TREASURE

D5.7: In-mold/structural electronics pilot reconfiguration, testing & optimization

06/03/2024 (M34)

Author: Stephan Harkema (TNO)

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 101003587

Technical References

Project Acronym	TREASURE
Project Title	leading the TRansion of the European Automotive SUpply chain towards a circulaR future
Project Coordinator	POLITECNICO DI MILANO (POLIMI)
Project Duration	36 months as of 1 June 2021

Deliverable No.	5.7
Dissemination level [1]	PU
Work Package	5
Task	5.6
Lead beneficiary	TNO
Contributing beneficiary(ies)	
Due date of deliverable	31-12-2023
Actual submission date	17-4-2024

Document history		
V	Date	Beneficiary partner(s)
V1.0	6-3-2024	TNO
V1.1	26-3-2024	TNO
V1.2	12-4-2024	TNO (review by EUROLCDs, UNIVAQ)
VF	17-4-2024	TNO

DISCLAIMER OF WARRANTIES

[1]PU= Public
PP= Restricted to other programme participants (including the Commission Services)
RE = Restricted to a group specified by the consortium (including the Commission Services)
CO = Confidential, only for members of the consortium (including the Commission Services)

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 101003587

possibility of such damages) resulting from your selection or use of this document or any information, apparatus, method, process, or similar item disclosed in this document.

EXECUTIVE SUMMARY

The pre-pilot line for printed electronics at Holst Centre has been tested and optimized to provide functional foils for electronic devices based on printed electronics. The combination of a rotary screen printer for conductive inks and graphical inks with an assembly line for SMT components enables the development of functional foils for electronic parts. Various conductive inks were analysed during the Treasure project to provide high quality printed circuitries from start to finish during a roll-to-roll printing run by employing screens with optimized emulsions and pressures.

During the Treasure project, injection molding was applied to flexible printed foils to obtain so-called in-mold (structural) electronic devices (IME). In these IME devices, the electronics are typically protected by an additional polymer resin that is applied onto the functional (flexible) substrate, making the device rigid, strong and durable. A significant challenge, however, results from this type of encapsulation for end-of-life treatment of such electronic devices. To remedy this, a design-for-recycling was tested in the Treasure project that incorporated a disassembly layer into the devices that is compatible with roll-to-roll high volume production, without significantly increasing the bill of material and costs of production.

This deliverable describes the pilot reconfiguration, testing & optimization and describes the use of the dismantling layer in IME devices.

After an introduction of the pilot line, followed by an introduction on in-mold electronics, the recent activities on the pilot line are described. Furthermore, the use of a disassembly layer in IME devices for the purpose of improving recycling by enabling dismantling of such devices is explained. Finally, the use of the pre-pilot line for the co-development of the Treasure IME demonstrator is provided.

TABLE OF CONTENTS

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 101003587

1. Pre-pilot line description

1.1. Introduction

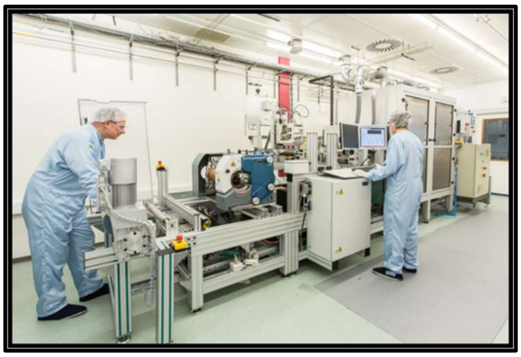
A roll-to-roll line for printed electronics has been developed at Holst Centre for prototyping purposes and research on roll-to-roll printing, assembly and optimization of processing. In the EU Treasure project, we looked more into the details of the printing process, the power usage and its applicability to a specific rigid form of printed electronics: in-mold structural electronics (IME). This deliverable will describe the roll-to-roll pre-pilot line and describe our activities.

