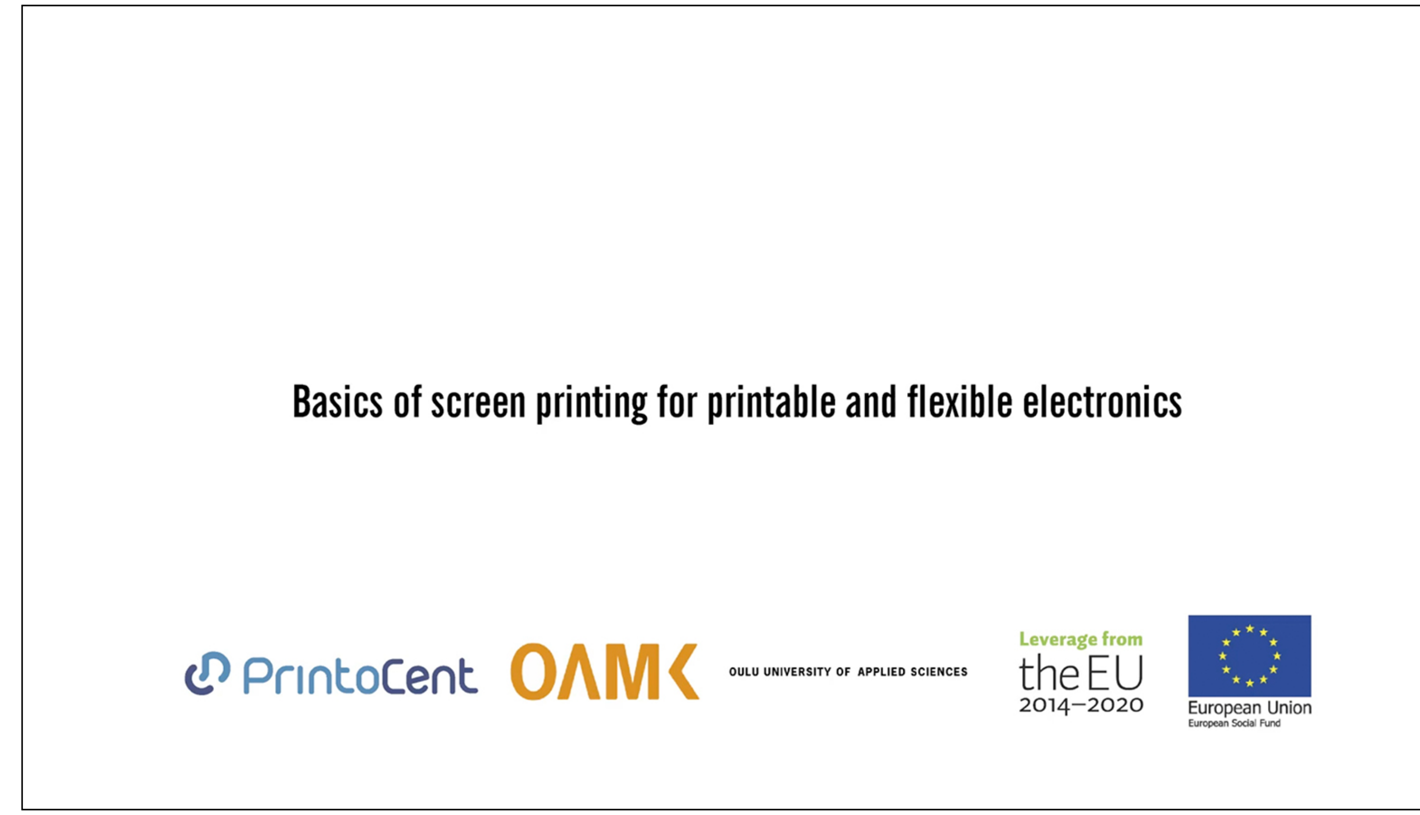
This guide provides practical guidelines for learning the basics of table top screen printing for printed electronic applications. The PrinLab laboratory at Oulu University of Applied Sciences has over ten years of experience of printed electronic application development and training of manufacturing methods. During the years, we have noticed two effective ways of learning. First, you can read and try to understand the enormous amount of academic publications from different material research and manufacturing methods. Then, you can learn by doing and start printing.

Screen printing is a common technology used in printed electronic applications in the electronics industry. Flexible materials, conductive inks and substrates enable printing electronics with various modes like thin or thick layers and large-area printing. Electronics can be printed onto different substrates such as plastic, paper and fabric. Screen printing can be utilised to pattern hydrophobic channels to control fluid flow, for example, on the diagnostic disposable test strips. It is also used as a manufacturing method in blood sugar test strips or other electrochemical applications. Screen printing is used in manufacturing RFID tags, temperature sensors and hundreds of small and large electronic devices from wrist to the control panels, which we use to create easier, enjoyable and functionable life.

The guide is published as a part of the Rapid Apps for Printed Electronics project, in which new educational materials and courses for printed electronics were developed. One goal for the project was to develop new applications that utilise printed electronic manufacturing methods. During the new product development, it became clear that in many companies, new product ideas were intended to be manufactured with screen printing. For example, in health applications, multi-professional teams evaluated the need for business and health. However, more complexity arose when questions for manufacturing were asked. Can the product be manufactured with printed electronic methods and materials? What is the benefit of printed electronics for this product? What to consider in product planning when screen printing has been chosen as the manufacturing method?

To be able to evaluate the proprietary manufacturing method you need to understand the basics of the method. That is why this guide is for. The core of this guide is in chapters 2 and 3. Chapter 2 starts with a short introduction to the theory of screen printing as well as to screen printing in practice. It clarifies the basics of what kind of parameters and equipment is needed for a good printing result. Chapter 3 focuses on multilayer structure printing and working safety.

This guide is meant for those who want to learn the basics of screen printing in practice. Whether you are a student, teacher, researcher or a product developer. We start from the beginning and make no claims about the completeness or depth for the more advanced printing experts or in other manufacturing methods. The guide is meant to work as a complement material beside the newest research and expert advice. It is meant for beginners who are starting their journey towards becoming future printed electronic experts. You are all warmly welcome on this journey with us.



Video *Basics of screen printing for printable and flexible electronics. This video shows the screen printing process in practice from preparations to printing and finishing actions. The permanent address of the video with subtitles is: http://urn.fi/urn:nbn:fi-fe2019050614470.*

1.1 Working group

The guide is compiled and edited in a working group at the printed electronics laboratory, PrinLab, located at Oulu University of Applied Sciences (Oulu UAS), Finland. The group has tens of years of experience of screen printing, research and development of the applications and the training of the printed electronics. Questions and feedback on this guide are highly appreciated. Please feel free to contact us: prinlab@oamk.fi. For more information about PrinLab´s facilities, please visit **oamk.fi/prinlab**.

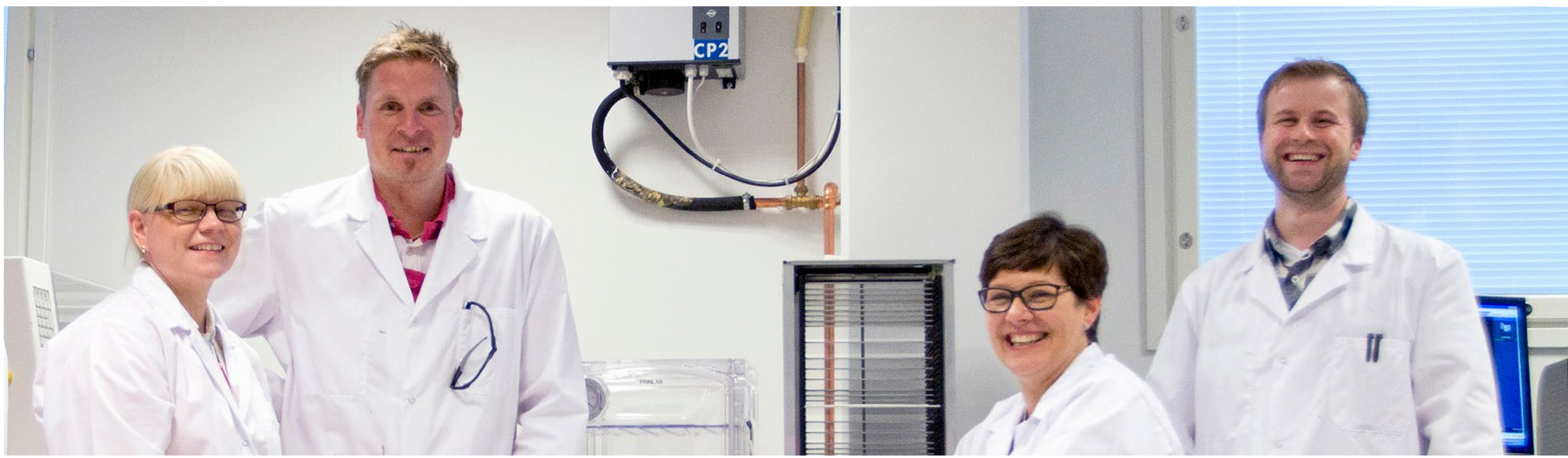


Figure 1. *The team behind the publication: Teija Tuhkala, Harri Määttä, Marja Nissinen, Tomi Tuomaala. Photo credit: Jussi Tuokkola.*

Tomi Tuomaala, researcher, Oulu UAS

Tomi works as a researcher at the printed electronic laboratory, PrinLab, at Oulu University of Applied Sciences. He has more than 10 years of experience in teaching and manufacturing methods in printed electronics. He has strong experience in various printing methods and application development. Tomi's research and experience has been the basis for this publication. He has participated in also as a trainer in different printed electronic courses.

Teija Tuhkala, project manager, Oulu UAS

As a project manager Teija has over ten years of experience in planning and managing development projects in printed electronics and higher education. Her special fields in the printed electronics are market and service development and commercialisation of the applications. She has experience in application commercialisation, inventions and patenting as well as developing education for printed electronics.

Harri Määttä, lecturer, Oulu UAS

Harri works as a lecturer at Oulu University of Applied Sciences. He is responsible for printed electronic education and PrinLab´s international cooperation. He is also a contact person for PrinLab services and the link between PrinLab, companies and the PrintoCent community. Harri has several years of experience in of research and development projects in printed electronics and company cooperations. His special field in the printed electronics is in different manufacturing methods and application development.

AKNOWLEDGEMENTS

Marja Nissinen, senior researcher, Oulu UAS

Marja has strong experience in developing electrochemical applications for printed electronics. She has over ten years of experience in different development projects and application development in the field of printed biosensors. Her contribution to electrochemical sensor development and advice for this guide is acknowledged.

2. Screen printing

TOMI TUOMAALA AND HARRI MÄÄTTÄ

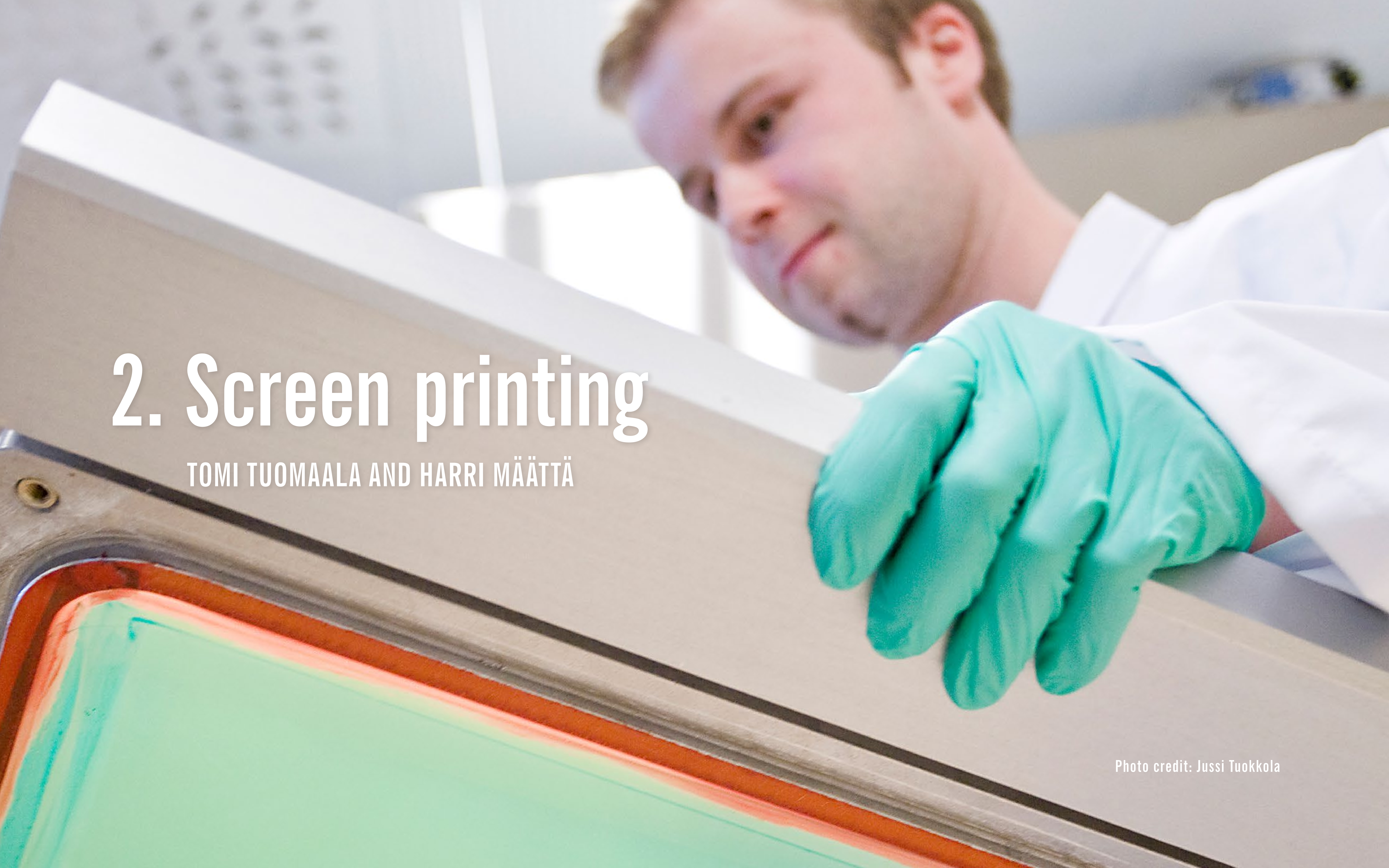


Photo credit: Jussi Tuokkola

2. Screen printing

Screen printing is widely used in the electronics manufacturing, textile printing and decoration of ceramics. Currently and increasingly also in the future, screen printing is used in the manufacturing of printed electronics.

Screen printing is a versatile printing method as it allows printing on a wide range of materials such as paper, textiles, wood, metals, glass and plastics. The viscosity range of the printing ink is wide, which bring benefits to the use of the method for the manufacturing printed electronics compared with other printing methods, where the usable viscosity range is not that wide. The properties of the print layer such as thickness or smoothness can be easily affected by expertise designing of the process parameters, the materials and the screen properties.

The most important issues in the process are the screen and its features, the properties of the printing ink and squeegee and the printing parameters of the machine. This chapter explains the most important issues and the design rules of the process.

Figure 2. *Screen printing with an EKRA E2 printer. Photo credit: Anne Peltola, Design Inspis Oy.*

2.1 Principals of table top screen printing

The main principle of the screen printing method is shown in Figure 3 below. The carefully selected and stretched screen material (screen fabric) is emulsified to the selected thickness, in which the print pattern is exposed, and excessive material is washed away.

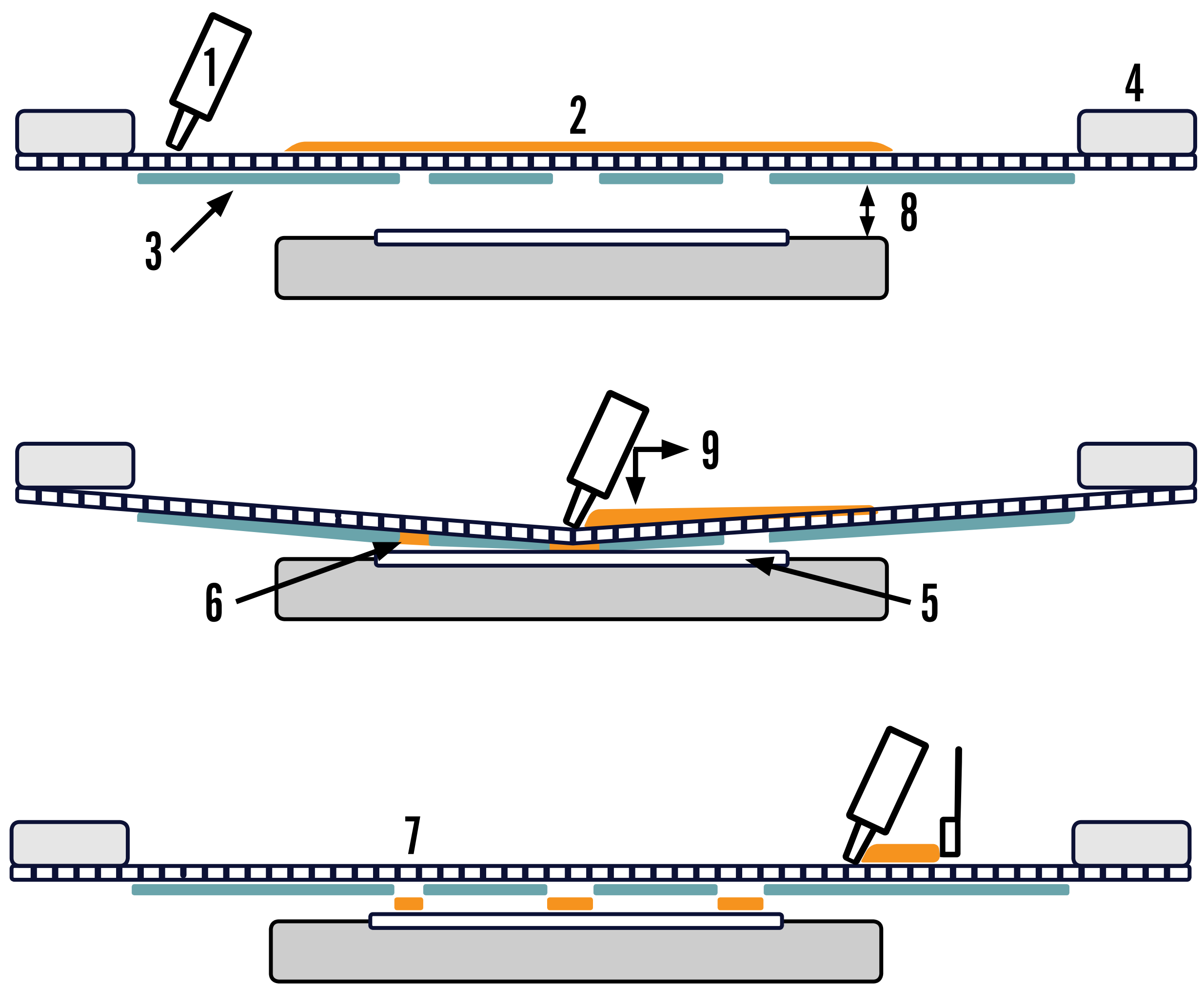


Figure 3. *The screen printing principle. Reproduced from [1], figure credit: Inka Väisänen, Design Inspis Oy.*

1 Printing squeegee
2 Ink
3 Emulsified screen fabric
4 Screen frame
5 Substrate
6 Through the screen transferred ink
7 Emulsion open area (the specified layout)
8 Distance between the screen and substrate (snap-off)
9 The forces acting on the ink

The printing ink is then applied over the screen fabric. The desired hardness and shape of rubber are selected for a squeegee, which squeezes and moves the printing ink in a controlled way through the screen fabric to the underlying printing platform. The emulsion on the screen fabric forms a non-printing surface, which clogs the screen fabric and through which the printing ink cannot transfer to the printing substrate. After the printing process, the printing platform is manually moved or it automatically moves to the drying unit, where the ink is dried or sintered. The drying method depends on the requirements of the printing ink used.

The most important components of producing good quality results in the screen printing process are the printing squeegee, screen, substrate, ink, the capability of used equipment and the process related printing parameters. The most important printing parameters are the speed and pressure of the squeegee, the distance between the screen and printing substrate, the printing ink properties and the ambient conditions. The highest quality printing results are created when the materials and parameters of the printing screen are chosen so that they meet the requirements of the intended print and are compatible with the printing ink. Also, the wetting characteristics and temperature resistance of the substrate material must be compatible with the printing ink. In many cases, it is useful to use a flood or a spreading squeegee if the ink is sufficiently viscous. The flood squeegee slows down the drying of the printing ink on the screen and pre-fills the mesh openings for the next print.

The range of different types of printers used worldwide is enormous. There are a number of printing devices available from table top manual devices to automatic and rotary screen printers.

In simple manual screen printing devices, substrate feed, printing ink delivery and printing are manual work. [2] In automatic printers, these features are fully automated. The printing device or printing process can also be partly automated, so that the operator manages a part of the process (usually sheet fed) manually. The registration of layers in multilayer printing can be done fully manually, semi-automatically using image recognition cameras and a manual positioning system, and in most sophisticated machines, fully automatically.

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[1] Hobby, A. 1997. Screen printing for the industrial user. http://www.gwent.org/gem_screen_printing.html. Date of retrieval 12.4.2018. Chapter 3.2. Fig 1. Gwent/Sun Chemical.

[2] Viluksela, P. Ristimäki, S. Spannäri, T. 2007. Painoviestinnän tekniikka. Otavan kirjapaino Oy. Keuruu. P. 91.

2.2 Process parameters of table top screen printing

Figure 4 below presents the main variables that must be taken into account during the screen printing process or when designing it.

To achieve high quality prints, it is important to optimise, manage, and coordinate the parameters of the main points shown.

Printing equipment

- accuracy
- repeatability
- registration system
- automation
- parameter control
- substrate attachment
- speed

Ambient conditions

- cleanliness
- temperature
- humidity

Printing process

- squeegee pressure
- squeegee angle and speed
- print direction vs. pattern
- snap-off
- amount of ink on screen
- flood squeegee

Substrate

- material
- cleanliness
- surface energy
- roughness

Printing screen

- mesh count (tpi)
- thread diameter
- mesh thickness
- open area %
- mesh material
- mesh weave
- mesh angle
- emulsion thickness
- mesh tension
- pattern size
- frame size and material

Printing squeegee

- material
- hardness
- shape
- size

Printing ink

- rheology (viscosity)
- shear resistance
- particle size
- solid content
- homogeneity
- compatibility with emulsion and substrate
- solvent or water based

Figure 4. *The main variables affecting screen printing quality. [1]*

As presented in Figure 4, there are several variables that can influence the print quality. In many cases, the most important variables are the pressure and speed of the printing squeegee, the speed of the flood squeegee and its distance from the screen as well as the snap-off distance. The snap-off distance means the distance between the print platform and the screen during the printing process.

The squeegee speed and the pressure of the squeegee are together a significant variable in the printing process. When the speed of the squeegee increases, the pressure should be increased. As the speed decreases, the pressure can be lowered accordingly. In other words, when the speed is increased, also the pressure needed for the ink to pass through the screen fabric increases.

Attention should be paid to the starting and ending point of the print. The starting point, i.e. the place where the squeegee is pressed when the print starts, should be adjusted so that it is 3 cm before the pattern on the screen. The squeegee should be raised up 3 cm after the pattern. [2]

The viscosity of the printing ink is of great importance to the selection of the speed of the squeegee. The higher the viscosity of the ink, the slower the speed of the squeegee. There must be enough time for the ink to flow through the screen opening to the printing substrate. When the ink has low viscosity, the speed should be higher so that the ink will not flow uncontrollably through the screen. It should be checked if the ink manufacturer has optimised the print speed for the specific printing ink.

The speed of the printing squeegee is considered fast if it is over 150 mm/s and slow if it is less than 25 mm/s. Usually, the speed is optimised somewhere between these numbers.

The correlation of the speed, ink viscosity and pressure are listed below.

- Higher speed – higher pressure
- Less speed – less pressure
- High viscosity – lower speed
- Low viscosity – higher speed

The pressure of the squeegee should be optimised to the lowest possible level. The pressure is sufficient, when the squeegee is able to scrape the screen during the printing process. Too low a pressure appears on the print as decreased sharpness and also unevenness of the deposited material may occur.

Excessive pressure affects the thickness of the deposited material and the spreading of the ink on the substrate. High pressure can also damage the screen and excessively wear the rubber of the squeegee.

The flood squeegee will bring the ink back to the start point and the process can continue seamlessly. The speed of the flood squeegee directly affects how quickly the ink dries and blocks the printing screen. The flood squeegee is necessary when using quickly drying inks or if the process is one-way. The speed of the flood squeegee may be the same or slightly faster than the speed of the printing squeegee. In the printing process, all printing ink does not flow through the screen. Some of it remains in the wires and openings of the screen, which is prone to dry quickly.

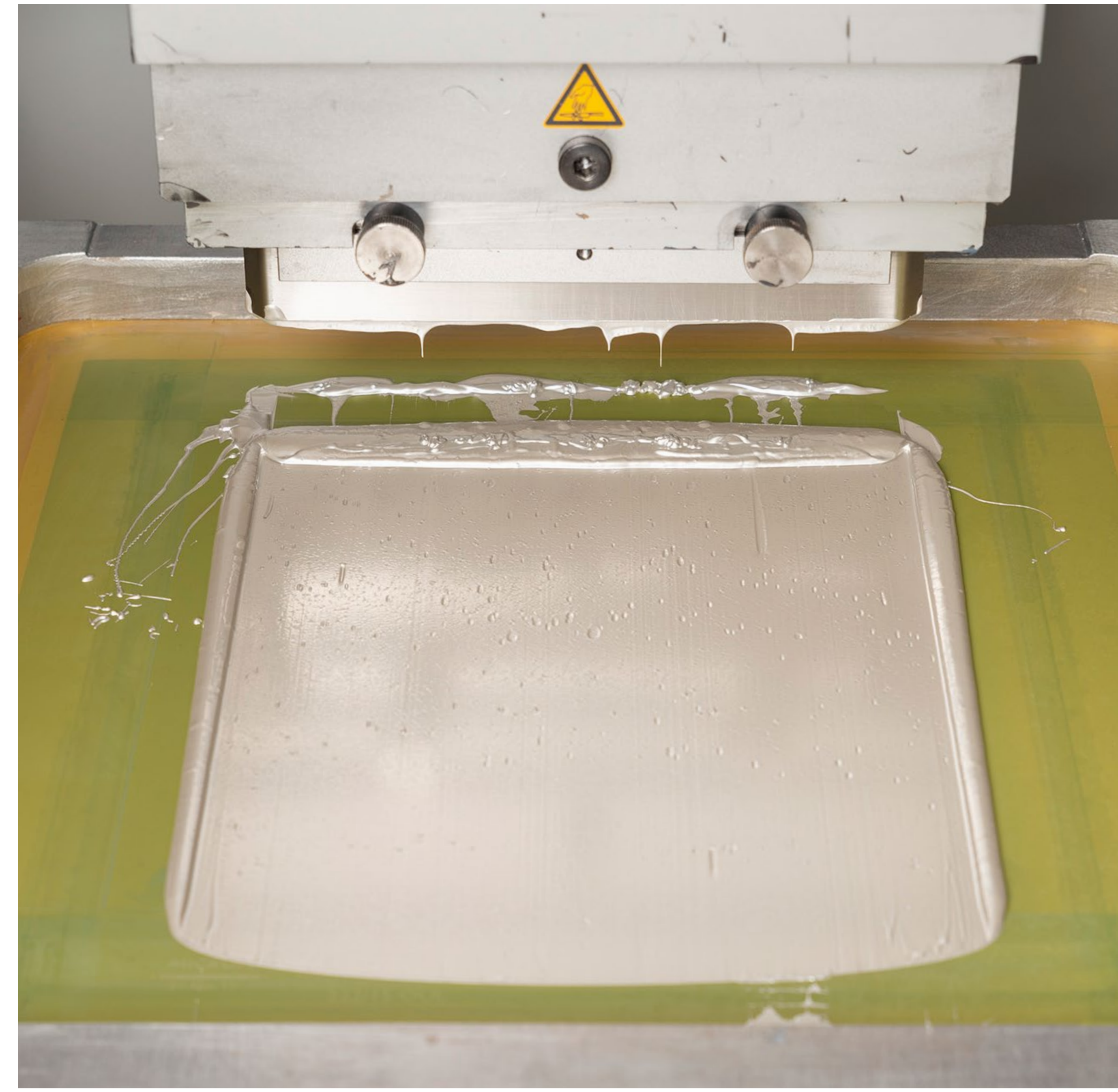


Figure 5. *Spreading of the ink on the screen with the flood squeegee. Photo credit: Jenina Bomström, Design Inspis Oy.*

Figure 6. *Snap-off. Image credit: Tomi Tuomaala, Oulu UAS.*

A thin layer of printing ink is applied with the flood squeegee on top of the opening. The ink keeps the screen moist and slows down the drying of the ink. The faster the flooding is, the less drying takes place on the screen.

It is best to keep the flood squeegee gap from the screen as small as possible. The higher the gap, the more printing ink is needed in the printing process to allow the ink to spread and cover the screen openings. The gap should be adjusted as small as possible using a feeler gauge. However, depending on the viscosity of the printing ink, the flood squeegee is not always suitable for the printing process. With low viscosity inks, it may be impossible to use the flood squeegee. As with the fast drying inks, this tool is almost indispensable.

A snap-off distance, i.e. the distance between the screen and the substrate, is also one of the important variables in the screen printing process. The distance is adjusted when setting the process parameters. In the printing process, the squeegee presses the screen in contact with the substrate. As the squeegee progresses, the screen separates itself from the substrate immediately after the squeegee if the snap-off is properly spaced.

The snap-off distance should be measured at the beginning of the printing process. With a 15x15 inch screen, the distance could be about 1.5–3 mm and up to 3–4 mm with plastic screens. For smaller screens, for example, a 5x5 inch screen, even less than one millimeter may be sufficient. [2]

When the snap-off distance is too high, the ink does not transfer to the substrate since the screen does not touch the substrate at any point. When the distance is too low, a large part of the printing ink remains in the screen opening as the screen remains in contact with the substrate while the squeegee continues. For this reason, the ink does not flow freely onto the substrate resulting in an uneven and unmanageable print quality. It is also worth noting the speed of the squeegee: if it is high, the snap-off distance has to be raised, too. The effects of the snap-off parameter are listed below.

Too low a snap-off will weaken ink transfer and result in bad and uneven print quality.

Too high a snap-off increases the need for pressure, screen wear, squeegee rubber wear and can also result in a thinner imprint. The stretching of the screen causes changes to the pattern, resulting in registration problems in multilayer printing.

The optimum snap-off distance is as close as possible to the substrate, but is sufficient enough to separate the screen from the substrate as the squeegee progresses.

To determine the correct snap-off distance, attention should be paid to the size of the screen, the mesh tension and material, the viscosity of the printing ink and the speed of the squeegee. Generally, a steel or polyarylate screen is stretched tighter than polyester or nylon screens, and therefore, the snap-off with these screens does not have to be so large. The larger the screen is, the greater distance from the substrate is required.

There are different devices for measuring the snap-off distance, which should be taken into the consideration to be used if the aim is to optimise the printing process and to secure the print repeatability and quality.

[1] Tuomaala, T. 2016. Manufacturing of Electrochemical Biosensor Platforms Using Screen Printing Methods in Oulu UAS PrinLab Environment. Oulu University of Applied Sciences. P. 29. http://urn.fi/URN:NBN:fi:amk-2016113018354. Date of retrieval 12.4.2018.

[2] Dupont. 2016. Basics of screen printing thick film inks. http://www.dupont.com/products-and-services/electronic-electrical-materials/articles/basics-of-screen-printing.html Date of retrieval 12.4.2018.

2.3 Printing screens

The screen printing screen consists of a frame, a mesh and an emulsion. The most important properties of the screen are the properties of the mesh, emulsion thickness value and optimal screen tension between the frame and the mesh. Figure 7 presents an example of the screen, where the mesh has been stretched onto the frame, the emulsion has been added onto the mesh and the photo plot work has been done.

The screen manufacturing process is presented in Figure 8. The customer specifies the optimal screen materials and parameters. The screen manufacturer stretches the mesh onto the frame, makes the emulsion and the photo plot, checking the quality of the screen, and finally delivers the finished screen to the customer. A normal delivery time for the finished screens is typically 1–2 weeks.

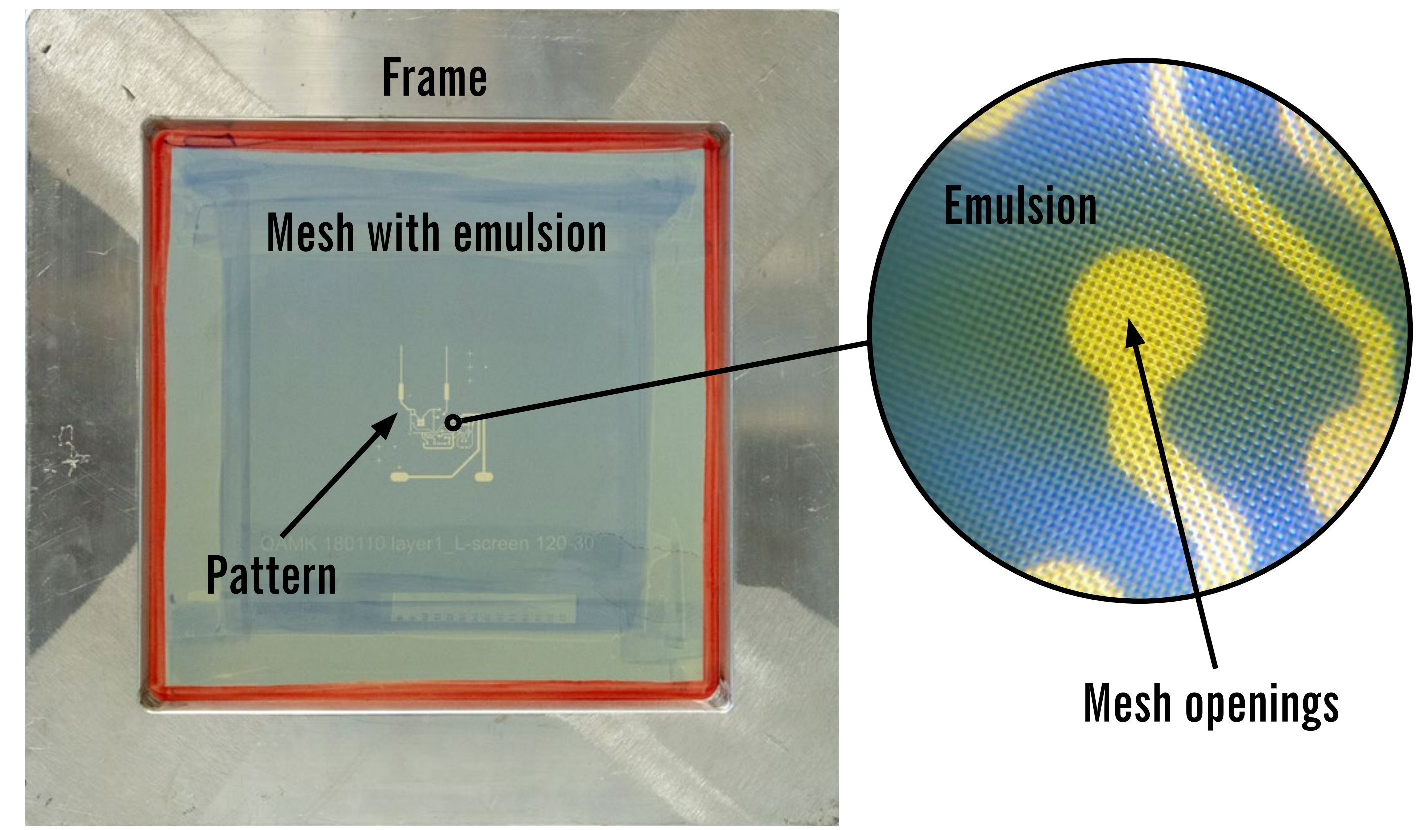


Figure 7. *An example of a print ready screen. Photo credit: Tomi Tuomaala.*

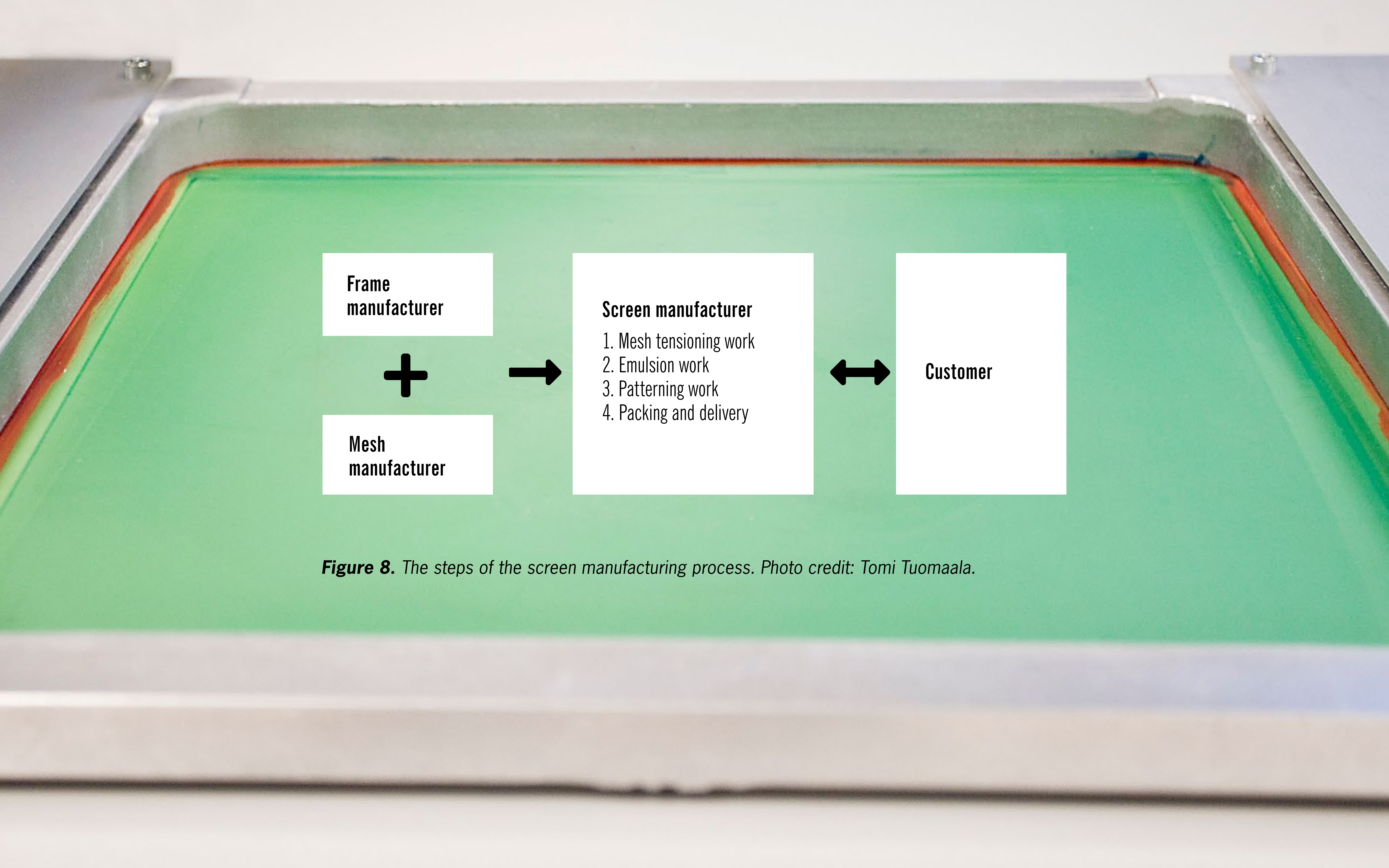


Figure 8. *The steps of the screen manufacturing process. Photo credit: Tomi Tuomaala.*

2.3.1 Screen materials and structure

The main function of a screen mesh is to enable the deposition of exactly right amount of ink onto the substrate. Also, the mesh holds the emulsion that makes patterning possible. The mesh material properties, structure and thickness must be of uniform quality. Also, the mesh material must be chemical resistant, because of the solvent-based printing inks and detergents.

The manufacturers of the screen printing mesh usually offer a wide range of different mesh materials. The most common mesh materials are nylon, polyester, polyarylate and steel. Usually, mesh materials have been developed for industries, where reproducible printing parameters, a high number of printing runs and the best possible printing quality are needed. Printing process engineers should have a good knowledge of the materials to be able to choose the proper mesh material for each process.

Figure 9. *Checking the mesh quality. Photo credit: Jussi Tuokkola.*

A nylon mesh is well suited for printing onto curved or uneven surfaces, because of the flexibility, mechanical resistance and elasticity. The advantage of the nylon mesh is also its inexpensive price. It is not advisable to choose nylon for a process that needs high precision printing and exact layer alignment accuracy, because of the elastic properties of the nylon mesh, which can cause distortion on the pattern. [1] [2]

Steel and polyarylate meshes are the answer to the demands of high precision and high quality printings. The basic properties of the mesh material are thinner thread diameters, greater mesh openings and thread distances. These meshes are very stable in the printing process, they do not stretch and loose tension easily. The polyarylate fabric is superior to the steel fabrics with its features of very accurate print quality. Figure 10 presents the 150x magnification of a polyarylate mesh with a thread diameter of 30 µm and 250 threads per inch.