1.2. Description of pre-pilot line

Images of the roll-to-roll (R2R) printing line are shown in figure 1. The line consists of the following building blocks:

- Motors to drive the line
- Web guiders
- Web-tension rollers
- SPGPrints RSI rotary screen printer
- Curing box
    - High power Heraeus NIR tool
    - Photonic flash curing

Figure 1a shows an overview of the front end of the printing line with the RSI rotary screen printer. The curing in this line is quite unique. Typically, conductive inks need a curing temperature of ~120 °C for 10 to 20 minutes. With a printing speed of 5 m/min this means an oven with a effective length of 50-100 meters is needed for curing the inks. Here we cure the inks with light, in particular a combination of NIR and photonic flash curing. The NIR light is poorly absorbed by the polyester films which are typically used for printed electronics. This means that only the ink absorbs the energy and the foil remains relative cool. Next step is the photonic flash curing. In this step, a series of Xenon flash lamps emits pulses of light of ~10ms at a high frequency. As it is visual light, again the light is very poorly absorbed by the polyester film but the conductive inks absorb the light very well. Using this method, a very high peak temperature is obtained in the ink, but, as it is at a high frequency, the heat transfer of the ink to the foil is limited. Figure 1b shows the middle part of the line with the curing box, and more details of the curing equipment are shown in figure 1c and 1d.


A


B

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 101003587

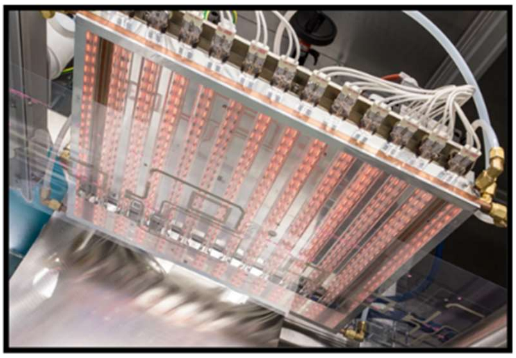

C

D

Figure 1: R2R printing line at Holst Centre, (a) overview of the line with the RSI screen printer, (b) middle part of the line with the curing box, (c) inside the curing box and (d) close-up of the NIR lamps.

1.3. Pre-pilot line lay-out

The pre-pilot line consists of two sections, each with winding and unwinding stations for rolls of plastic foil. These sections were not developed to provide a continuous process from printing of graphics to assembly of SMT components. This pre-pilot line was designed for research & development of printed electronics and is suitable for low volume prototyping. The power usage per station is provided in the corresponding figures for the graphics line and the SMT assembly line, being *Figure 2* and *Figure 3*. For the development of roll-to-roll printing, we opted for a single rotary screen for printing in the first section of the line, as each layer needs to be optimized for printing and drying. Later sections of this deliverables will further elaborate. Industrial production using roll-to-roll methodologies would / could focus on multiple rotary screens and short bursts of drying, followed by a stage of more extensive drying. This line runs at a speed of at least 5 meters per minute.