Polyester meshes are more cost-efficient and enable a high quality printing line, but they do not win the properties of polyarylate or steel meshes. Polyester meshes are mostly used by graphic, textile and packaging industries. Steel and polyarylate meshes are popular in printed electronics applications, where the precision requirements are higher and the pattern scale is smaller. [2]

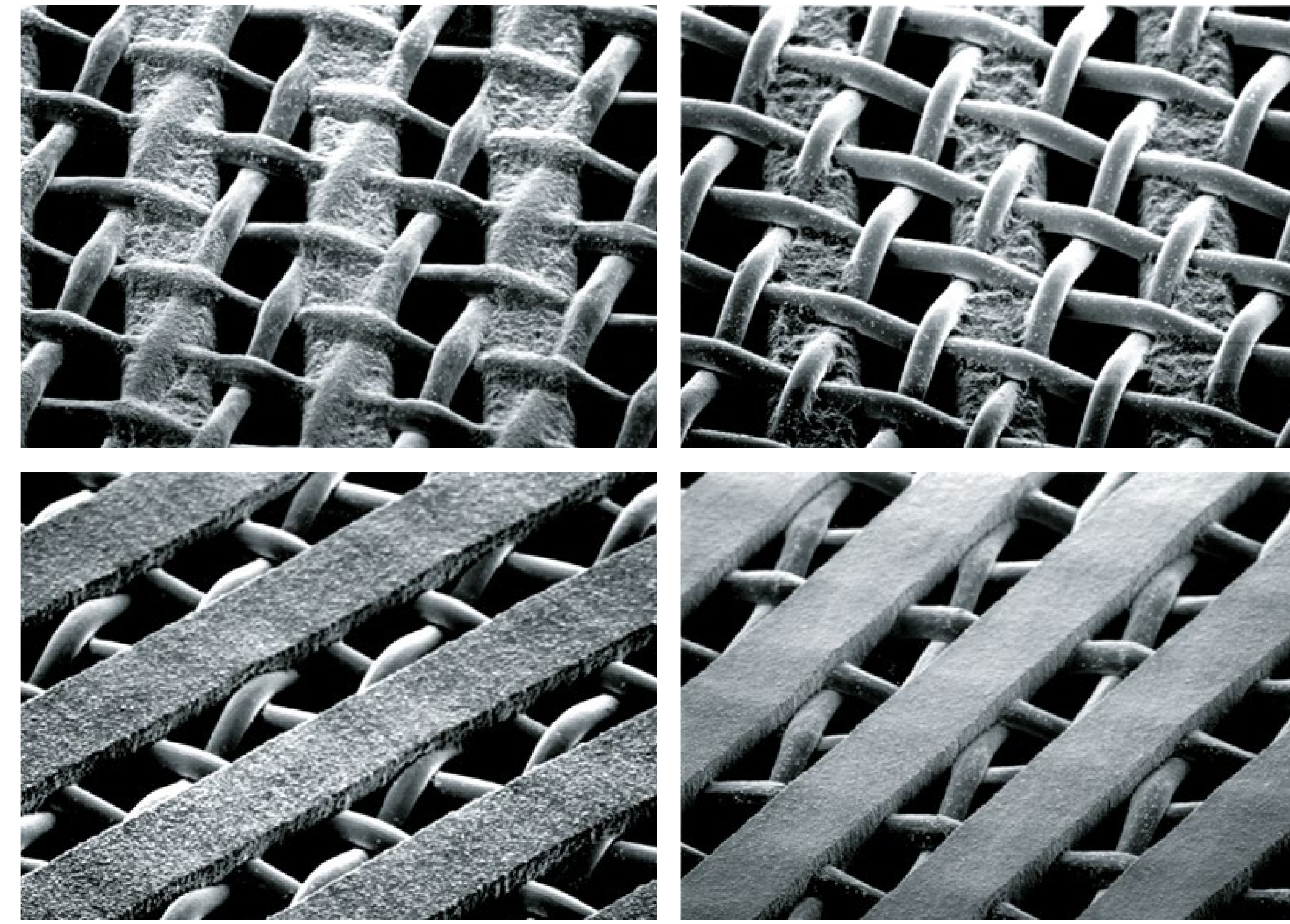


Figure 10. *A 150x magnification of polyarylate mesh of NBC Meshtec VScreen 250-30µm. [3]*

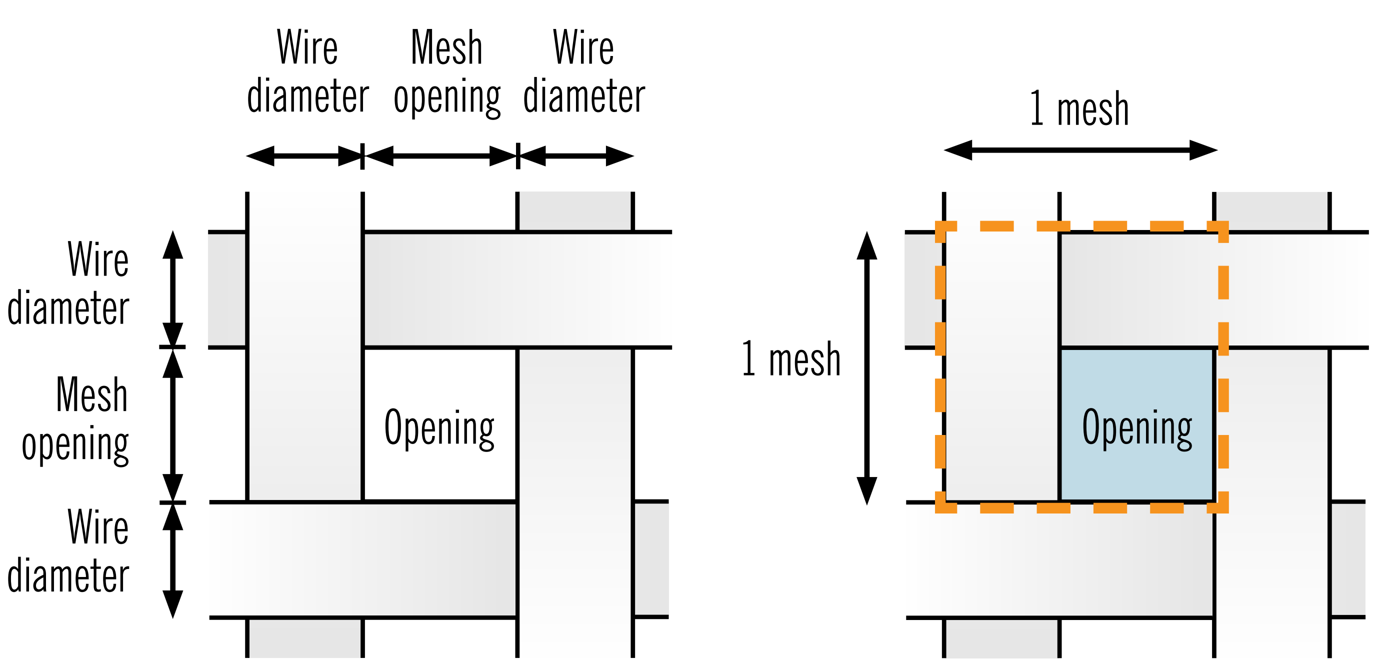
In the screen printing process, it is important to consider whether the stability of the polyester mesh is sufficient for the manufacturing of multi-layered structures and whether the alignment accuracy and repeatability are sufficient. The properties of meshes can be compared with the help of technical data sheets from different mesh manufacturers. They offer diverse information about the mesh materials and their properties.

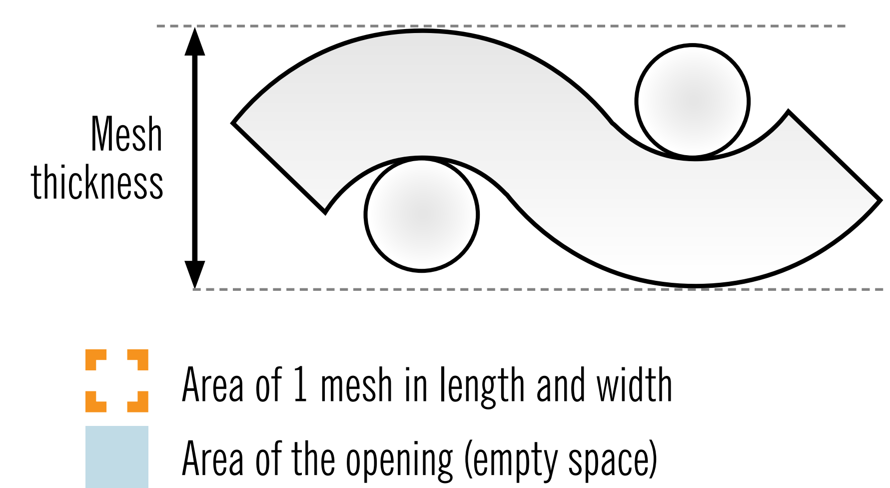
2.3.2 Properties of screen meshes

A screen mesh consists of knots, threads and openings between them. The screen mesh structure is presented in Figure 11 below. The properties of the screen mesh directly affect the quality of print. It is important to consider the diameter of the thread, the thickness of the mesh and the mesh opening area. The opening area is expressed in per cent, other values are expressed in micrometres. If the printing ink of the particle size is known, it is important to check the distance between the threads. Typically, thread distances are called mesh opening.

Mesh density, i.e. a mesh count means how many threads or knots are located in a mesh per a certain distance. The mesh count could vary from 30 threads/inch to 500 threads/inch.

A bigger mesh density/count and a thinner mesh pass through less ink and allows more accurate and smaller patterns to be printed. A thinner thread diameter and a bigger mesh count also enable more smoothness and capability to print thinner lines and more detailed pattern.





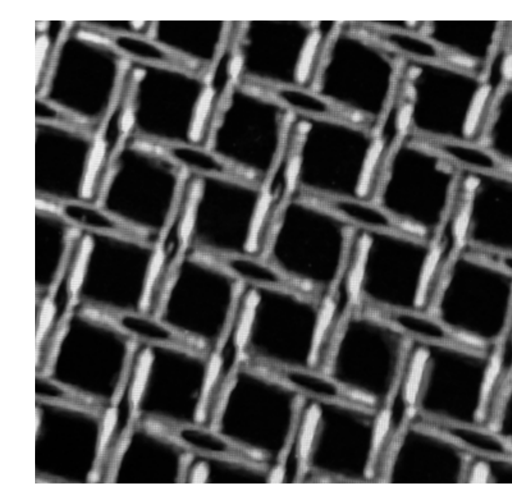


Figure 11. *The mesh consists of knots, threads and openings between them. [7]. Reproduced from [8], figure credit: Inka Väisänen. Photo credit: Jenina Bomström.*

2.3.3 Screen frame

A screen frame is usually made of steel or aluminium. The object of the frame is to keep the screen mesh in place with a certain defined tension. The frame works also like an ink manger. In the screen printing process, the tension of the screen mesh must remain constant. If the screen tension value changes, the print quality will not be reproducible. It can also cause registration problems between the printing layers. The frame must also be solvent resistant, because most of the printing inks are solvent-based. For these reasons, the recommended material for the frame is steel or aluminium. [4]

The size of the frame is chosen based on the dimensions of the printed pattern taking also into account the size of the used squeegee. The maximum size for the printed pattern is two-thirds of the internal dimensions of the frame. The best print result is achieved by dimensioning the print pattern half the size relative to the internal dimensions of the frame. Figure 12 presents an example of the dimensions of the printing pattern relative to the inner dimension of the frame. [5]

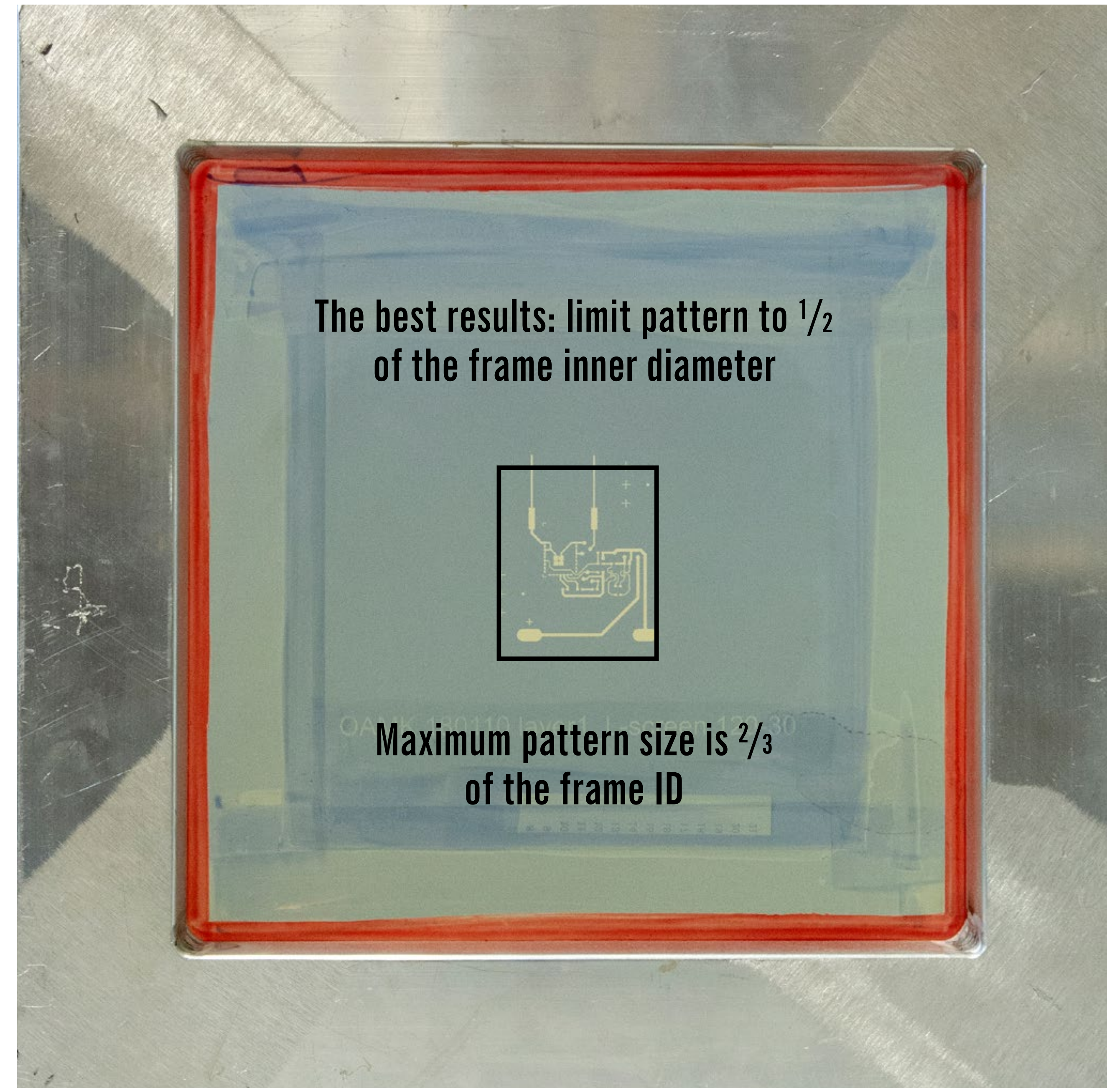


Figure 12. *The limits for the screen pattern size. Photo credit: Tomi Tuomaala.*

A bigger screen or frame needs more mesh material, and therefore, a bigger screen is more expensive. The mesh is mounted onto the frame to the desired tension and angle. The angle is called a “mesh angle”. Typically, the mesh angle is 90, 45 or 22.5 degrees. [4] A smaller mesh angle reduces or eliminates the distortion caused by the stretch of the mesh. [6]

A 22.5 degree mesh angle is recommended if the focus is a high-resolution print, narrow line widths or narrow insulation spacing. A 45 degree mesh angle is recommended if the resolution requirement is not high, but the edge of the printing line needs to be smooth. A 90 degree mesh angle is mostly used in the coating or plating process or in processes where precision requirements are less important.

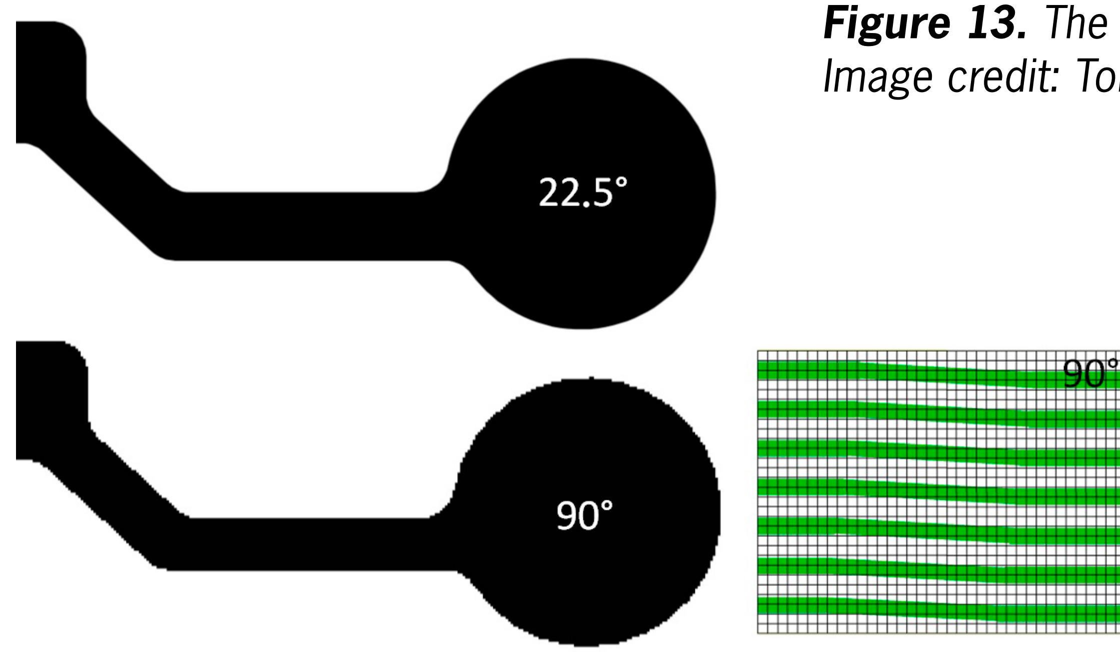


Figure 13. *The mesh angle effect on the printed line. [6]. Image credit: Tomi Tuomaala.*

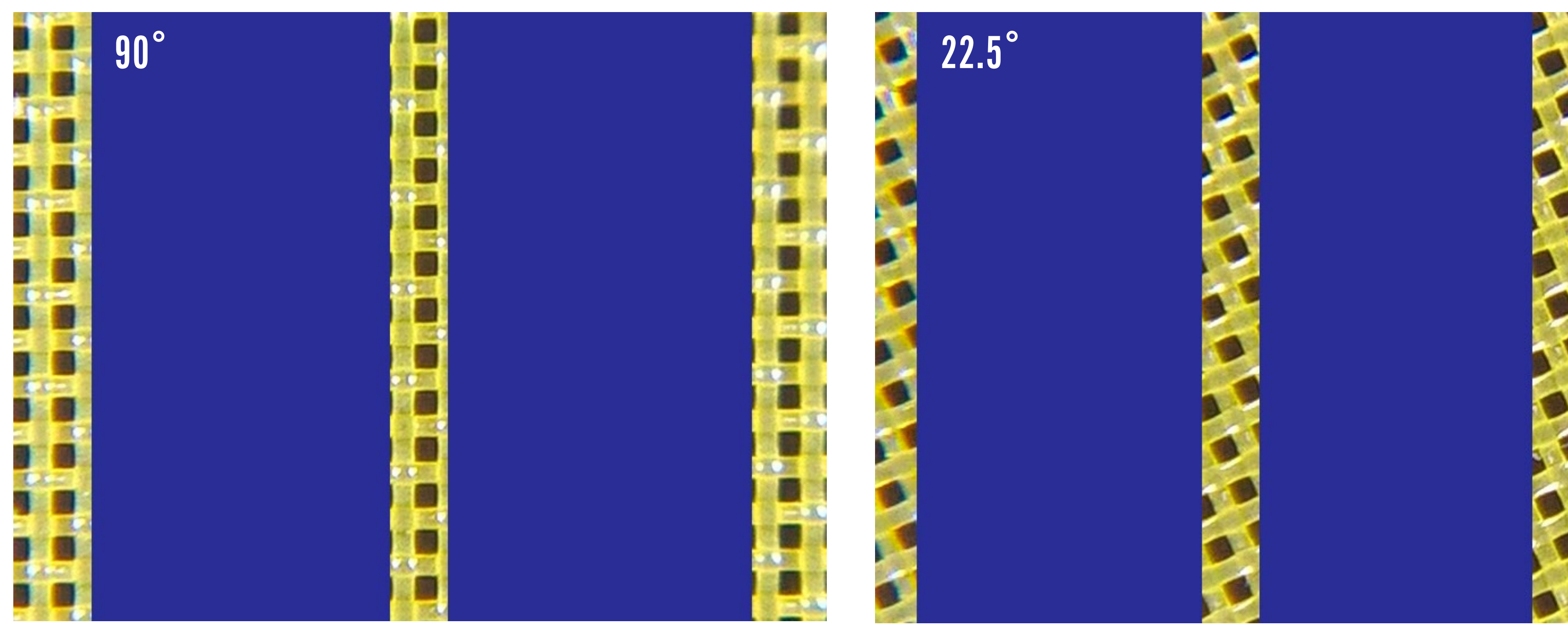


Figure 14. *Different mesh angle positions. [6]*

2.3.4 Mesh tension

The tension of the screen mesh must be checked regularly. The tension is one way to monitor the condition of the screen. During the printing process between the screen and a substrate, there is always a small gap. The screen mesh is somewhat elastic, and therefore, when the squeegee pressure is applied, the screen mesh is stretching because of the pressure of the squeegee of top on the screen. During the printing process, the squeegee moves forward, and because of the gap and the squeegee pressure, the screen peels off from the substrate immediately after the squeegee and deposition of the ink is controlled.

The tension meter is an instrument, which is used for checking the screen tension. The screen tension unit is N / cm. Figure 15 presents a method of checking the screen tension. Usually, the screen tension values are between 15–40 N / cm, depending on the mesh materials, the printing quality needs, the used substrates and squeegees. Usually, the tension of a metal mesh is higher than that of nylon or polyester meshes. The supported and recommended tension values of mesh materials can be checked from the screen mesh manufacturer's data sheet.

In the printed electronics, precision demands are usually high, therefore it is important to follow the condition of the screen and the mesh tension regularly. The repeatability and registration accuracy of the printed layers depends on the condition of the screen. A change in the mesh features affects the print quality.