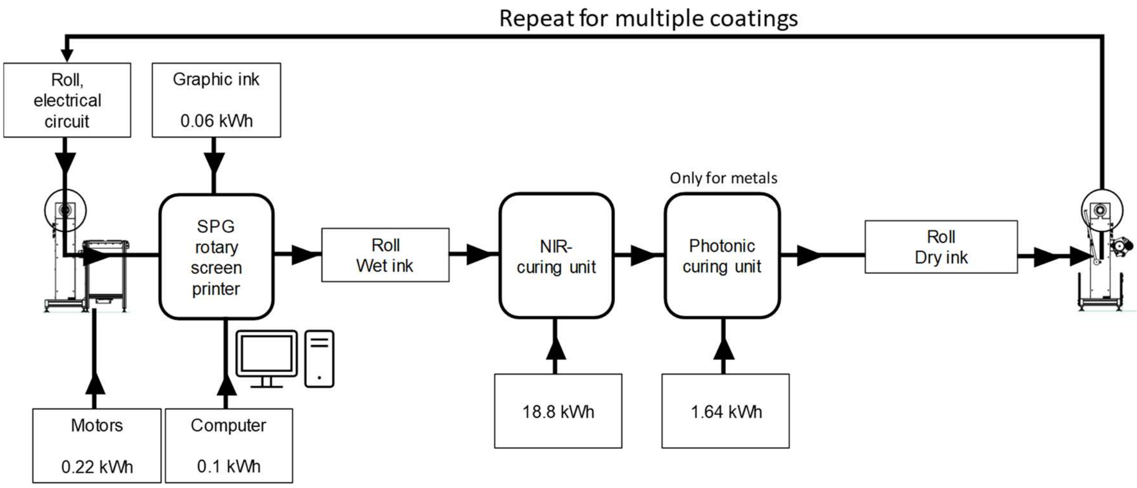


Figure 2: pre-pilot line lay-out for rotary screen printing of conductive and non-conductive inks

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 101003587

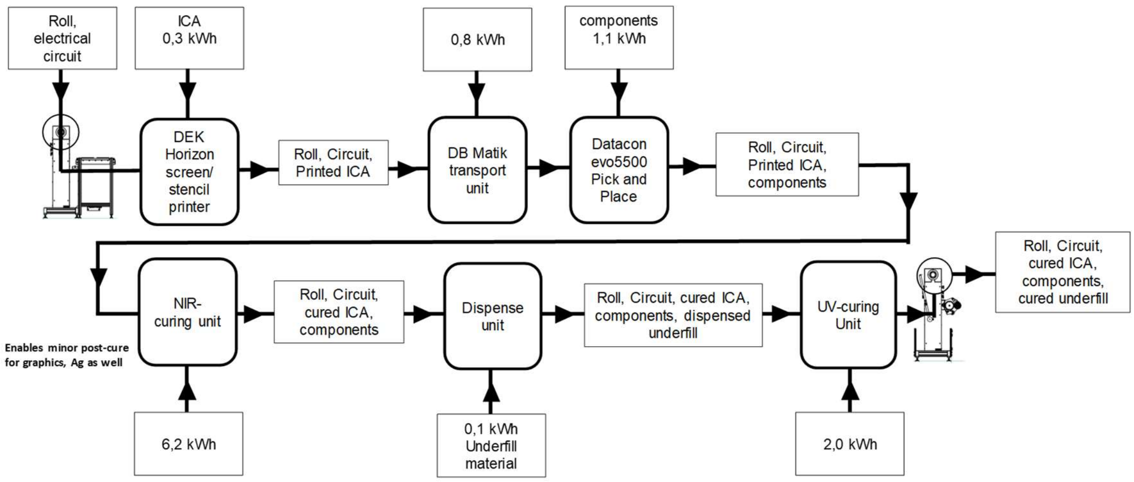


Figure 3: pre-pilot line lay-out for stencil printing of conductive adhesives, SMT component pick & place, underfilling with structural adhesive and curing

The assembly line consists of a stencil printing station for deposition of conductive adhesives, pick & place station for SMT components, NIR curing, optionally in combination with photonic sintering / curing, underfilling and finally UV curing for the structural adhesive. In our pre-pilot line, the pick & place station is time-determining step, which translates in a relatively high power usage per device in comparison to a faster industrial process.

2. In-mold structural electronics

2.1. Introduction

In-mold structural electronics is term used for a variant of printed electronics where devices, assemblies or products are realized by combining in-mold decoration or in-mold labelling with functional elements based on printed electronics. In printed electronics, the electronic circuitry is manufactured by printing and curing of conductive inks. The circuitry may consist of conductive tracks for external contacting and internal wiring, but also to create sensors, antennas and other electrical features or functionalities. The circuitry can be combined with elements from traditional electronics, such as semiconducting components that include capacitors, resistors, light-emitting diodes, driving chips, sensors and so forth, but also other type of electronics, such as solar cells, external sensors, eternal PCB driving boards, and so on. In-mold structural electronics are rigid due to the use of thermoplastic materials that are glassy, and thus rigid, at room temperature and become soft above their glass transition temperature. Unique to IME is the combination of printed electronics onto 2D substrates to achieve the 2½ or 3D shape of the final product through a process called high-pressure thermoforming. Subsequent injection molding provides stability, rigidity and encapsulation of printed electronics from environmental influences.

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 101003587

2.2. Typical processing of IME (test) devices

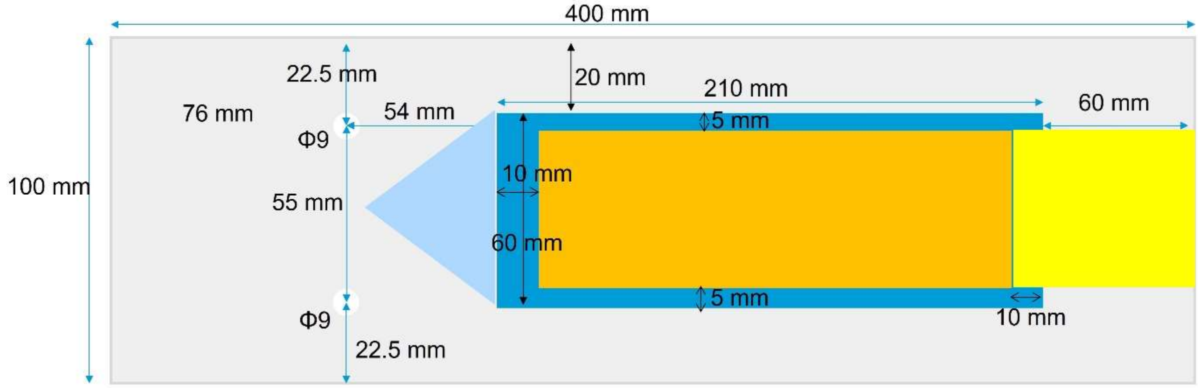


Figure 4: design of the IME lighting devices with lateral dimensions for 2D processing the functional foil; yellow corresponds to the contact area; the area in dark-blue, light blue and orange is over-molded with polycarbonate resin; orange corresponds to the functional area that is covered by NADL and contains light-emitting diodes, printed circuitry and a capacitive touch button; at the tip of the light-blue area, the polycarbonate is injected and allowed to spread evenly before flowing over printed graphic layers and circuitry.

Test devices were manufactured using sheet-to-sheet processing onto a 175 or 250 micron-thick polycarbonate substrates (Makrofol DE 1-1, Covestro), onto which 2 layers of black and 2 layers of white graphic inks (Noriphan N2K 945 and 954, Proell) were separately screen printed using a Dek Horizon 03i with 250 SD mesh screen. Each printed wet layer was roughly 19 microns thick. The graphic layers were cured using a Spidé Mistral 360 conveyor reflow oven set at 85°C, at a speed of 35 cm/min, which took approximately 5 min. Post-curing of the entire stack, as specified by the supplier, was done for 2-4 hours in a box oven. On top of the stack of graphic layers, the Ag circuitry was screen printed with commercially available silver ink (ME604, DuPont) at a thickness of 11-12 microns. Following curing of the Ag circuitry at 120°C for 10 minutes, a transparent non-adhering disassembly layer (NADL) was screen printed using similar settings and squeegees to obtain a 16 μm thick coating after curing in a conveyor reflow oven set at 45°C. A water-based non-adhering material S112 (Kiwo, De) was chosen as NADL for its low adhesive strength on various hydrophilic materials.