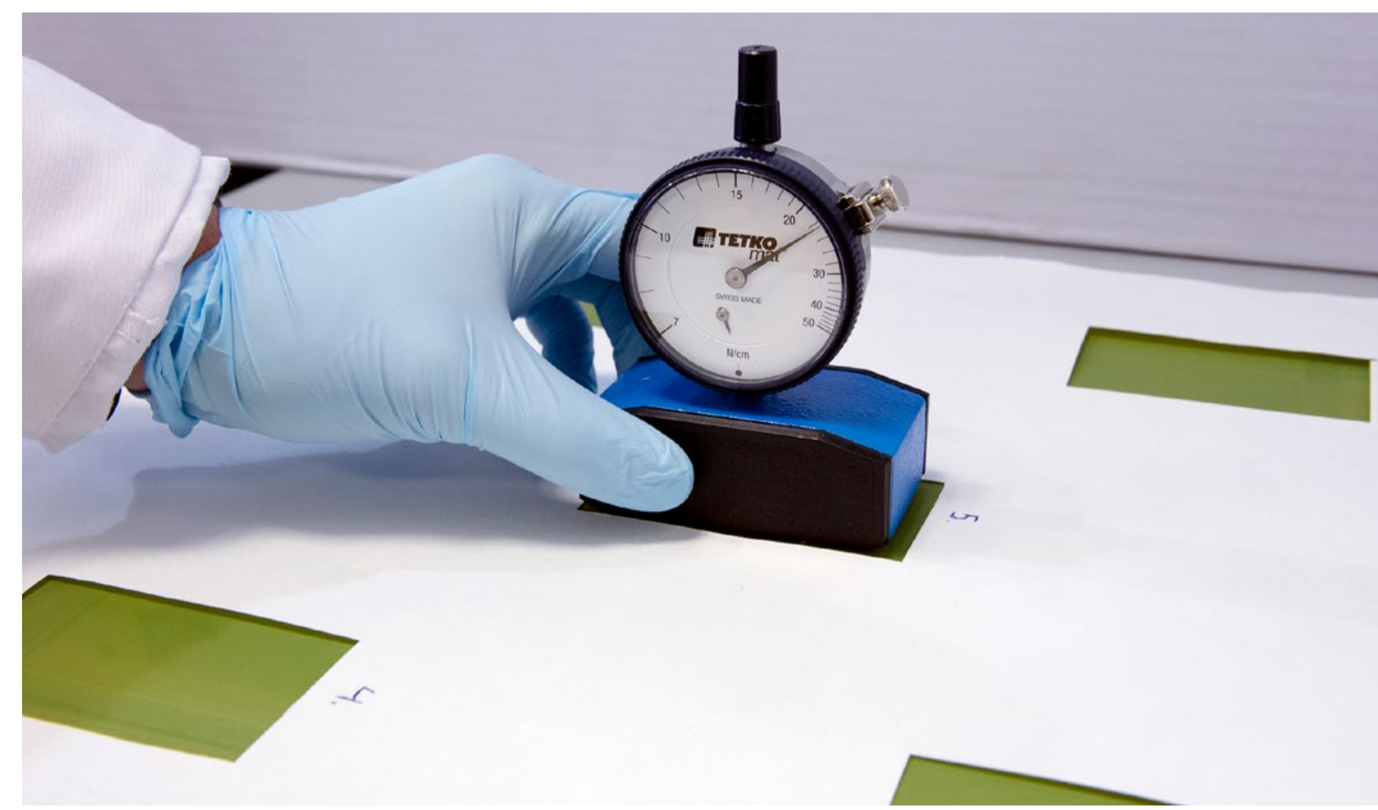


Figure 15. *Measuring the tension of the screen. Photo credit: Anne Peltola.*

2.3.5 Emulsion

The surface of the screen mesh is coated with a photosensitive emulsion. The emulsion is spread over the screen and dried. After the emulsion has dried, the desired print pattern is exposed through a positive film using a UV light. The UV-protected area of the positive film keeps the UV light away from the emulsion surface and that part of the emulsion does not cure and is washed away. The thickness of the emulsion and the mesh form the total thickness of the screen. The thickness of the emulsion is one critical value for the total thickness of the layer if the width of the pattern line is under 10 mm. [1] [2]

There is a variety of emulsion materials available and usable with different screen mesh and printing inks. When choosing the emulsion, it is good to use the screen manufacturer's recommendations and data, if possible. During the selection for the emulsion material, it is important to know the specific properties of the emulsion. For example, if the emulsion is solvent resistant, it has an effect on how well printing ink will wet on top surface and what kind of emulsion thickness is possible to achieve. [5]

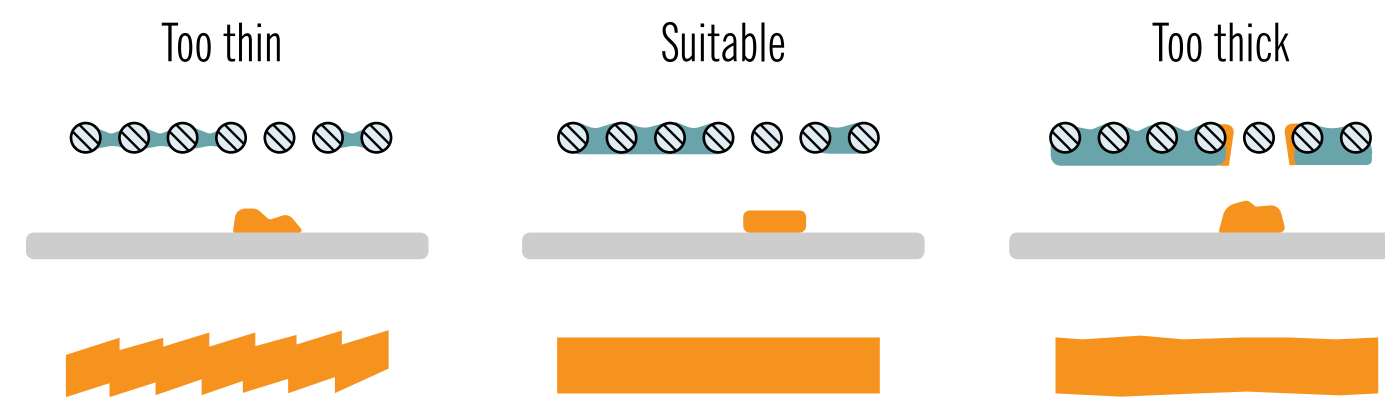


Figure 16. *How the thickness of the emulsion affects the print line. Reproduced from [7], figure credit: Inka Väisänen.*

Because the emulsion has to overlay the mesh threads, the emulsion slightly covers the mesh threads from the substrate surface. This improves the printing ink flow under the threads onto the substrate. Figure 16 presents the importance of the thickness of the emulsion during the printing process. A high viscosity ink and a too thin emulsion will cause a serrated edge in the printing. A too thick emulsion causes problems with the flow of the ink through the mesh, so that the theoretical ink volume is not what is expected. As a basic rule, the thickness of the emulsion should be about 10 % of the thickness of the mesh, usually about 5 to 30 μm.

If there is a need to increase the thickness of the printed pattern and the pattern opening area is under 2 mm, it can be realized by increasing the thickness of the emulsion. It should be noticed that if the pattern opening area is over 2 mm and the emulsion is thick, it causes the thicker line edge.

Table 1 below shows that when the thickness of the total layer is calculated and if the width of the pattern line on the emulsion is less than 2 mm, the thickness of the emulsion is still a critical value. However, if the pattern opening is more than 10 mm in width, the thickness of the emulsion is no longer significant.

Width of the pattern openings	**Relevancy for the total thickness of the printed pattern**
< 2 mm	100 %
2–5 mm	67 %
5–10 mm	33 %
> 10 mm	0 %

Table 1. *The emulsion relevancy for the total thickness of the print line. [5]*

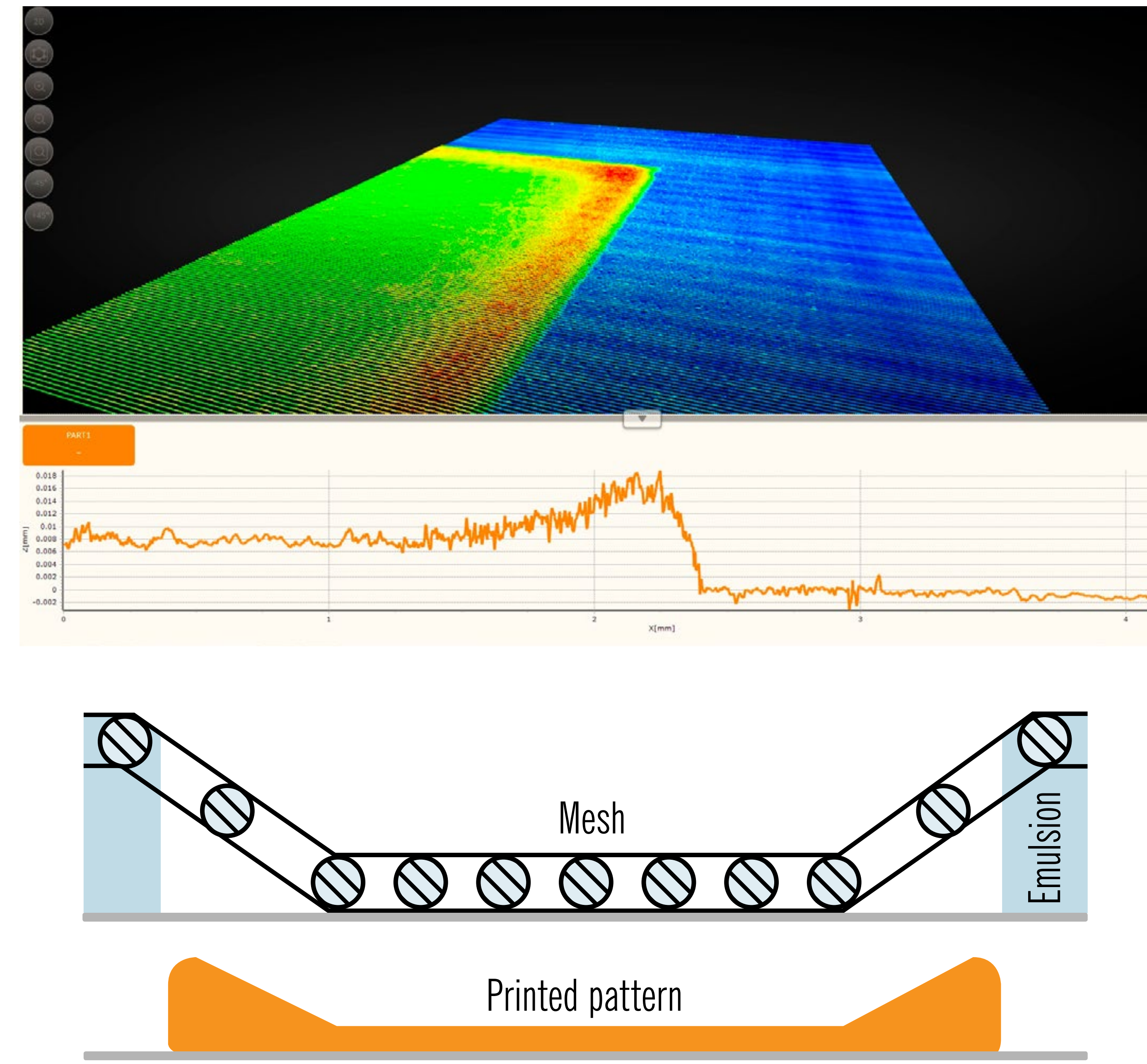


Figure 17. *An example of the printed pattern if the pattern opening is higher than 2 mm and thickness of the emulsion is high. Image credit: Tomi Tuomaala. Reproduced from [7], figure credit: Inka Väisänen.*

2.3.6 Design rules for screen printing screens

The printing screen consists of a frame, a mesh and an emulsion with a pattern. For printed electronics applications, usually the print line needs to be exactly at the desired thickness, relatively wide and smooth. The printing ink and its viscosity must also be taken into account when designing the screens. In this chapter, the aim is to highlight the most important design rules for printing screens to achieve the desired printing result.

The most important values of the screen are

- the number of threads by inch or metric (mesh count)
- mesh thickness
- opening percentage (mesh opening)
- thread thickness
- distance between the threads
- emulsion thickness
- mesh angle
- mesh tension.

The higher the mesh count value is, the smaller is the distance between threads and the diameter of the thread, which means smaller capacity to pass the ink. This usually means a better capability of printing thinner, narrower and smoother layers.

Before selecting the screen mesh materials, it is necessary to know what the desired thickness of the layer and line width is, including basic information about the used printing ink. Below are listed some important things that need to be considered when designing the printing screens.

- The mesh must be chosen so that the diameter of the mesh thread is three times thinner than the narrowest line width of the printed pattern.
- The distance between the threads must be three times larger than the particle size of the printing ink. [7]
- The thickness of the emulsion should be at least 10 % of the mesh thickness.

- The recommended tension value for the mesh can be found from the mesh manufacturer's technical data sheets; usually the tension is around 15–40 N / cm.

The Theoretical Ink Volume (TIV) value can be found on the technical data sheets of the mesh. The TIV value means the mesh capacity to pass through the printing ink; the unit is cm^3/m^2. The TIV value may also be thought to be the wet thickness of the ink layer in micrometres. In reality, the wet thickness is about 10–20 % lower than the TIV depending on the viscosity of the printing ink, the throughput of the ink and also of the thickness of the emulsion. The thickness of the emulsion can still fine-tune the total wet thickness if the line width of the pattern is under 10 mm. The significance of the emulsion to the wet thickness has been described in Table 1 on the previous page. The viscosity also plays a big role for the total wet thickness. The viscosity relevancy may vary from 25 % to 50 % depending on how viscous the printing ink is.

[1] PVF. 2015. Precision mesh & solutions for industrial applications., http://pvfgmbh.de/en/wp-content/uploads/2015/01/PVF-SCREEN-PRINTING-BROCHURE-2014-KL.pdf. Date of retrieval 31.5.2016

[2] Gamota, D., Brazis, P., Kalyanasundaram, K., Zhang, J. 2004. Printed organic and molecular electronics. Kluwer academic publishers. USA. P.310–311

[3] Screen printing application products, V-SCREEN. NBC Meshtec. http://www.nbc-jp.com/eng/product/screen/mc/vscreen.html. Date of retrieval 15.3.2019.

[4] Viluksela, P., Ristimäki, S., Spannäri, T. 2007. Painoviestinnän tekniikka. Otavan kirjapaino Oy. Keuruu. P.90

[5] Pittson, R., Jones, L. 2014. Screen printing training materials. Wales, Pontypool: Gwent Electronics materials ltd.

[6] SaatiPrint. 2001. Tech tips for screen printers. http://www.catspitproductionsllc.com/Documents/SaatiPrint%20TechTip%20Handbook.pdf. Date of retrieval 3.4.2019. P.35

[7] Hobby, A. 1997. Screen printing for the industrial user. Gwent/Sun Chemical. http://www.gwent.org/gem_screen_printing.html. Date of retrieval 13.4.2018 . Chapter 4.6 and 5.6. Gwent/Sun Chemical.

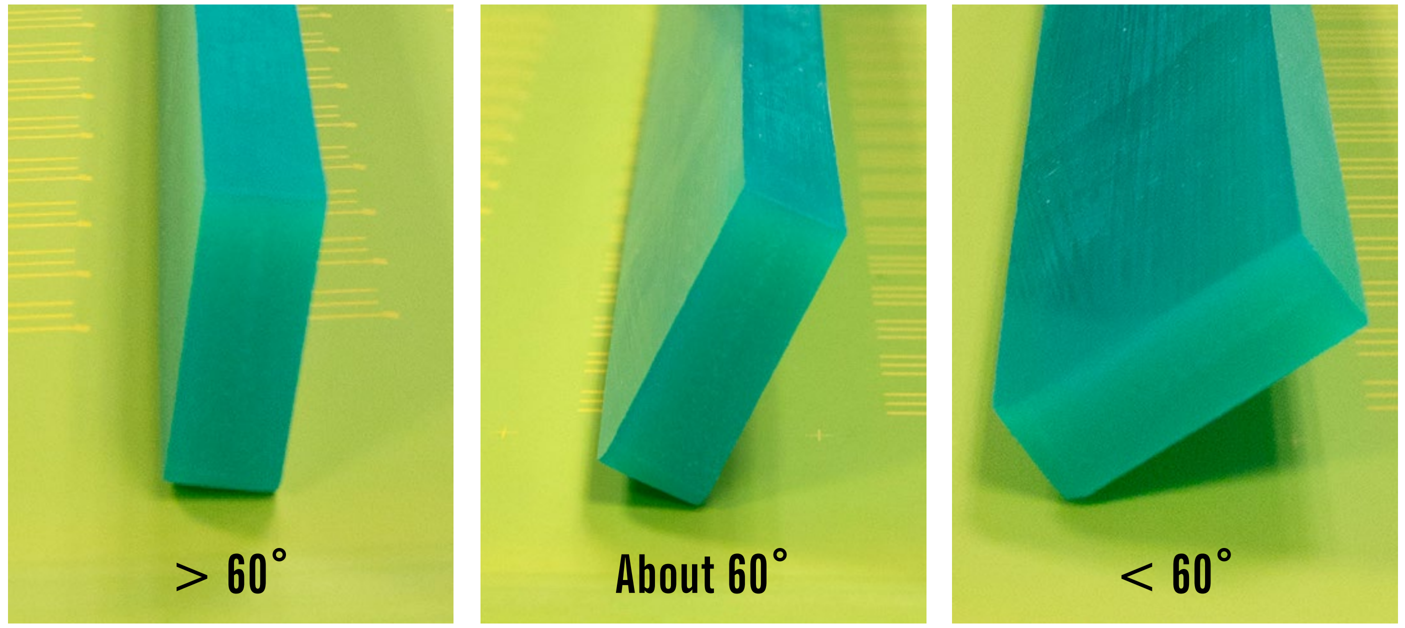
[8] http://www.murakami.co.jp/english/products/fiber.html. Date of retrieval 15.4.2019.

2.4 Printing squeegee

The role of the squeegee in the screen printing process is to squeeze the printing ink through the screen openings onto the substrate under the screen. Squeegee rubbers are available in different sizes, shapes, hardness and materials.

The angle of the squeegee affects the downward force of the printing ink. Too large an angle does not push the ink well enough through the mesh. A small angle results in poor doctoring of the ink, the ink under the squeegee will try to lift it off from the mesh and the ink transfer will deteriorate.

If a rectangular shape of the squeegee rubber is used, the optimum angle is about 60 degrees. During the printing process, the angle is approximately 45 degrees, because of the rubber elasticity. [1] Figure 18 presents the importance of the squeegee angle. Too large an angle causes poor filling and good clearance. A smaller angle gives poor clearance, but good filling.



Poor filling, good clearance. | Good filling and clearance. | Smaller angle giving poor clearance, but good filling.

Figure 18. *Squeegee angle effect on quality. Photo credit: Anne Peltola.*

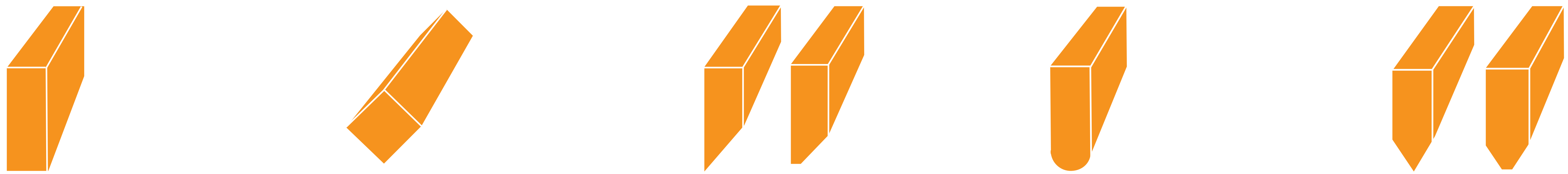
2.4.1 Squeegee size, form and material

Solvent-based printing inks are typically used in screen printing. The squeegee rubber material should withstand these solvents. A commonly used rubber material is the polyurethane. Depending on the chemical composition of the polyurethane or the solvents used, the rubber may harden or soften by the use of the solvent. [2]

The size of the squeegee affects how it is stretching the screen mesh from the edge of the screen, thus causing distortion on the print pattern and alignment accuracy. The size of the squeegee also affects how rapidly the screen mesh and squeegee rubber wear down. The squeegee should be 1–2 cm wider than the pattern. It is recommended that the rubber should be slightly narrower than the adapter. If the rubber is wider than the adapter, it will cause vibration, which can weaken the print quality.

The inner width of the screen frame should be at least twice as large as the width of the squeegee. [3] It is also important to note that if the screen pattern is too large in comparison with the screen diameter, too wide a squegee has to be selected and the process will not be optimal.

The squeegee rubbers (blades) are available in many shapes, which are suitable for different purposes. Figure 19 presents the most common types of rubber blades and where they are best suited.



Rectangle
is widely applicable for different substrates, inks, generally used in graphics and textiles, also usable in printed electronics.

Diamond
is a good blade for very accurate printing llines. It is popular in printed intelligence processes and in stencil printing.

Single cut
is used for uneven or irregular substrates.

Round
is used for textile printings.
It has maximum color transfer.

Double cut
is used for glass or plastic cylinder-shaped surfaces, including textiles.

Figure 19. *Different squeegee rubber shapes. Reproduced from [4], figure credit: Inka Väisänen.*

Figure 21 below presents the printing blades that are commonly used in manufacturing printed electronics. The two most popular blade types are a rectangle and a diamond. A blade may also consist of a number of different harnesses, soft/hard/soft structures. For example, the structure of the blade may have a stiffener inside and softer material on the edges. An interesting choice is also a blade where a separate background plate supports the rubber blade. A supporting rubber structure enables to use more pressure during printing. Figure 20 presents the advantage of structurally supported blades for longer lasting printing processes. The softer rubber gets worn and loses its hardness and the doctoring is weakened.

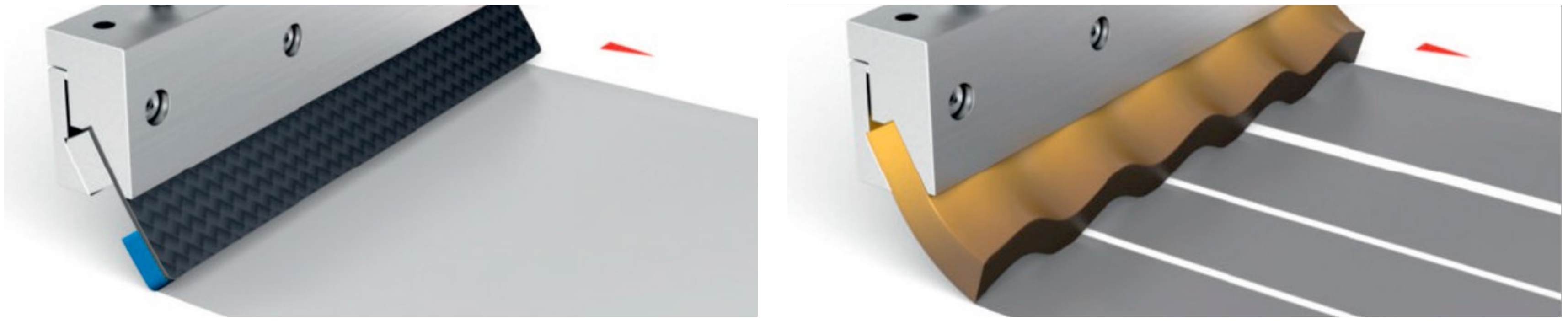


Figure 20. *The difference between a basic rectangular blade and an RKS carbon S HQ blade. [5]*

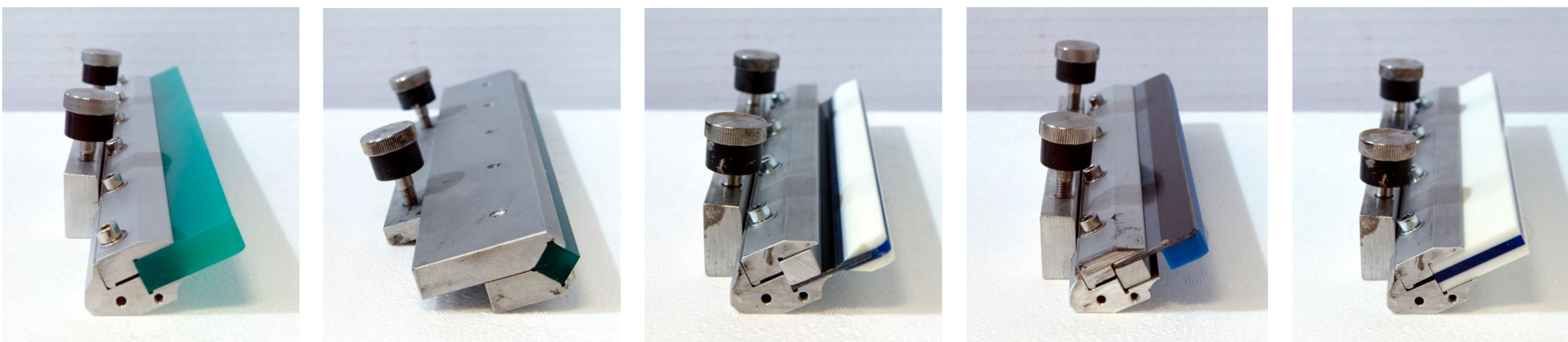


Figure 21. *The mostly used printing blades. Photo credit: Anne Peltola.*

2.4.2 Squeegee hardness

In the screen printing process, the hardness of the squeegee rubber blades is indicated at the shore A scales. The scale usually varies between 55 to 95 shore A. The shore is an important criterion for the suitability of rubber blades for the printing process and quality. The blades are usually colour-coded. Squeegee manufacturers sell their blades by announcing mainly the hardness. However, there is also a significant difference between the elasticity, stiffness, stretch and flexibility of the blades. [4]

The purpose of Figure 22 is to show the affect of the hardness of the blade to the amount of transfer of the printing ink through the screen mesh. Generally, the hardness of squeegee blades is classified into three categories: soft, medium and hard. A softer blade, such as 60–65 shore A, should be used if the substrate is uneven, the printing ink has a low viscosity or line width is wide, for example for the coating purposes. A medium hardness from 70 to 75 shore A is the most commonly used one. A hard blade from 80 to 90 shore A is the best with high viscosity inks, because the printing pressure can be set higher. A hard blade is most widely used with very thin meshes, where the aim is to print very thin layers.

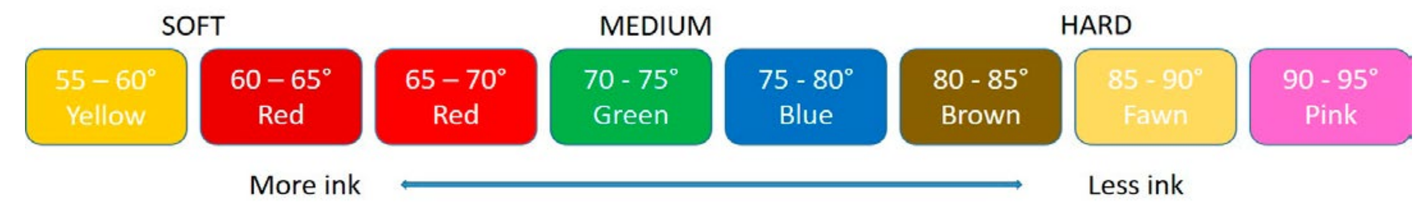


Figure 22. *The hardness of the blades and their characteristic colors. Reproduced from [4], image credit: Harri Määttä.*

[1] Hobby, A. 1997. Screen printing for the industrial user. http://www.gwent.org/gem_screen_printing.html. Date of retrieval 13.4.2018. Chapter 6.5. Gwent/Sun Chemical

[2] Gamota, D., Brazis, P., Kalyanasundaram, K., Zhang, J. 2004. Printed organic and molecular electronics. Kluwer academic publishers. USA. P.314

[3] Dupont. 2016. Basics of screen printing thick film inks. http://www.dupont.com/products-and-services/electronic-electrical-materials/articles/basics-of-screen-printing.html. Date of retrieval 14.6.2018

[4] Trelleborg. 2016. Unitex Squeegees, Printing for the long run. https://www.trelleborg.com/en/printing/products--,-a-,--solutions/screen--printing. Date of retrieval 9.4.2019. P. 3 and 7

[5] RKS. 2018. PRINTED ELECTRONICS/SOLAR. Product catalogue. https://user-90869221.cld.bz/RKS-GESAMTKATALOG-2018-2019/26/. P. 32

2.5 Screen printing inks

The requirements for the printing quality are higher for electronic applications than for graphical printing. This means that the inks vary quite a lot, and in many cases functional printing inks are more difficult to handle than graphical printing inks.

In screen printing, the features required by the printing ink include, but are not limited to, the permeability properties with the mesh and the emulsion and the adhesion and wetting properties with the substrate. The ink drying properties during printing are also important, for example how quickly the viscosity of the ink is changing during the printing process because of the solvent evaporating from the ink. The printing ink must also have suitable curing properties with the used substrate. These important properties are the curing temperature and time. Usually, commercially available functional screen printable inks are optimised for the printing process.

The printing ink usually consists of a pigment, a binder, solvents and other additives [1]. In printed electronics, there are also

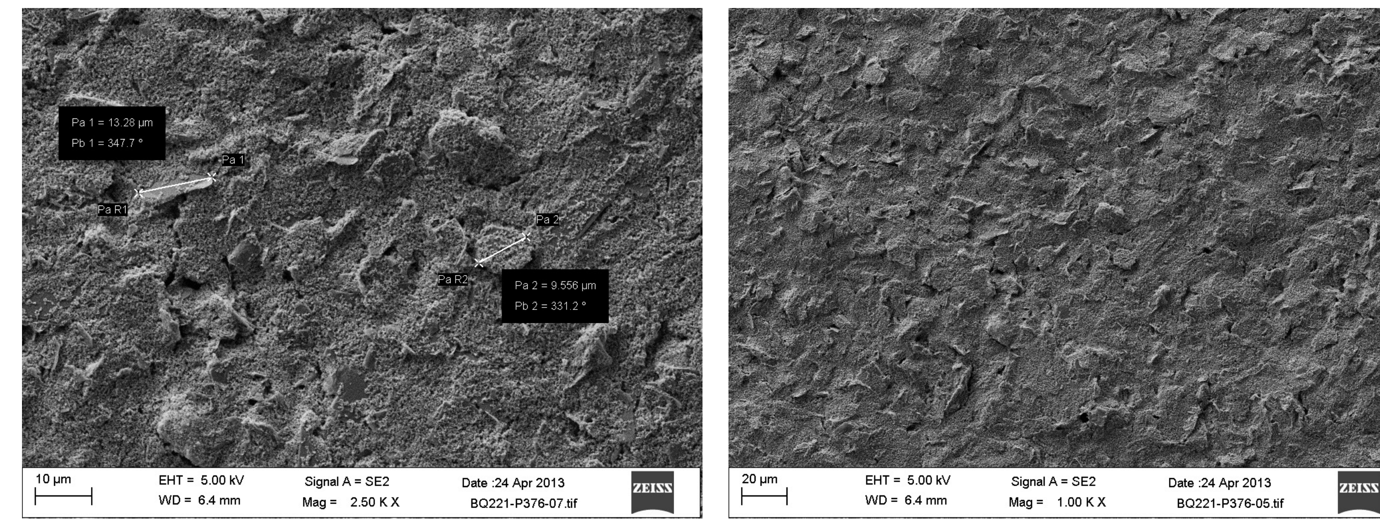


Figure 23. *A FESEM image of the carbon particle based ink printed on the PET substrate. [2]*

functional particles, such as graphite, silver, copper or other metals, metal oxides or organic materials. These functional materials make the intelligence properties for the ink. In printed electronics, the metal content of the ink could be up to 90 wt%. The metal particle size usually ranges from some hundred nanometers up to several micrometers. Figure 23 above presents the field emission scanning electron microscopy image of some of screen printable carbon particle based ink, which is screen printed and cured onto the PET substrate.

The viscosity of the screen printing ink may vary from 0.5 to 70 Pa s. During the printing process, the ink moves in front of the squeegee blade across the screen and flows through the mesh openings onto the substrate. If the ink viscosity is too high or low, it will cause problems to the process or the process parameters are more difficult to optimise. It is also good to remember that solvent evaporation and shearing during the printing process may change the viscosity of the ink.

In screen printing, the ink does not penetrate 100 % through the mesh. The thicker the ink is, the smaller amount can reach the substrate, of course, depending on the mesh count, the thread diameter and the mesh opening percent. If the viscosity is low, such as water or buttermilk, the ink is more challenging to control in the printing process. The ink tends to flow through the mesh independently and cause quality problems. The process is not controllable if the ink can independently flow through the mesh.

Figure 24 presents the viscosity of the effect of the printing ink when it is drained freely into the jar. This is a simple way to analyze if the viscosity level is optimal. Various rheological measuring instruments or methods can monitor the viscosity more accurately.

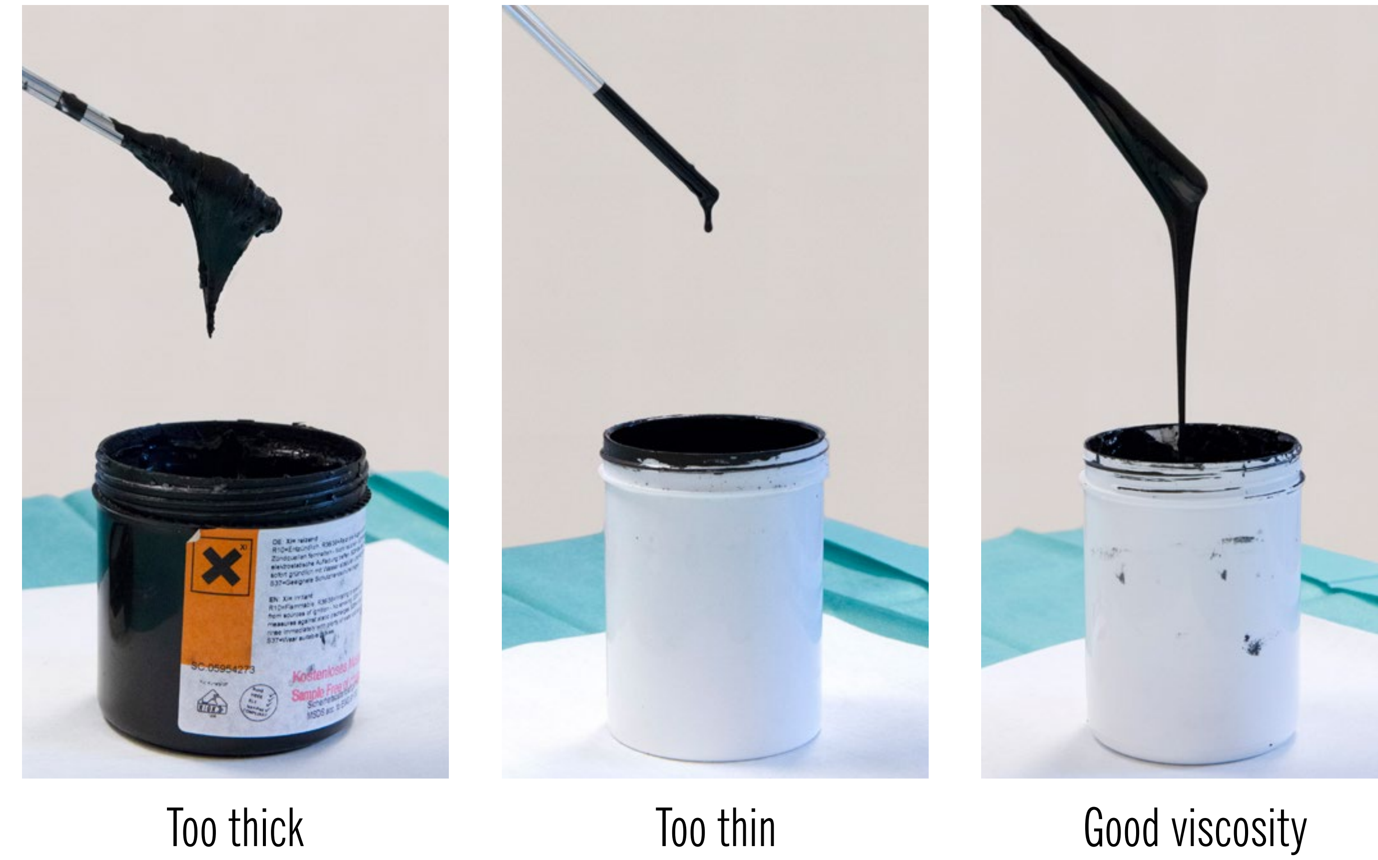


Figure 24. *Viscosity check of inks. Photo credit: Anne Peltola.*

It is important to read the technical information about the ink from the manufacturer's data sheets before printing or even ordering. Sometimes the viscosity of the printing ink is too thick and needs to be modified. Usually, an ink manufacturer gives the information for the proper solvent type for each ink. A simple way to check the quality of the printing ink is to use a grindometer, which measures the fineness of a grind or a particle size in the printing ink. If there are clearly detectable single clumps, it is recommended to use fresher ink if possible or to evaluate the ink quality more widely.

The particle size determines how long the distance between the mesh threads can be. The distance between the threads must be three times larger than the maximum particle size of the printing ink, e.g if the particle size of a printing ink is 10 µm, the distance between the threads must be at least 30 µm. [3]

Figure 25. *The principle of a grindometer. Photo credit: Jenina Bomström.*

[1] Viluksela, P., Ristimäki, S., Spannäri, T. 2007. Painoviestinnän tekniikka. Otavan kirjapaino Oy. Keuruu

[2] Nelo, M. 2012. Bioprint -project. Carbon particle based ink printed on the PET substrate. FESEM image. Microelectronics Research Unit, University of Oulu.

[3] Hobby, A. 1997. Screen printing for the industrial user. http://www.gwent.org/gem_screen_printing.html. Date of retrieval 13.4.2018. Gwent/Sun Chemical.

3. Manufacturing of a multilayer structure

TOMI TUOMAALA AND HARRI MÄÄTTÄ

Photo credit: Jussi Tuokkola

3. Manufacturing of a multilayer structure

The choice of a manufacturing method is largely affected by the ability of the method meeting the requirements of the product being manufactured. In the printed electronics manufacturing, screen printing is best suited to a situation, where a quite thick printing layer is required, the requirements of the printing capacity are moderate or high and where it is important to ensure the availability of commercial printing inks and substrates. Screen printing is also well suitable for manufacturing a multilayer structure.

The yield, quality and especially repeatability of the screen printing method are well suited to the challenges posed by the alignment of the multilayer structure. The screen printing method enables the printing of overlapping layers with accuracy of tens of µm, which is sufficient for a wide range of structures.

In order to get a good quality print result of a multilayer structure, the first objective is to find the correct parameters for the screens and the printing process. In addition, the material choices, such as substrates, inks and accessories used, the manufacturing conditions as well as the geometric dimensions of the multilayer structure will affect the printing result.

In the manufacturing of a multilayer structure, it is essential to guarantee sufficient registration accuracy. The requirements of registration accuracy can be met by ensuring the correct screen design and fabrication and by ensuring that all the materials and process parameters are well tested and used exactly as has been planned.

3.1 Screen design

The screen design should start, by carefully going through the requirements for the layout or component to be printed. When screen printing is to be used as a manufacturing method, the designer should also consider the restrictions set by the manufacturing method. However, this applies to any manufacturing method, not just to screen printing.

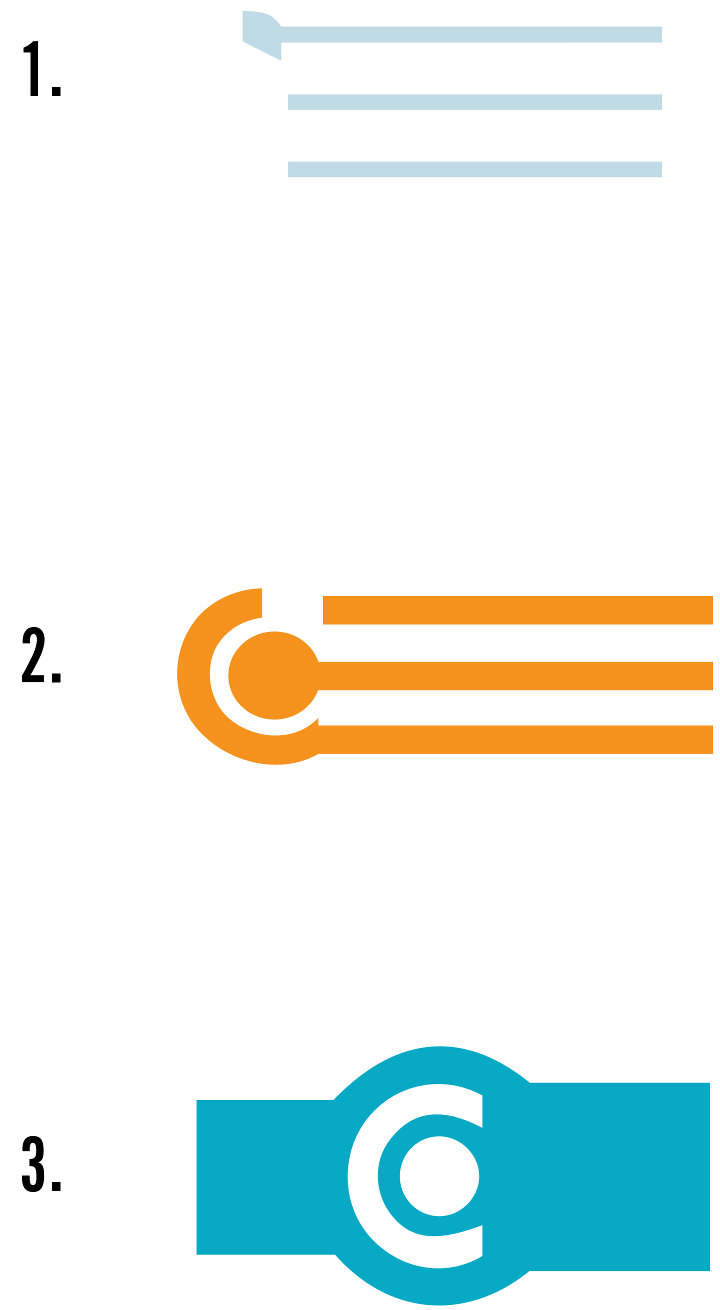
The screen design should be done using an appropriate CAD or other design or drawing tool. When choosing the right tool, the designer should be aware of the screen manufacturer's recommended file format for the layout file. In some cases the file conversion to a specific format is possible, but causes more expenses and might result in the deformation of the layout if not carefully checked.

When designing the screens for a multilayer process, it is advisable to use the same tension screens for all layers. If the screen tension varies between different layers, it may be necessary to use a higher snap-off distance or higher squeegee pressure in the printing process. This can cause registration errors.

As mentioned in paragraph 2.3.3, the maximum size of the layout should be only half or less the inner diameter of the screen. When designing really large layouts, the choice of manufacturers might be limited because of their screen size capability.

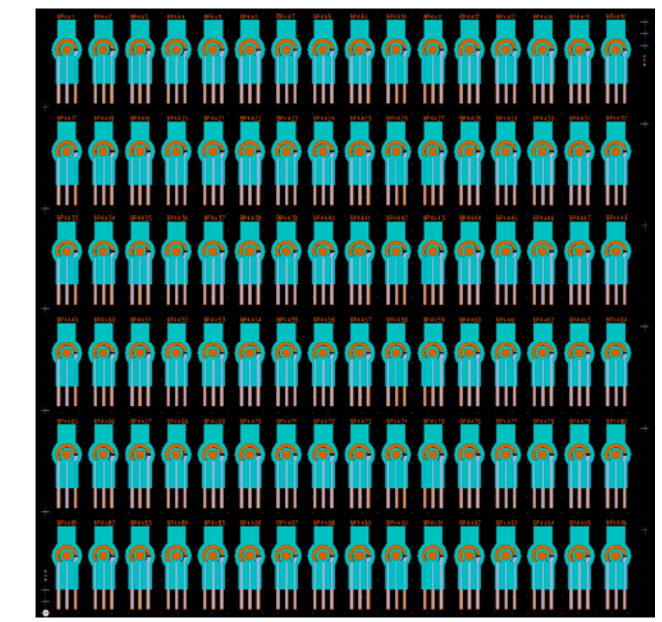
The choice of screen parameters directly affects the layer thickness, and together with the process parameters, the roughness of the printed surface. In addition to the printing process and the screen, the smoothness of the surface can be influenced by a thicker layer of material, whereby the roughness caused by the screen mesh nodes and threads is slightly levelled before the final drying.

Layer layouts



CAD drawings for different layers

Image of the layers assembly



Printed electrochemical sensor platform

Figure 26. *CAD drawings of the electrochemical sensor platform layers. Figure credit: Inka Väisänen. Screen images: Harri Määttä. Photo credit: Jenina Bomström.*

The screen material should be chosen based on the needed resolution and mechanical properties. These properties can be checked from the manufacturer´s data sheet. Table 2 beside presents one manufacturer´s data sheet, where you can find the most important parameters, such as the mesh count, open screen surface percentage and theoretical ink thickness (also known as theoretical ink volume, TIV). In some cases, there might even be some recommended application areas.

For example, if the aim is to produce layer thickness of 14 µm, the 380 mesh count with 24 µm thread diameter screen material should be chosen.

Next Generation TLCP (Thermotropic Liquid Crystal Polymer)
Monofilament Mesh for High Precision Screen Printing Applications

V-SCREEN NEXT™
Extra Value with Advanced Mesh Technology

Mesh code		Mesh count		Thread diameter	Mesh thickness	Mesh opening	Mesh open area	Theoretical ink volume
		/cm	/inch	µm	µm	µm	%	cm^3/m^2
V-SCREEN NEXT	420-20	165	420	20	27±3	40	45	12.1
	380-20	150	380	20	27±3	47	49	13.3
	380-24	150	380	24	33±3	43	41	13.6
	330-24	130	330	24	33±3	53	47	15.6

The above specifications may change without notice as a result of product quality improvements.
Please ask your sales representative or supplier for availability or more information.

Table 2. *An example of the screen material manufacturer´s data sheet. [1]*

[1] Specification for VScreen. PDF file. NBC Meshtec inc. A Polyarulate Hybrid Monofilament Mesh for the Most Advanced Screen Printing Applications. 2018. http://www.nbc-jp.com/eng/product/screen/mc/vscreen.html.

3.2 Printing materials and parameters

The most important materials used in manufacturing are printing inks and substrates. It is also necessary to select all other materials and accessories to be used to fit the selected printing process. The screen for each layer must be designed properly and the size, shape, angle and hardness of the printing squeegee and flood squeegee must be selected carefully.

The challenge of functional printing inks and substrates is very often their availability, lead and delivery time, price and minimum order quantity. The minimum order quantity may be too large for smaller manufacturing batches and vice versa, the availability in a larger volume might be limited.

Usually, the materials are available as a sample in smaller batches at low cost, which is important in product development and when finding the proper materials for manufacturing.

The purpose of this chapter is to present the characteristics of the most commonly used materials in printed electronics and the variables that affect the selection of materials.

Figure 27. *A paper-based biosensor with a fluidic channel printed with carbon, silver and polymer inks. Photo credit: Anne Peltola.*

3.2.1 Screen printing inks

The functionality of the ink in printed electronics can be, for example, electrical conductivity, semiconductivity or reaction to light or heat.

The printing ink generally consists of pigments, binders, additives, solvents and, for example metal particles that provide the desired functionality for the ink. The binders are binding the particles and the pigments in solutions and increasing the viscosity of the ink. Additives are improving the ink flexibility, viscosity, surface energy and how the particles are behaving in the ink solution. [1]

The inks in the screen printing process have a wide viscosity range. It can be up to 70 Pascal second. The viscosity must reach the level when it is controllable in the process. The ink cannot flow uncontrollably through the mesh onto the substrate. The process must be controlled with the force of the squeegee and openings of the mesh.