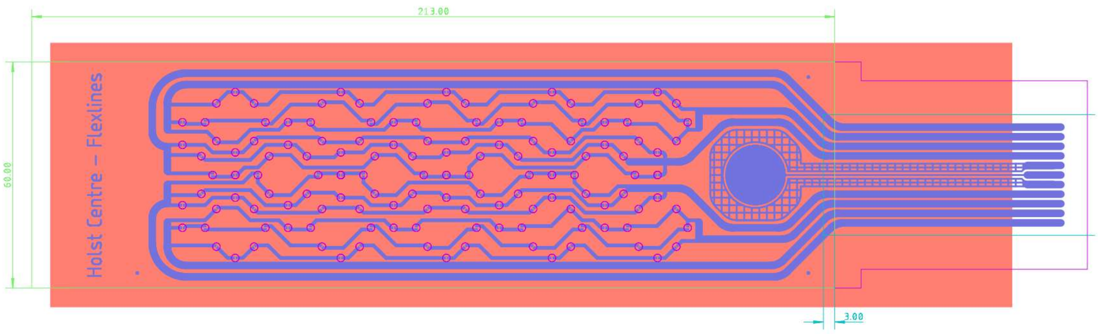


Figure 5: IME functional foil design

To accommodate SMD components, the NADL contained openings for the 132 green (SML-P13PTT86R, Rohm) or white LEDs (SCMP13WBC8W1, Rohm) through which the LEDs were bonded using a conductive adhesive and a Mycronic My200DX-14 Pick and Place machine. Optional vias were designed for the NADL for higher adhesive strength of the encapsulant to the functional substrate. Local dispensing of the NADL at the SMD components followed to prevent (strong) adhesion to the encapsulant. The dyed NADL was chosen to track the layer's integrity during processing and subsequent dismantling. The 132 LEDs were, by design, subdivided in 4 LED strings with equal division of LEDs amongst them, leading to 4 external contacts for the LEDs and an additional capacitive touch pad for intensity control. The half-circular design of the IME

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 101003587

lighting device featured no local topology and did not require thermoforming prior to encapsulation. Encapsulation was accomplished by injection molding using an Engel Victory 50 with a custom-made half-circular mold with a 4 mm cavity, which added roughly 65g of transparent polycarbonate resin. Before this, a Trotec Speedy 300 CO_2-laser was used to reduce the size of the substrates to match the mold. The functional substrates with printed circuitry were then pre-heated to 90-100°C, either in a box oven or in the mold, to reduce water-uptake by the water-based NADL. At the least, 30-60 s of heating was applied within the mold. Additional pre-drying in a box oven is considered beneficial. The pre-dried Sabic Lexan 123R polycarbonate pellets were heated up in the injection-molding device to 300°C and subsequently injected into the cavity at pressures between 250-500 bars, at a flow rate of 5 cm^3 / s and with a dosage volume of 30-65 cm^3. A hot runner enabled further heating of the polycarbonate resin up to 330°C just prior to injection. Upon injection, the flow of hot resin originated from outside the active area at the opposite edge of the external printed Ag contacts to minimize shear forces and thermal load on the printed circuitry and components. Injection-molding parameters were optimized in the ranges indicated above. During injection of the resin, after a set dosage volume, the pressure phase started with a predefined (and constant) duration of 21 seconds, followed by a cooling phase of 25 seconds.

2.3. Treasure solution to improve recyclability of IME devices

Similar to other electronics and electronic devices, IME combines plastics with metals, semiconductor technology and carbon-based coatings that improve aesthetics or provide a function within the layer stacking as protective, adhesion or otherwise supporting layer. The coatings and bulk plastics are chosen and tuned to provide a highly reliable part that can last for years. Metals and components are largely fully embedded within the plastics. While this is highly favourable for protecting the electronic functionalities, this is less than favourable for recycling at end-of-life.

A design-for-recycling was pursued for IME that uses a dismantling layer within the stack design. A water-based material was chosen as non-adhering dismantling layer (NADL) for its low adhesive strength on various hydrophilic materials, including polycarbonate. The dismantling layer was screen printed to obtain a 16 μm thick coating after curing in a conveyor reflow oven set at 45°C. To accommodate SMD components, the dismantling layer contained openings for the 132 green (SML-P13PTT86R, Rohm) or white LEDs (SCMP13WBC8W1, Rohm) through which the LEDs were bonded using a conductive adhesive and a Mycronic My200DX-14 Pick and Place machine.

Optional vias were designed for the NADL for higher adhesive strength of the encapsulant to the functional substrate. Local dispensing of the NADL at the SMD components followed to prevent (strong) adhesion to the encapsulant. The dyed NADL was chosen to track the layer’s integrity during processing and subsequent dismantling.

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 101003587

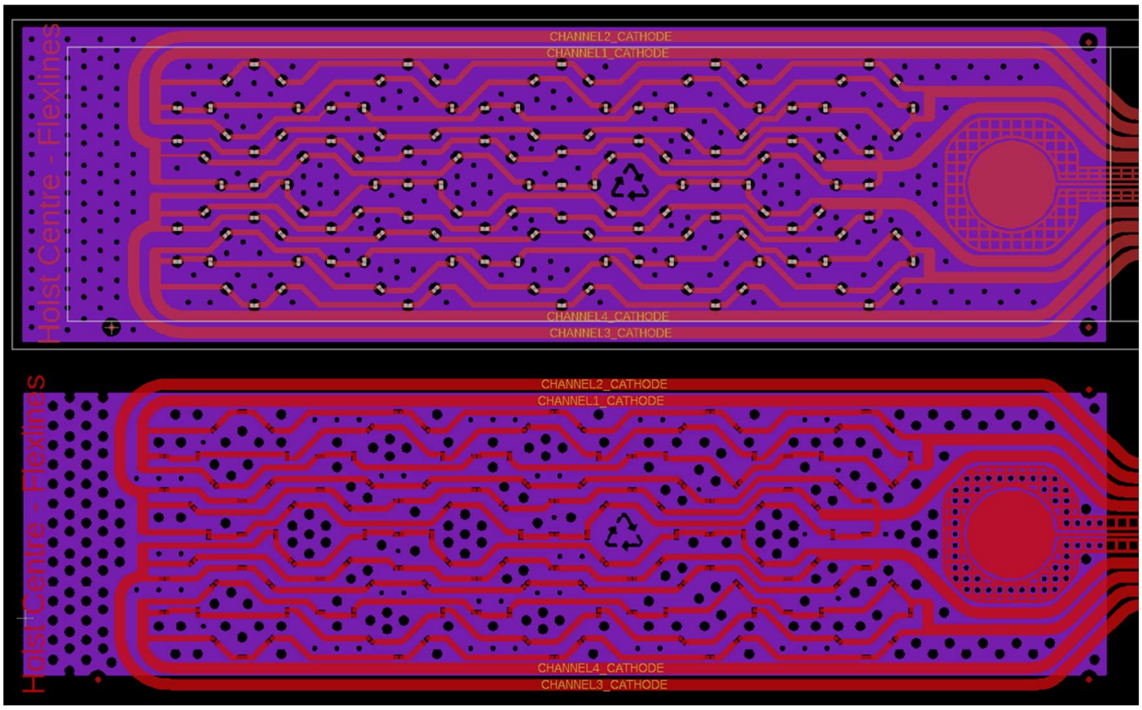


Figure 6: designs used for Treasure IME test devices with the NADL

Figure 7: printed disassembly layer (blue variant)

The exact composition of the dismantling layer was not investigated, as sales conditions do not permit this. A few observations were quite interesting and prompted us to further examine the use of this particular dismantling layer:

- Dissolves readily in water
- Becomes more resistant to dissolution upon heating
- Dissolution in water after processing is temperature/time dependent
- Sustains the injection molding process if pre-dried just before injection molding

Figure 8: IME dummy devices to optimize injection molding: from D1 to D8, the pre-drying was used.

Pictures in *Figure 8* show the impact of pre-drying on injection molding hot polycarbonate onto the water-based coating. In D1, the dismantling layer is completely smeared out. In D8, the printed patterns are clearly visible. Pre-drying was done at temperatures at or above 90°C for roughly 10 minutes. Pictures in *Figure 9* also indicate that there is a positive effect on a defect we noticed in the polycarbonate. Multiple folds were observed in the polycarbonate substrate upon injection molding. While typically the substrate is kept cool, we noticed an improvement upon heating. We address the folds to thermal expansion of the polycarbonate in combination with clamping the substrates at all sides in the mold. These defects can be avoided by different sample handling.