The solvent-based inks are popular because they offer more opportunities to bind different materials, such as various polymer mixtures produced with various solvents. The advantages of the solvent-based printing inks are, for example better adhesion with different substrate materials and better abrasion resistance.

The disadvantage of the solvent-based ink is the rapid evaporation of the solvents during the printing process, which causes changes to the ink properties. Because of the evaporation of the solvent, the ink viscosity is not stable during the printing process. The evaporation of the solvent increases the ink viscosity and thus changes the way the ink is flowing through the mesh. Therefore, the print quality may change during the printing process.

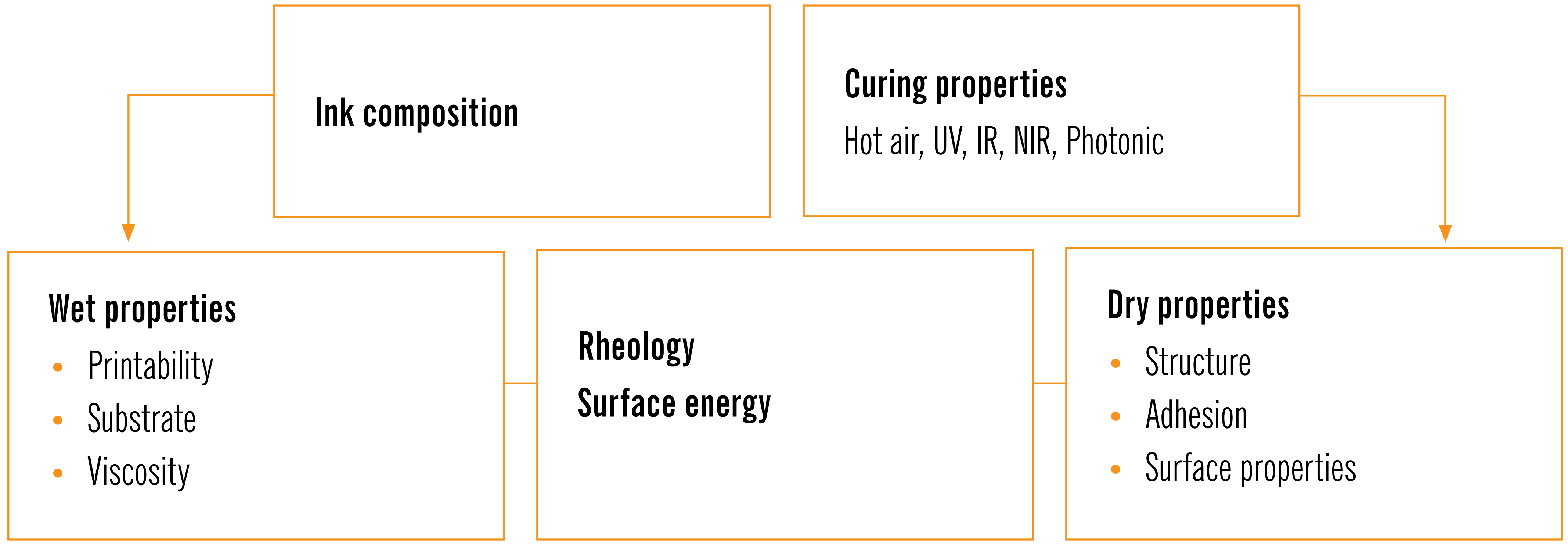


Figure 28. *The main properties of the printing ink. [2]*

When the printing ink is handled and stored correctly, it will work as expected. It is essential to keep the ink in good condition. In order to keep the ink stable, follow the storage instructions, which can be found on the ink manufacturer's technical data sheets. The expiration date is indicated on the jar label. The jar should not be kept unnecessarily open and the temperature of the room as well as the moisture should be kept stable within the limits. Before the printing process, the ink should be mixed up and its quality should be properly evaluated. It is also important to ensure that the temperatures of the printing ink and the ambient are equal. At the end of the printing process, the used ink should not be returned into the original jar. By following these instructions above, the operator will ensure that the ink is ready for the process.

3.2.2 Substrates

In printed electronics, the printing substrates are usually different types of plastics, paper or textiles. The important properties of the substrates are, for example flatness, smoothness, roughness, flexibility, bendability, stretchability, chemical and temperature resistance.

In terms of the ink adhesion and wetting, the surface energy of the substrate must be optimal in comparison to the surface tension of the ink. As illustrated in Figure 29, the surface tension for optimal wetting should be lower than the surface energy of the substrate. In many cases, the adhesion and wetting properties of solvent-based inks are better than those of water-based inks, because the surface tension of the solvent-based inks is lower.

For the best success of the printing process, it is important that the surface of the substrate is clean and does not exceed ambient temperature.

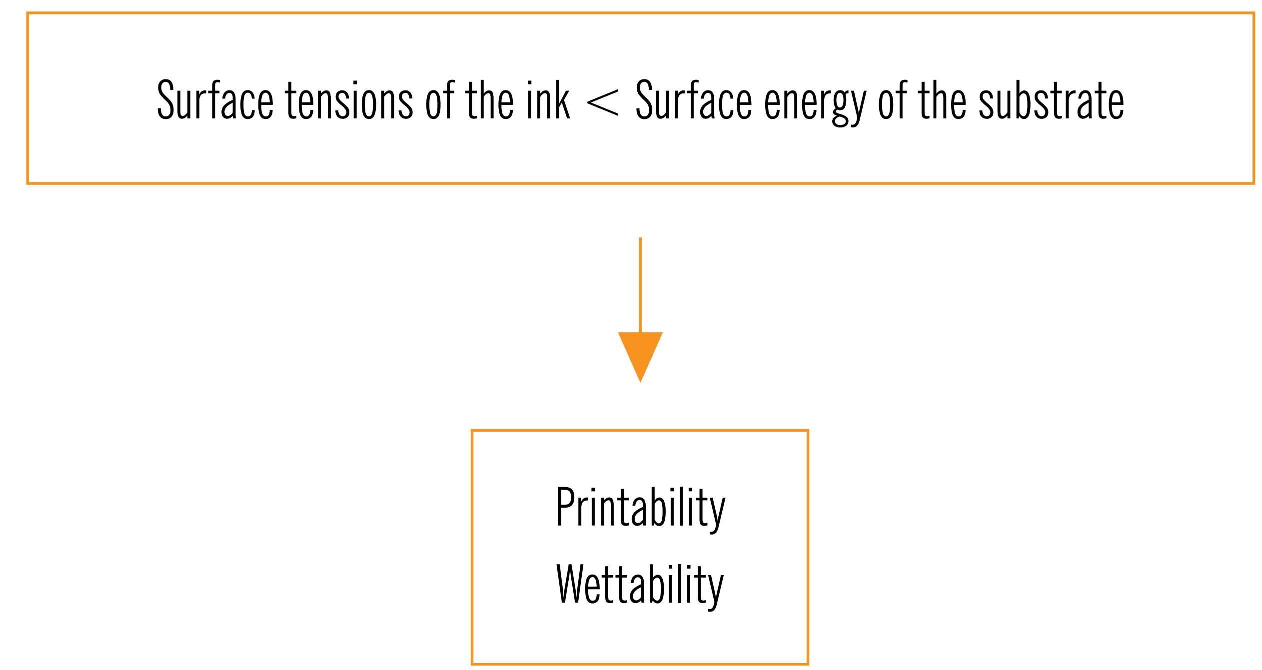


Figure 29. *The surface tension of the ink effect on printability. [3]*

The pre-treatment of the printing substrate involves preshrinking in the oven, cleaning and, if necessary, the surface energy optimisation by a plasma or corona treatment. Different types of plastics have limited temperature resistance, and often many plastic substrates shrink during the ink drying process. The shrinkage can be controlled by preheating the substrate in the oven before the printing. This will allow a better registration accuracy in the multilayer printing process.

Pre-treating means changing the surface energy of the substrate so that the ink will have better adhesion and wetting on the substrate. Also, it cleans the surface of the substrate and decreases the electrical static charge.

WETTING

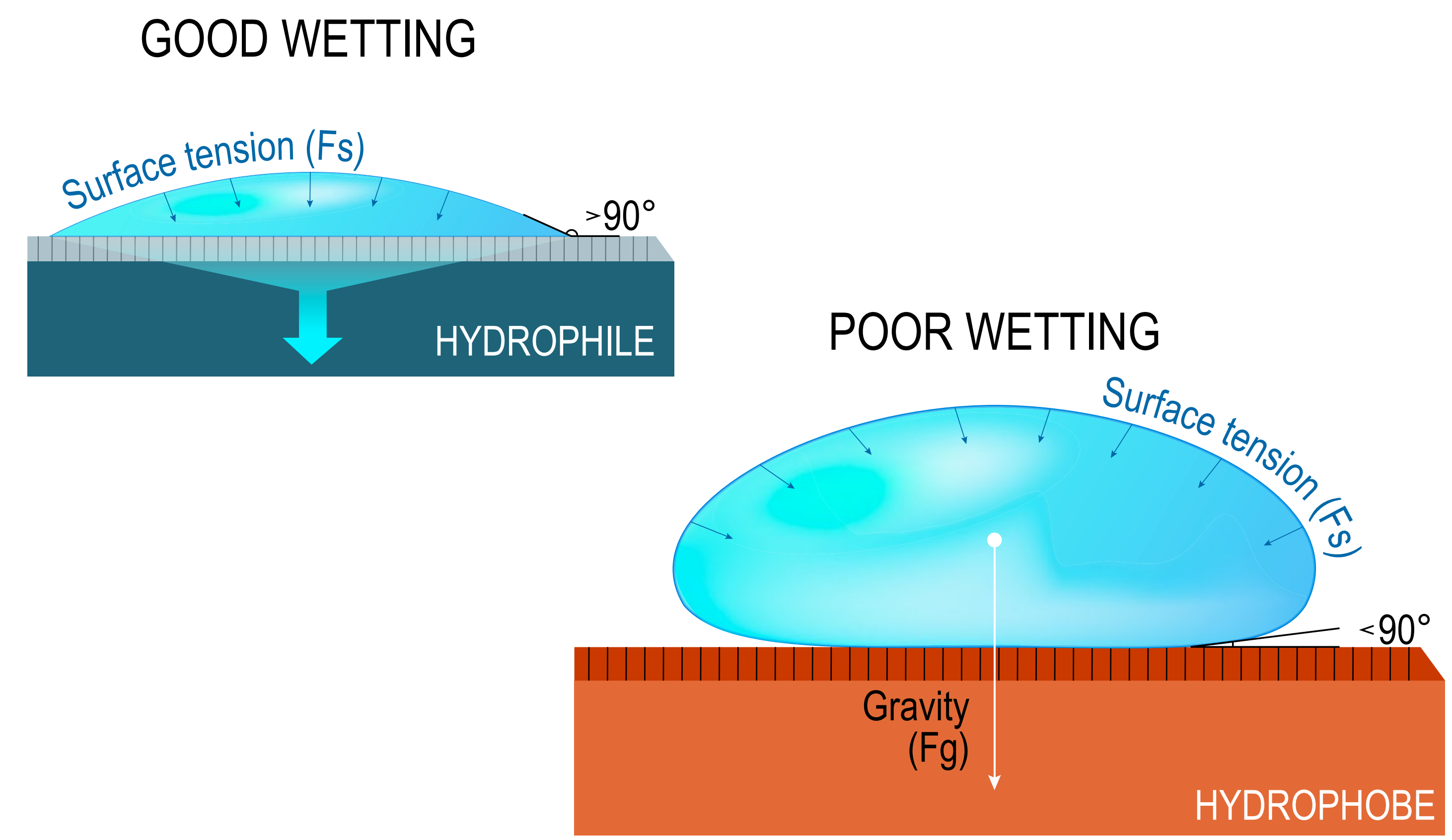


Figure 30. *Effect of the surface tension on the wetting of the hydrophilic and hydrofobic substrate. Photo credit: Shutterstock.com.*

3.2.3 Printing parameters

The viscosity of the ink has a great effect on the process parameters together with the screen and the squeegee blades. The lower viscosity of the ink, the higher mesh count of the mesh is needed for a controllable process. When using low viscosity inks, the speed of the squeegee blades may need to be increased and the pressure of the squeegee may need to be decreased.

By using high viscosity inks, the ink needs more time to flow through the mesh onto the substrate, thus the speed of the squeegee blade should be slower and the pressure of the squeegee must be higher. Also, with high viscosity inks, it is recommendable to use as stable squeegee blades as possible.

The higher viscosity of the ink does not use all total ink volume capacity of the mesh. The thicker ink does not flow very easily through the mesh onto the substrate, but a part of the ink will be stuck onto the mesh wires and openings. Low viscosity inks penetrate more easily through the mesh, but they may also be more difficult to control in the printing process.

The smoothness of the substrate must be taken into account when designing the printing process or the screens. When the substrate is smoother, a thicker mesh can be used, which means that the mesh tension can be higher and the gap between the mesh and the substrate can be smaller. This allows a smaller squeegee pressure and the screen is worn less.

[1] Fespa Finland Association. 2014. Ammattikurssi seripainamiselle. Part 1. P.125

[2] Gamota, D., Brazis, P., Kalyanasundaram, K., Zhang, J. 2004. Printed organic and molecular electronics. Kluwer academic publishers. USA. P. 173

[3] Conductive Inks. Sanaur, S., OE-A Workshop, 13.3.2018. Munich.

3.3 Preparation of the printing process

The most important steps of preparing the printing process from cleaning the surface to the documentation and protection of the finished product are shown in Figure 31 below. The printing process is divided into several phases. Each step involves many of things that will be opened and clarified in this chapter.

All fabricated products should be traceable. Therefore, product information management for the entire process is important. The aim is that all parameters and materials related to the manufacturing of the product could be retrieved afterwards, if necessary. Usually, machine parameters can be saved on the working files during the printing process.

1. Cleaning of the laboratory table surfaces
2. Pretreatment of the substrates
3. Process parameters and mateterials selection
4. Condition check of the screen
5. Preparation of the print machine
6. Inks preparation
7. Printing and curing
8. Washing of the screen and equipments
9. Documentation

Figure 31. *The steps related to the printing process.*

3.3.1 Pre-treatment of the substrate

The first step in the printing process is cleaning the laboratory surroundings and surfaces. After that, a pre-treatment of the printing substrate takes place.

It must be checked from the manufacturer's data sheet what is the shrinkage of the substrate at a certain temperature. If this information is not available or it is measured at a different temperature, the printing substrate should be subjected to temperature testing at a drying temperature of the printing ink. The aim of this test is to find out if the drying temperature of the printing ink is enough to shrink the material and how much it would shrink.

The test procedure will be as follows: make a marking on each side at the longest distance from each other that can be measured accurately and measure this distance. Keep the material in the oven at the selected temperature and the time period, which is needed for the drying of the ink (check from the data sheet). Take the substrate out of the oven and measure whether the distance of the markings has been shortened. If the shrinkage is not observed, it is not necessary to make the pre-oven procedure for substrate prior to printing.

The substrate must be cut to a right dimension, so that the printed layout will fit into the substrate and that it will fit into the oven.

Finally, the substrate is cleaned by gently wiping it with a clean room cloth with isopropanol to avoid fingerprints, dust or other stains on the surface of the substrate, which could affect the print quality.

3.3.2 Pre-treatment and quality of printing inks

Solids of solvent and water-based printing inks tend to sink to the bottom of the container during the storage, and thus the solvent remains on the surface. It is very important to carefully mix the contents of the printing ink container using a glass jar or electric mixer. A data sheet should be checked for instructions on the possible recommended stirring time. Figure 32 beside illustrates what printing ink looks like when it is still in the container.

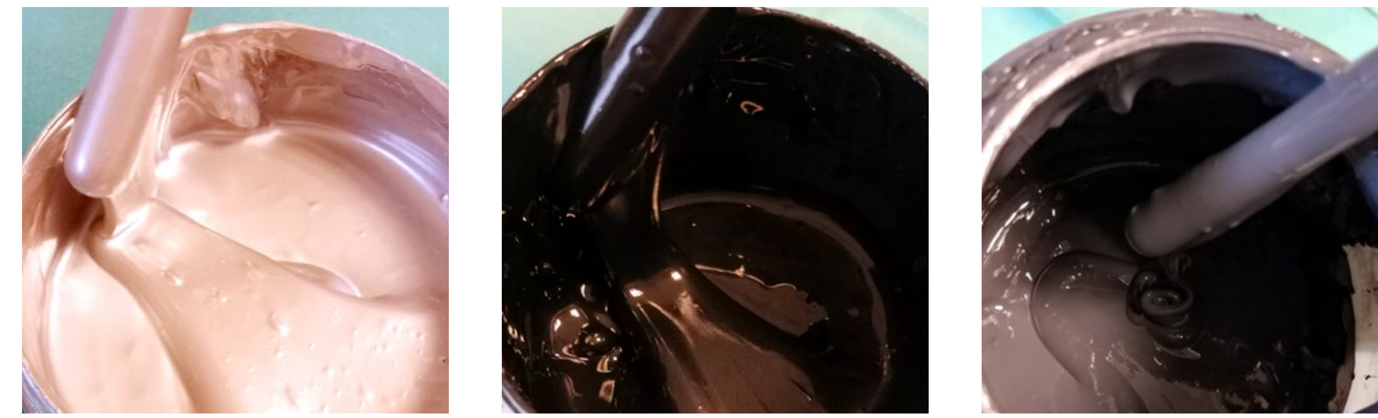


Figure 32. *Left: silver/silver chloride ink, middle: graphite ink, right: dielectric ink. Photo credit: Anne Peltola.*

Usually, there is dried printing ink residue at the edge of the printing ink container. When opening a container, one can drop a lot of dried ink particles into the ink, which can cause problems in the printing process.

Small particles of a few micrometers inside the printing ink can accumulate and clog when the printing ink gets older or is stored for a long time. A grindometer can be used to see the particle size of the printing ink. Figure 33 on the next page shows a test made with a grindometer to a graphite ink. On the top of the measuring scale of the grindometer, a small amount of printing ink was placed, and the print ink was pulled over the measuring range. From the grindometer scale, the particle size of the printing ink can be read, and it is possible to observe whether there are any clogs formed in the printing ink. In this case the maximum particle size of the ink is approximately 10 µm.

The maximum particle size 10 μm.
The line where the ink is placed steadily.
What is the effect on the screen openings?

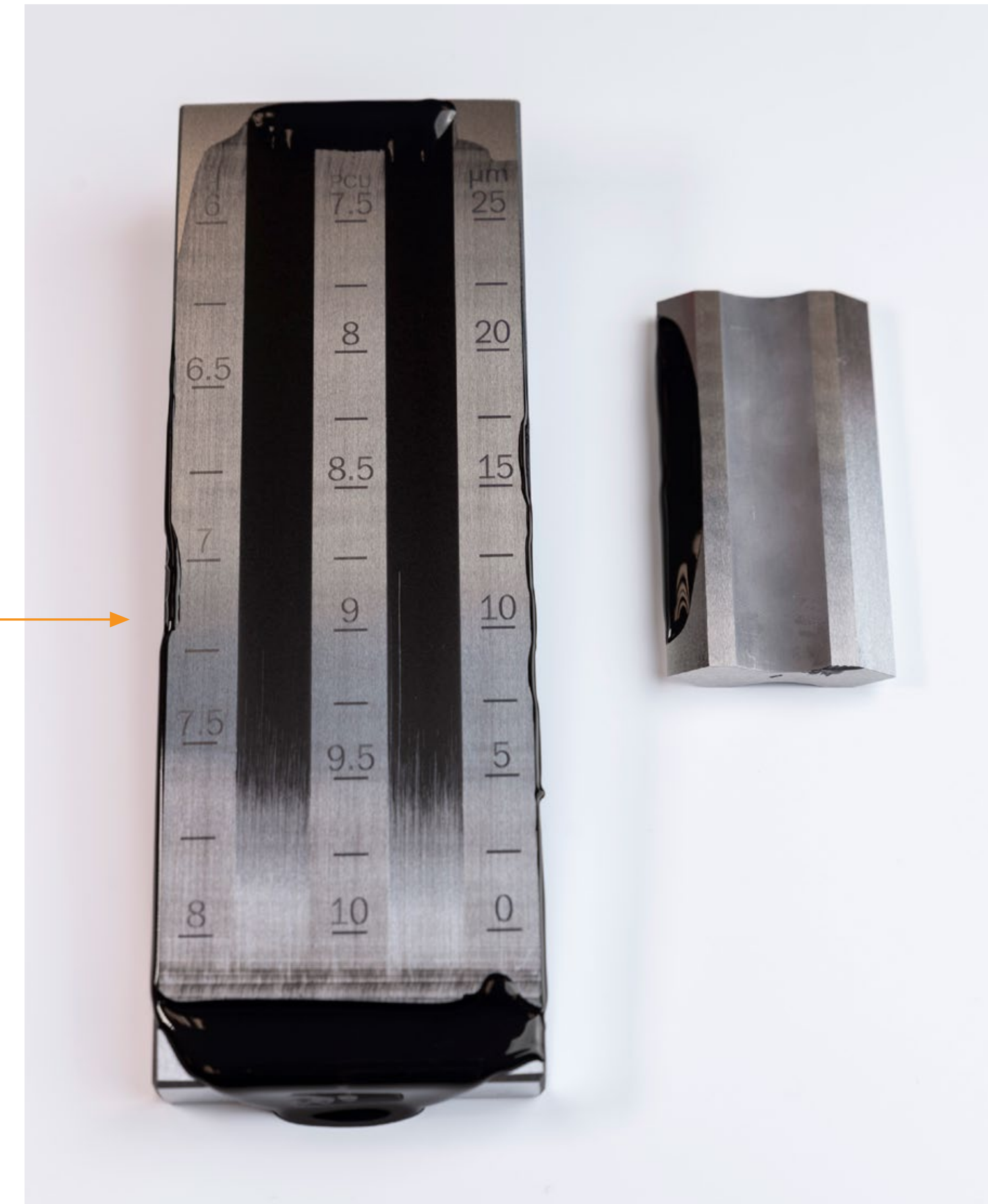


Figure 33. *Particle size measurement from the ink.*
Photo credit: Jenina Bomström.