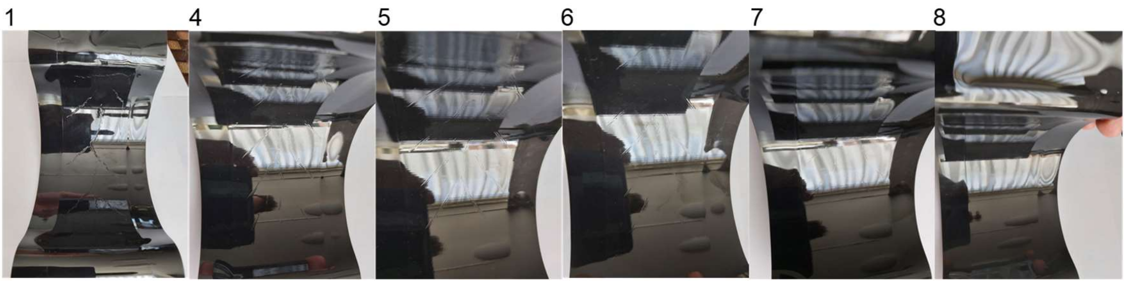


Figure 9: IME dummy devices to optimize injection molding: from 1 to 8, the temperature in the mold and time in the heated mold was extended to reduce the effects of thermal expansion of the substrate upon being covered with hot polycarbonate resin.

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 101003587

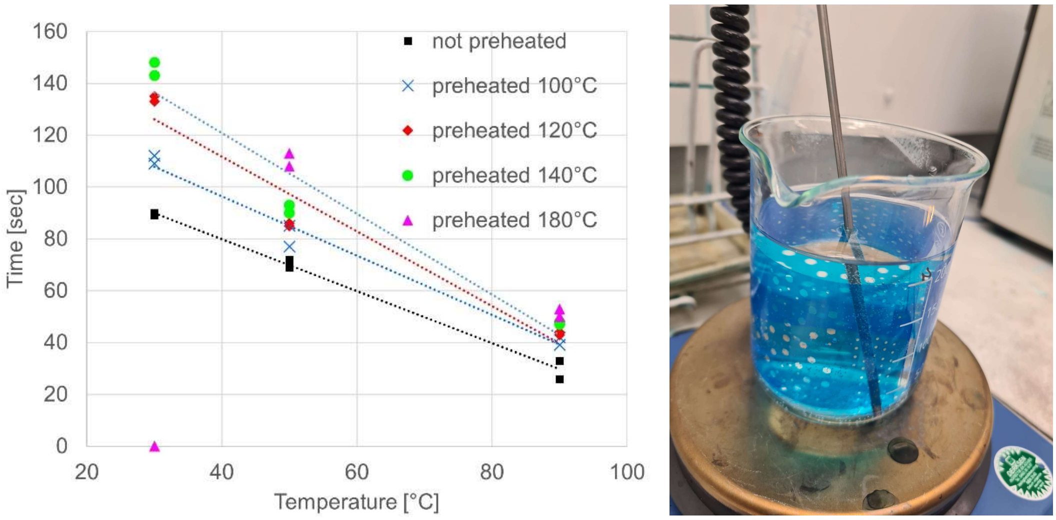


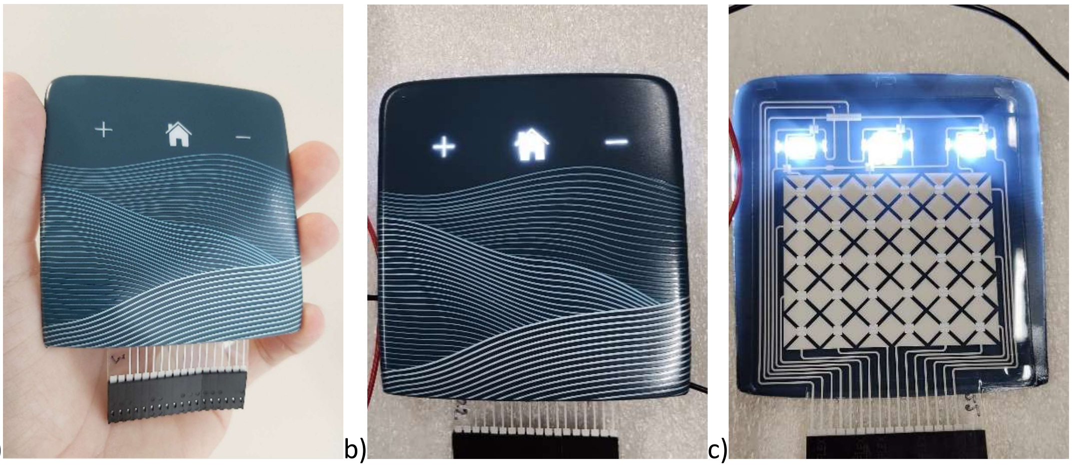
Figure 10: dissolution of the disassembly layer in cool or heated water after pre-drying the layer at temperatures between 100°C and 180°C for ten minutes. Note that the datapoint for 180°C preheating yielded a 0 for washability at 30°C: the NADL could not be removed.