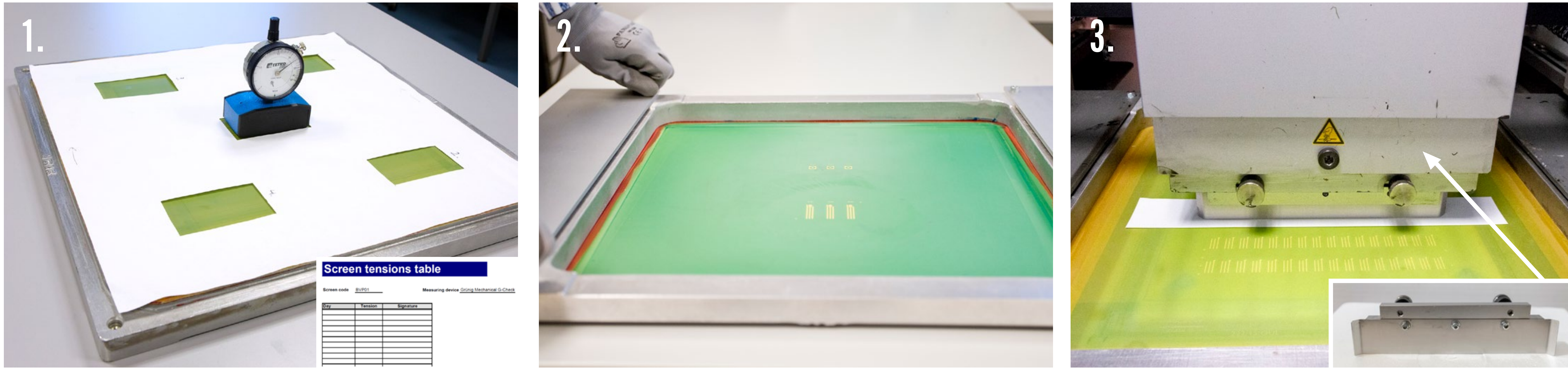
3.3.3 Printing screen and machine preparation

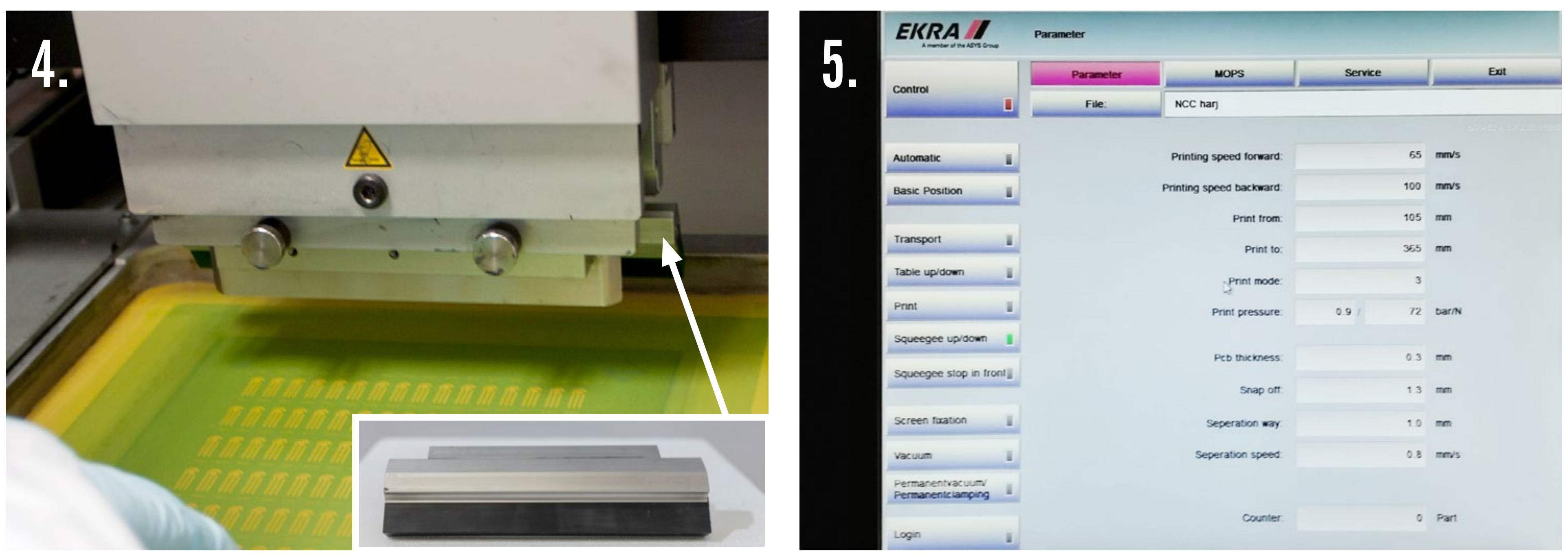
The preparation of the printing machine and the printing parameters assigned to it is the most important step in the screen printing process along with the proper design and quality of the screen.

The condition of the openings of the screen should be checked by a microscope or a corresponding quick and easy method. Close attention should be paid to the critical (usually the smallest) sections of the layout.

Figure 35 on the next page presents the most important steps for setting up the printing machine.

Figure 34. *Checking the printing parameters. Photo credit: Jussi Tuokkola.*





1. Checking the tension of the screen.
2. Attaching the screen to the adapters.
3. Setting the flood squeegee.
4. Installing the printing squeegee and distance between the screen and the base.
5. Printing parameters.

Figure 35. *Setting up the printing machine. Photo credits: Jussi Tuokkola, Anne Peltola and Jenina Bomström. Image credit: Tomi Tuomaala.*

The screen tension should be checked with a tension meter and the reading should be compared with the reading measured in the first inspection. The tension of the screen should always be marked to a screen tensions table before the printing. The table is used to monitor whether the condition of the screen is weakened during different printing cycles.

The printing screen should be firmly attached to the adapters if they are needed. The screen is held in place with the attachment mechanism of the printing machine during the printing process. If the process optimisation requires, a flood squeegee is essential when using certain printing inks. A specific thickness of a plastic film or a feeler gauge is used for setting the optimum height of the flood squeegee. It should be noted that the optimal height can be different with different inks.

After optimising the flood squeegee, the sharpness and condition of the printing squeegee rubber is checked and the squeegee is carefully installed in the machine. The substrate is then placed on the vacuum table of the printing machine and the vacuum table is driven under the printing screen. The distance between the screen and substrate is then adjusted to the optimised distance specified earlier. The same above-mentioned preparations should be repeated when several layers are printed.

Figure 36. *Setting up the squeegee. Photo credit: Jussi Tuokkola.*

3.4 Printing safety

Everyone has the responsibility for occupational health and safety. Accidents can be caused, for example, by ink handling, slipping and stumbling, and working on the machine. These can be avoided by everyone's own actions and using appropriate protective equipment. The operator may also become sensitised through a repeated skin contact or through an airway to the solvents and chemicals of the printing inks. The importance of the operator´s own operation care is high when using the inks regularly. Material Safety Data Sheets (MSDS) of the material include instructions for the proper protection and handling of materials used.

The material safety data sheet is a material manufacturer's release detailing the hazards adverse effects, storing and safe use of the material as well as first aid instructions. This document has to be always available for the users of solvents and inks.

The manufacturer’s technical data sheet (TDS) contains information on the mixing and practical use of the material. Usually, it also contains information on the recommended screen properties or suitable solvent additives. Before new material is used, it is important to carefully read these two above-mentioned documents from the material manufacturers, before a new material is used.

Figure 37. *Chemicals can cause you serious health damage. Photo credit: Shutterstock.com.*

3.4.1 Personal protection and handling

Protective gloves, goggles, a motorized respirator, safety shoes, overalls and laboratory jackets are the most used protectives of the screen printing operator. It is recommended to use a rubber apron and rubber boots with larger quantities of chemicals or solvent-based printing ink materials if there is a high risk of chemical splashing.

A basic protection against contamination is given by using disposable protective gloves that are usually made of nitrile rubber or neoprene plastics. Longer periods of exposure, for example during the screen washing process, require better protection. Thicker protective gloves give a better chemical resistance against heavy solvents. Even if the protective gloves are in use, hands must be washed thoroughly when leaving the laboratory. Eating food, drinking or enjoying refreshments are never allowed in the laboratory. For laboratory safety, it is important that every member of the working group has proper training for working at the laboratory.

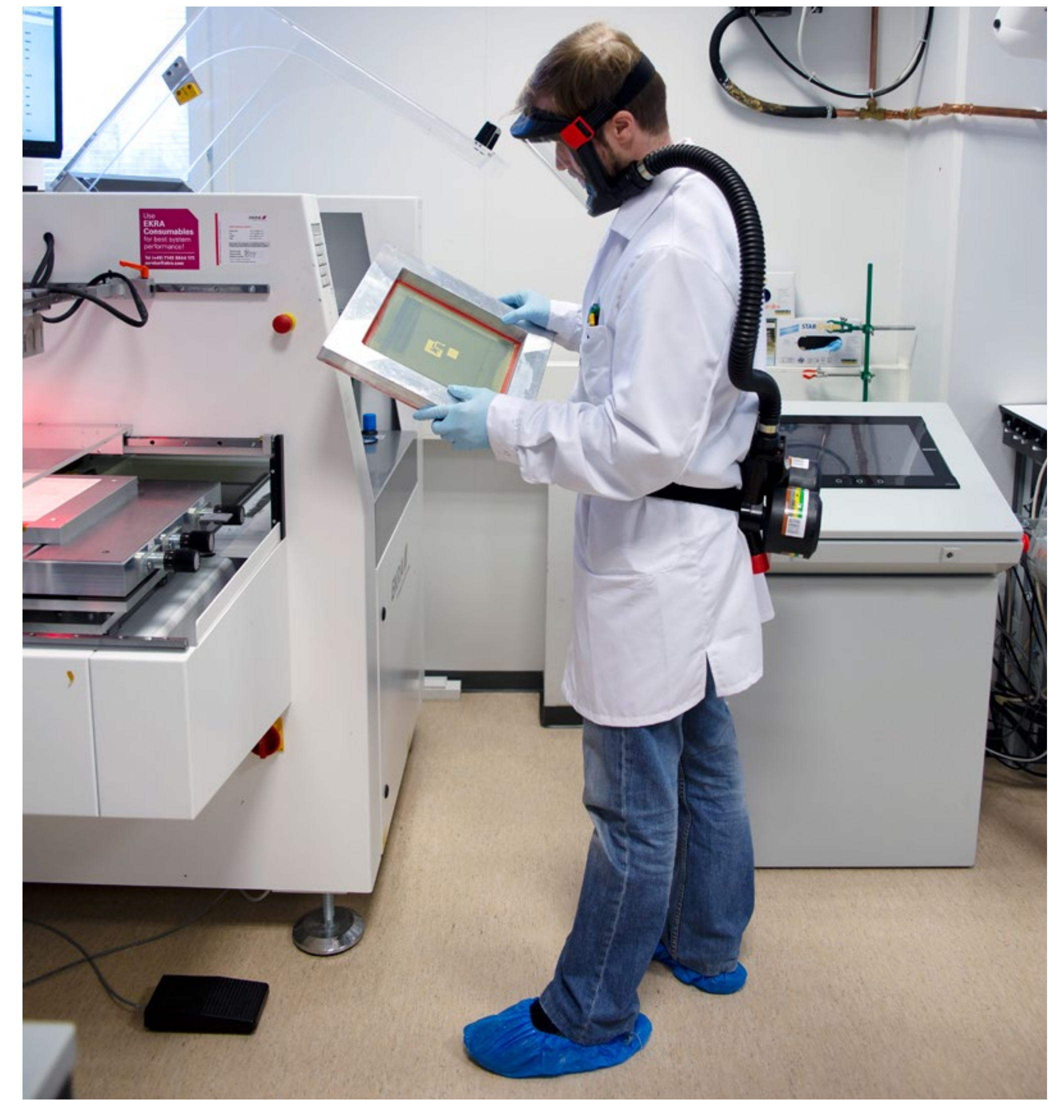


Figure 38. *Personal protection. Photo credit: Anne Peltola.*

Protective goggles and the motorized respirators are also required to resist certain chemical. Respirators must be filtered so that the operator is for sure safe from the chemical vapors or the solid particles from the used materials.

3.4.2 Surroundings and equipment

Figure 39. *A laboratory environment with a local exhaust systems. Photo credit: Anne Peltola.*

Each operator takes responsibility for the laboratory environment and the safe use of the equipment. In manufacturing printed electronics, the cleanliness of the environment and laboratory is the starting point for a successful printing process. A clean and tidy laboratory is also a safer place to work. A cleanroom environment would bring opportunities to manufacture products that require special cleanliness. Often a cleanroom environment is not available, and therefore, the laboratory cleanliness can be affected by proper dressing and behaviour in the laboratory.

Since the materials are often solvent-based, there must be a sufficient ventilation in the laboratory to ensure that chemical vapours are under the permitted limits. Drying ovens and printing equipment must also be equipped with a sufficient local exhaust ventilation. In the screen washing room, there must also be a proper local exhaust ventilation.

The printing inks must also be stored as required, usually in a refrigerator, freezer or cabinet with a local exhaust ventilation. It must also be ensured that the chemicals cannot leak into the public sewage network.

3.4.3 Environmental thinking and responsibility

The operator can have an effect on material loss during the manufacturing process. By printing effectively and sensibly, materials and energy can be saved. By preparing the printing process well, it is possible to succeed at once without the material waste or unnecessary work hours. The most common consumables accessories or materials in the screen-printing process are listed below.

- inks
- squeegee rubbers
- screens
- solvents
- electricity
- compressed air
- wipers
- gloves
- protective clothings

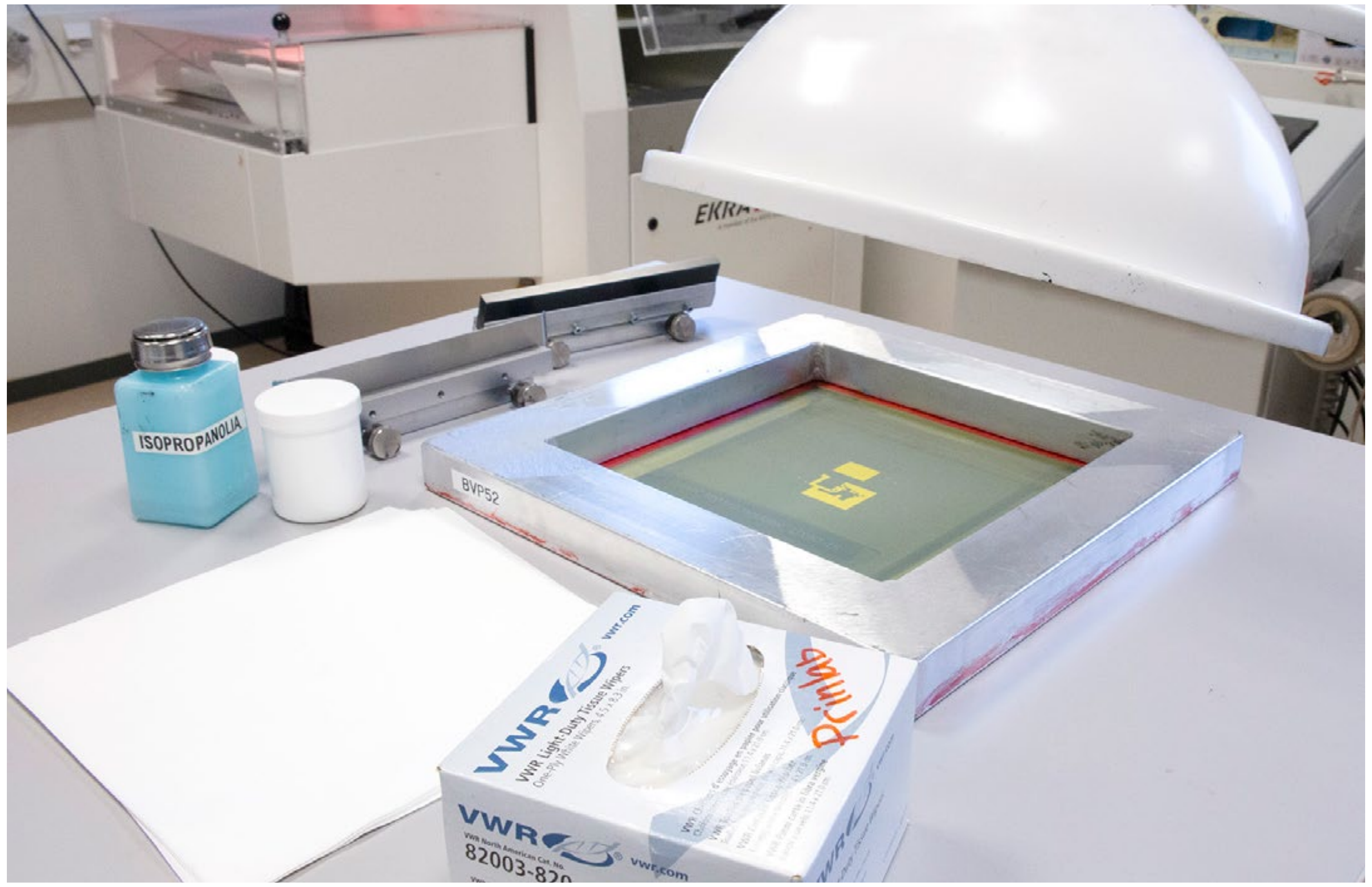


Figure 40. *Acessories you need for printing electronics. Photo credit: Anne Peltola.*

It is sensible to keep just the needed amount of the printing ink in stock. The materials expire in a few months and after that, the valuable printing ink becomes just hazardous waste.

The squeegee rubber can often be used several times, but it is still meaningful to check that the edge is still sharp, and the properties of the rubber are not changed during storage. The condition of the squeegee rubber has a direct impact on the print quality. It also has a big effect on material waste and unnecessary working hours.

Checking the condition of the screen is reasonable before the printing process as the condition of the screen directly affects the success of the printing process. It is also good to remember that printing process parameters can affect the lifetime of the screen.

Make a tree happy.

First think, only then print!

3.4.4 Waste

Waste from the screen printing process can roughly be categorized into wet waste and dry waste. Dry waste is usually printed sheets, cleaning wipes, paper, metal or plastic. These may include hazardous waste and must be recycled properly with the help of a local authorized waste management company. Wet waste typically consists of solvents or printing inks and is usually hazardous waste.

Waste treatment is a part of the safety laboratory work and healthy working environment. For example, the ISO 14000 standard specifies requirements for an effective Environmental Management Systems (EMS), It instructs how to handle the environmental issues.

In addition, it is good to familiarize yourself with the environmental protection laws. They apply to the industrial and other activities, which cause or may cause environmental pollution. The law applies to the operations where the waste management is necessary. In this publication, we have met the standards of the Finnish environmental protection law. [2] Remember to check the requirements of environmental protection of your country.

Figure 41. *Remember proper waste recycling.*
Photo credit: Anne Peltola.

[1] ISO 14001, 2018. Enviromental management systems. https://www.iso.org/search.html?q=14001. Date of retrieval 13.4.2018.

[2] 527/2014, 2018. Environmental protection law. http://www.finlex.fi/fi/laki/alkup/2014/20140527/. Date of retrieval 13.4.2018.

3.5 Multilayer printing and registration

In multilayer printing, it is important to ensure sufficient registration accuracy to reach the best possible result. To do this, the screen has to be designed and fabricated properly, the printing ink must be controlled on the screen and printing device parameters have to be exactly as planned and tested.

In the control of the printing ink, it is essential that it does not dry on the screen structure, thus preventing the free flow of printing ink through the screen onto the substrate. Some of the printing inks easily block the openings of the screen, and therefore, a solution to slow down the drying and, consequently, to improve the yield, must be used. Solvent-based retarders are one solution, but also the internal temperature of the device should be as low as possible. The most preferable way of preventing the drying of the ink is to use a flood squeegee, which spreads the ink onto the openings of the screen while keeping the openings moist and slowing the clogging of the screen.

The registration accuracy should be ensured by keeping the squeegee pressure as low as possible so that the stresses caused by the pressure would not distort the patterns. In many cases, small pressure also provides the most even print quality.

The total width of the pattern exposed on the screen and the inner dimensions of the screen define the most suitable width of the printing squeegee. The width of the squeegee used should not be too wide in relation to the size of the screen, because minor distortion in the formation of the pattern on the substrate might occur, thus weakening the registration accuracy.

3.5.1 Printing the first layer

Usually, when the printing ink is developed for the screen printing process, printing parameters can be found fairly easily. The printing will start by setting up the device and spreading the printing ink on the screen. In Figure 42 below, the left-hand side illustrates the situation in which the printing ink is applied onto the screen for the first print.

Used ink is the Silver/Silver Chloride 60/40 C2130809D5 by Gwent/Sun Chemical. The picture on the right shows how the screen looks after the printing event when the flood squeegee has spread the printing ink over the openings. All the main process parameters for the printing process are shown in Figure 4 in Chapter 2.2.

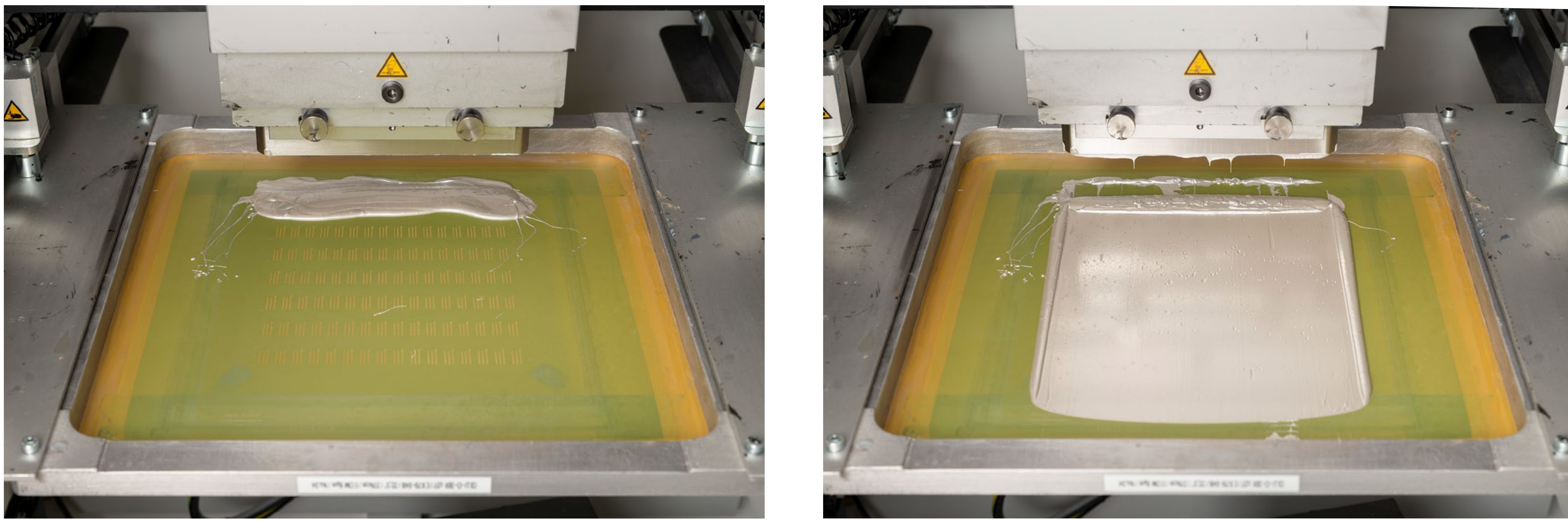


Figure 42. *The start and end positions of printing the first layer. Photo credit: Jenina Bomström.*

The first layer prints should usually work well without bigger optimisations. After the last printed sheet, the accessories and the screen should be carefully washed if intended to be used again. The sheets are dried at the temperature required by the ink. The printed sheets should be identified by an order number. Please note that the first couple of sheets should be discarded, because the process might not be stabilized yet. The process might also change during long prints therefore the quality of the prints should be well confirmed and sheets with the quality outside of the requirements should be left unused Figure 43 beside presents the example 1st layer printed onto a PET substrate. In Figure 43 on the side of the sheets + marks are the alignment marks for the print layer registration.

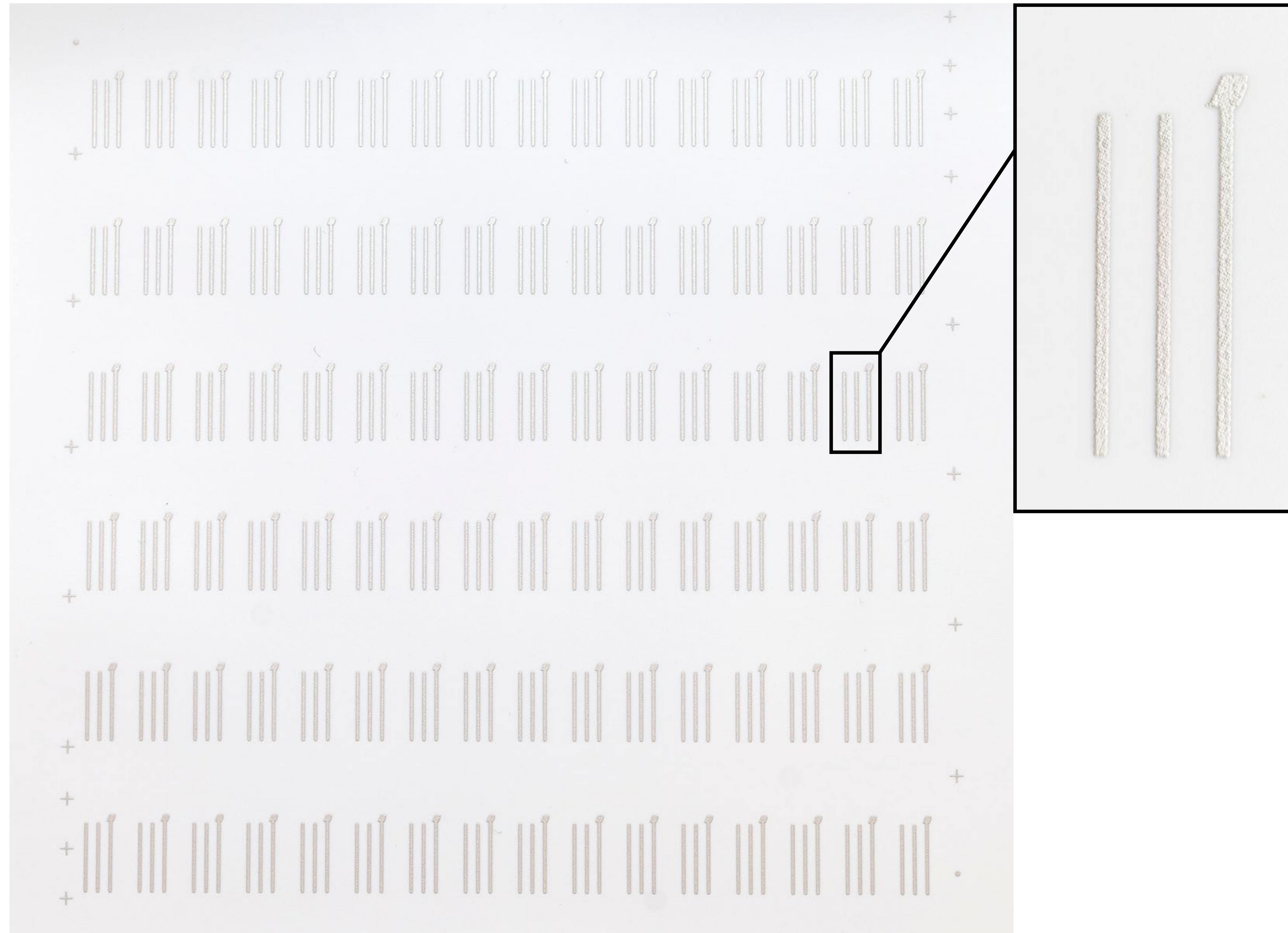


Figure 43. *Printed 1st layer. Photo credit: Jenina Bomström.*

3.5.2 Printing the second layer

The second layer is printed on top of the first layer by applying it accurately utilizing alignment marks. The parameters of the printing should already be well tested by preceding tests and used exactly as planned. The carbon sensor paste C2030519P4 by Gwent/Sun Chemical is used for second layer.

In Figure 44 below, the left-hand side illustration shows a situation where the printing ink is applied onto the screen. The picture on the right presents how the screen looks after the print event when the flood squeegee has spread the printing ink over the screen.

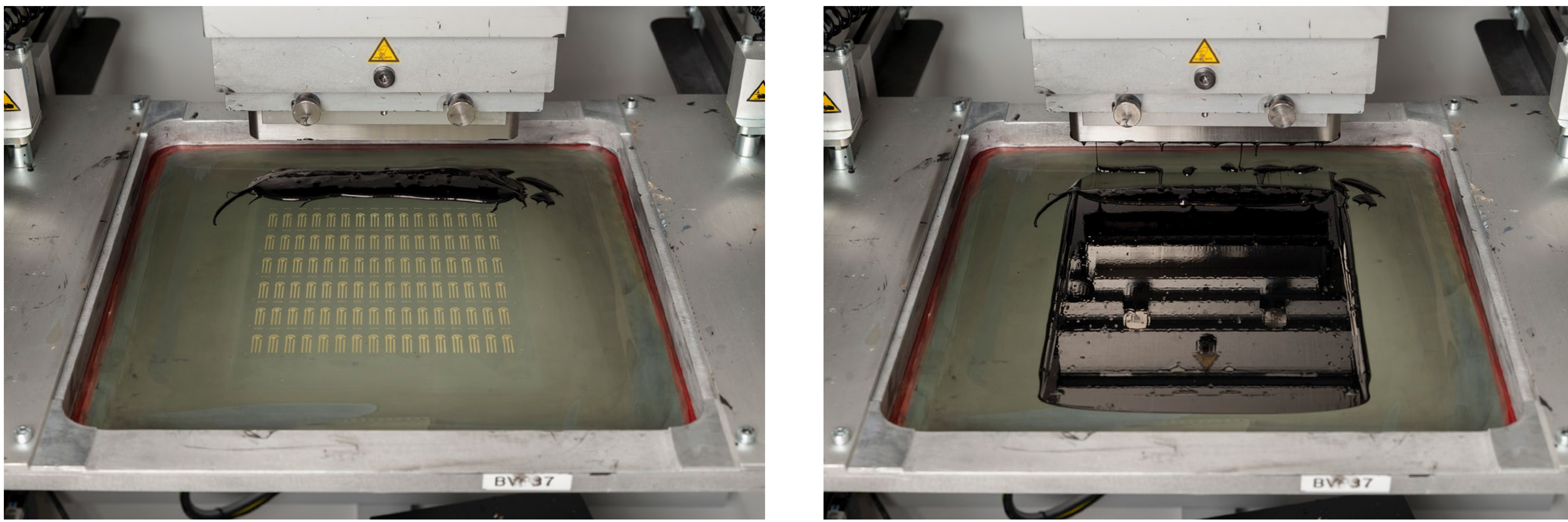


Figure 44. *Start and end positions of printing the second layer. Photo credit: Jenina Bomström.*

The first printed sheet is the alignment print. The positions of the alignment marks are taught to the printing device. After teaching the marks, the alignment sheet is removed from the vacuum table and replaced with the first actual sheet, where the first layer has already been printed. The first layer sheet is positioned by the alignment system of the device in the correct position on the vacuum table.

Figure 45 below presents the image of EKRA E2 manual optical alignment in the user interface of the device. On the left-hand picture, the alignment is still a little bit off. After a slight fine adjustment, the sheet is positioned in the right place on the vacuum table. The green dots on the user interface show that the sheet is exactly in the right position and the printing could be started. This procedure is repeated for all the sheets before printing.

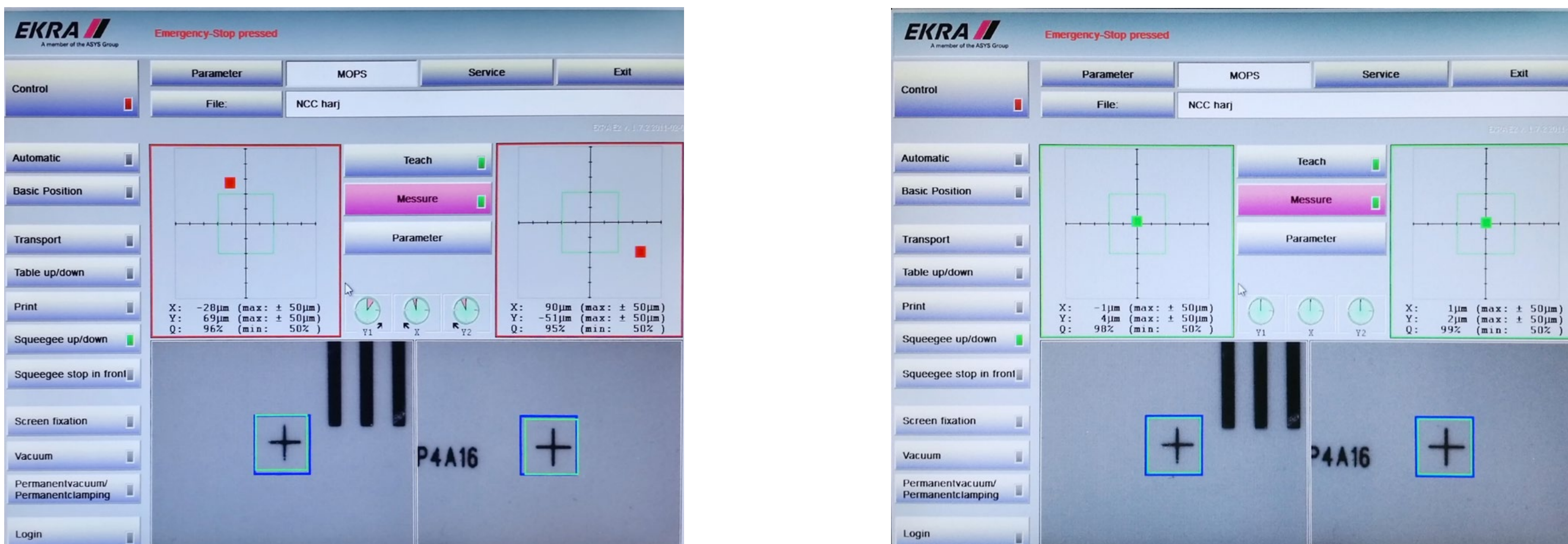
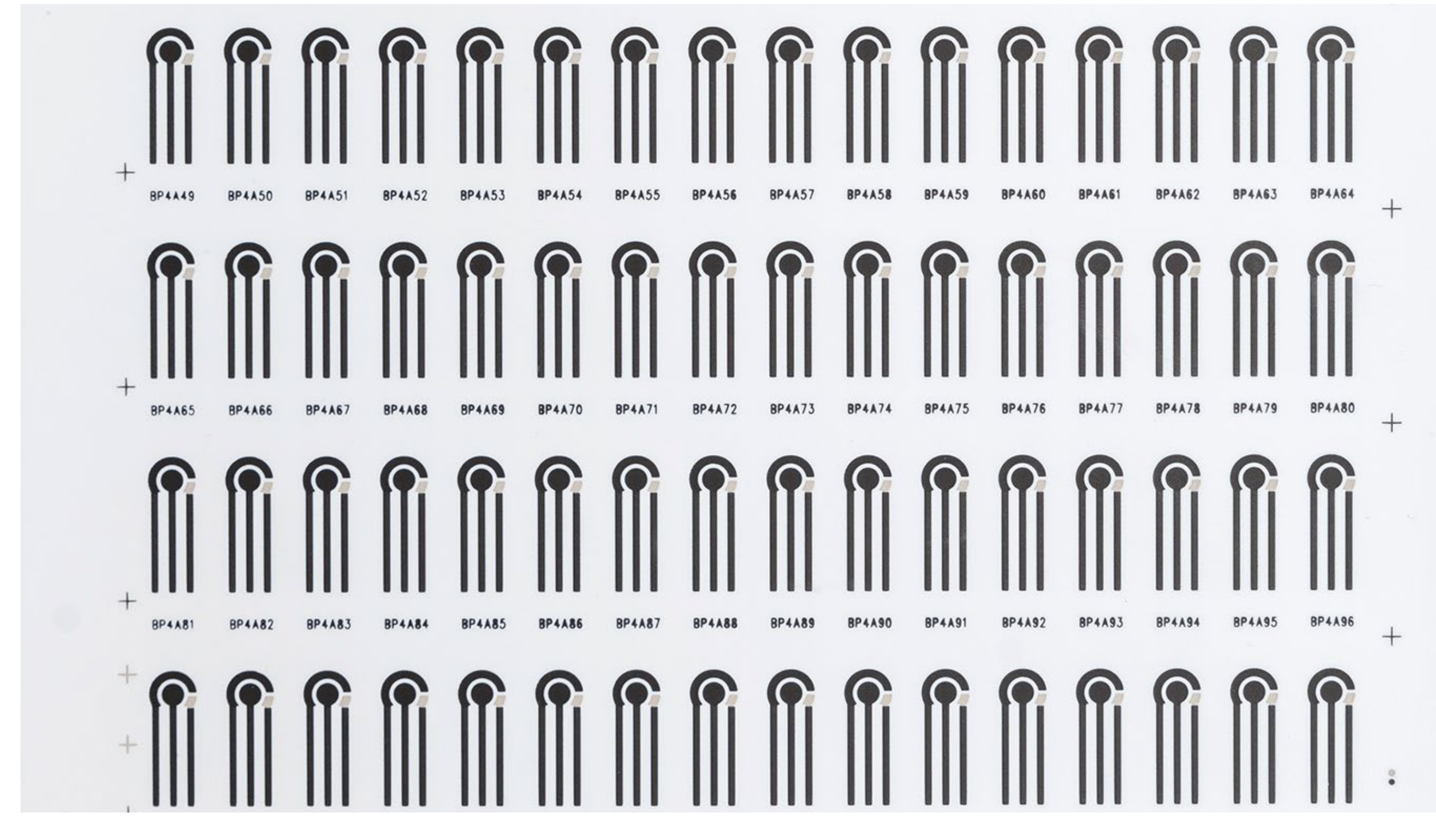


Figure 45. *Principal of EKRA E2 manual optical positioning. Image credit: Tomi Tuomaala.*

The quality of the printed layers should be carefully observed. If needed, the printing parameters should be changed to ensure the best quality. Registration accuracy can be analysed as an example with optical measurement methods. The quality of printed patterns can also be measured electrically.

We presented here as an example of how to print two of three layers of the electrochemical biosensor platform. Technically, the stages of the printing process for different layers remain the same. For multilayer printing in the case of the biosensor platform, the registration accuracy, quality of the printing surface and electrical properties of the sensor are prerequisites to the functionality of the end-product.



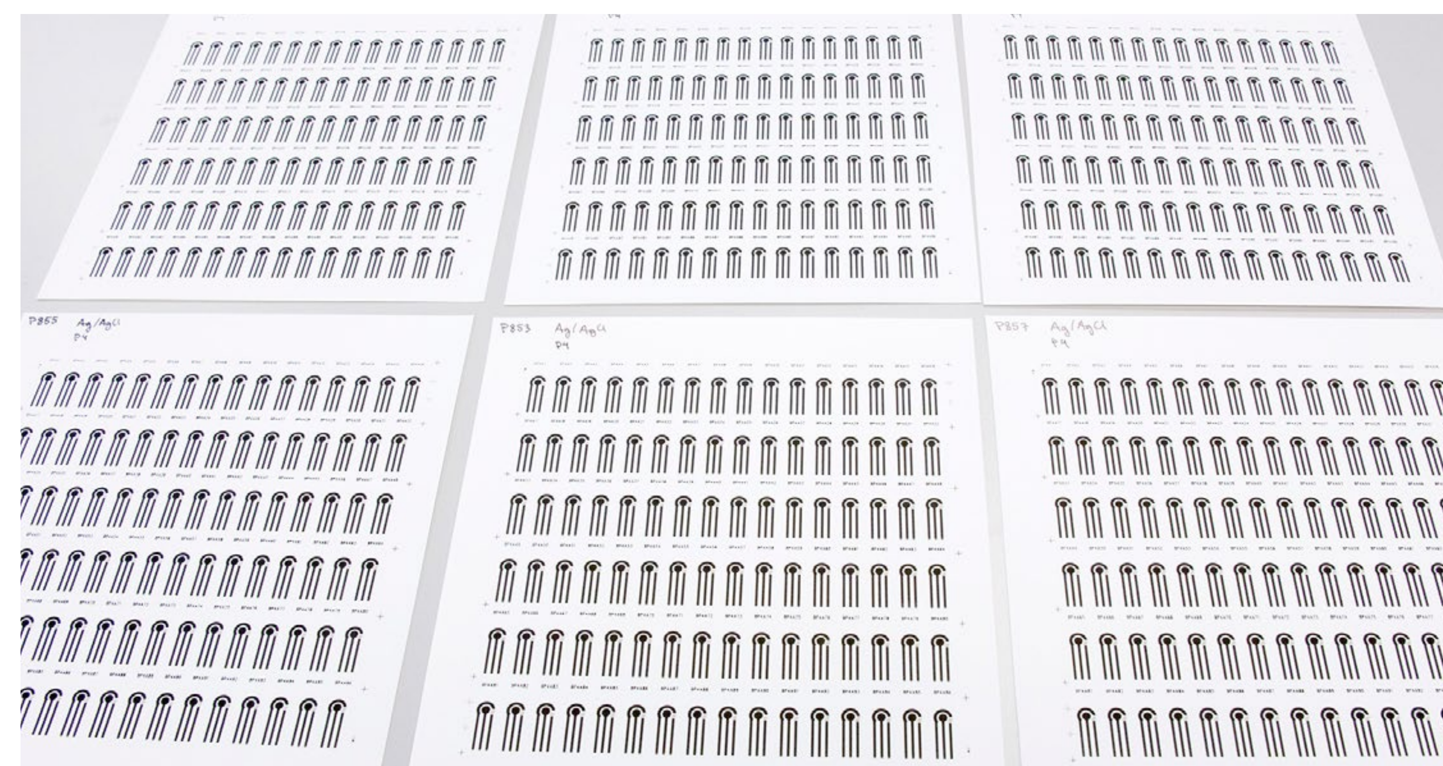


Figure 46. *The second layer printed on top of the first layer. Photo credit: Jenina Bomström.*

4. Conclusions

TEIJA TUHKALA

Photo credit: Jussi Tuokkola

4. Conclusions

To print electronics with new materials and technologies requires a lot of curiosity, practice and patience. Not to forget a safe printing environment. The rest of the application development depends on an innovative approach and attitude. Once you are familiar with the restrictions and huge potential of the functional materials and technologies used, the world of printed electronics opens its' business potential and usability to change the traditional way of manufacturing electronics.

Table top screen printing is an effective way to develop applications. The printing process itself consists of many steps from preparing the materials to printing parameters and post-treatment methods. It is essential to understand how different choices made by the operator effect on the printing quality.

Repeatability and traceability are the key issues when considering the quality of the printing process and product information. It is important to keep a record of all the parameters during the process. Modern machines have a library, where the common printing parameters are saved. Despite the machine library, the conditions like humidity or temperature, substrate and ink choices and pre and post-treatment actions need to be written down by the operator. Without proper laboratory notes, the repeatability of the printing process and the quality of the result are at risk.

Figure 47. *A ready-to-use biosensor test strip for blood sugar levels. Photo credit: Shutterstock.com.*

A simple way of handling the product specification is to keep a record of different supplies. Figure 48 presents the basic printing parameters used at PrinLab. As well as basic information and the operator´s own information, the record should include parameters such as printing speed, snap off and squeegee type. Ambient temperature, relative humidity (RH) and post-treatment information is important, too. Besides the printing parameters, different parameters from screens and inks are collected. As an example, screen parameters include the following: 1) operational codes (project code, purchase date, screen code, etc.), 2) screen parameters (screen type, mesh count, emulsion thickness, thread diameter, mesh openings, tension and frame size) and 3) general information (pattern used, supplier, notifications, etc.).

Printing parameters and service table 2.5.2018

Machine:	Ekra E2
Project:	PrinLab

PrinLab codes and materials						Printing parameters							Ambient			Drying			Notes
Date/operator	Printing ordinal number (PXXX)	Screen code	Layer / name	Ink	Substrate	speed forward - bckwrd (mm/s)	from - to (mm)	Print mode	Print pressure (bar/N)	PCB thickness (mm)	Snap off (mm)	Squeegee type	Squeegee shore	Ambient temp (°C)	RH %	Temp (°C)	Time (min)	snap off 0=	Notes

Figure 48. *An example of a laboratory diary. Image credit: Teija Tuhkala.*

Table top screen printing is a good and cost-effective way to produce electronics in small-scale production. With good tracking records it easier to adjust the parameters and find solutions if printing problems occurs. Once the desired result has been achieved, it is time to consider moving on to mass manufacturing and roll-to-roll printing. Even if all the technology is available and materials developed, the printing process might still need some adjusting.

As presented in this guide, the process of table top screen printing is a complex subject with many holes to stumble upon. We concentrated on the technical side of the printing process in order to help learning in practice. Many important things such as material choices, post-treatment or quality control in multilayered sensors had to be left out for the next publications. Despite the complexity, we truly think that printing electronics with the screen printing method can be learned. It is a part of a longer journey from the ancient China to print tomorrow's electronics.

Figure 49. *RFID tags are common end-products. Photo credit: Shutterstock.com.*

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