The injection molding process, in combination with the curing of the SMD components, which occurs after the NADL had been printed, and the pre-drying, leads to an increased resistance of the solubility of the NADL in water. We choose not to further investigate this, as we would be required to analyse the material in detail, which we believe is in violation of the sales conditions.

This approach was submitted to Journal of Cleaner Productions with the title "Dismantling of in-plastic embedded printed electronics"[2]. For further information and description of the use of this NADL in the design-for-recycling for IME, we suggest to continue with reading this article.

2.4. Application to IME devices co-developed with Walter Pack

Same way of working was applied to a first series of test devices developed together with Walter Pack. A functional foil was printed at Holst Centre with a significant area coverage of Silver and a NADL on top to allow dismantling. *Figure 11* shows a collection of photographs for this device in off-state (a), on-state (b): front-side and (c) on state: backside.



a) b) c)

Figure 11: devices co-developed with Walter Pack with embedded dismantling layer; a) off-state, b) on-state, c) backside in on-state

[2] https://doi.org/10.1016/j.jclepro.2024.141837

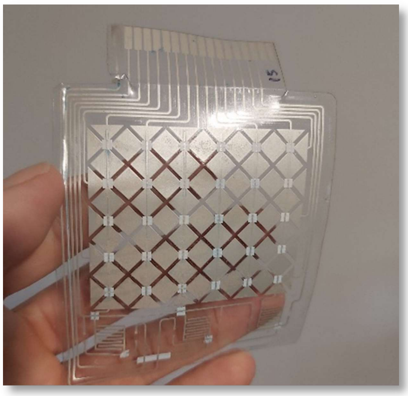


Figure 12: dismantled functional foil from devices as shown in Figure 11

The purpose of the experiment was to examine overmolding of the NADL at Walter Pack facilities and prepare for future trials aimed at delivering the Treasure IME demonstrator. Later in this document, this demonstrator will be described. Dismantling of this first example device was accomplished in a similar fashion as described above for Flexlines test samples.

3. Pre-pilot line activities

3.1. Introduction

Activities using the pre-pilot line were carried out in work packages 5 and 6 in the EU Treasure project. WP5 tasks concerned simulation of IME processing using the pre-pilot line and optimization of the printing. WP6 tasks concerned prototyping automotive parts in collaboration with Walter Pack .

Most effort in optimization of printing concerned:

- Printing of especially conductive inks
  Many silver inks have been developed over the years. Not all are immediately applicable in IME devices. IME is realized by thermoforming under high pressure and high temperatures, which requires all inks to flex and stretch during this process. Moreover, the injection molding process may also affect the integrity of the printed circuitry.
- Screen choice and optimization of the screen emulsion
  The combination of screen and ink is more stringent than expected up front. Emulsion type, ink type and printing parameters need to be optimized together for optimal printing results.

In the next sections, these topics are further elaborated on.

3.2. Emulsion optimization

A very important aspect of the screen printing process is the emulsion which is used on the screen. The emulsion has amongst others an effect on the ink throughput through the screen, how the ink releases the screen, the definition of the printed structures and the stability of the printing process.

Here we compare the printing results of a standard conductive Silver ink using a screen design with 3 different emulsions. For each emulsion the print parameters have been optimized and the print results were analysed and compared using microscopy and resistance measurements.

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 101003587

Figure 13 shows the print design that was used for these experiments. In red there are 2 structures that were used for analysis. The antenna structure was used for evaluating the print quality and resistance values and the 200µm lines with 200µm gap were mainly used to evaluate the print quality and line definition.

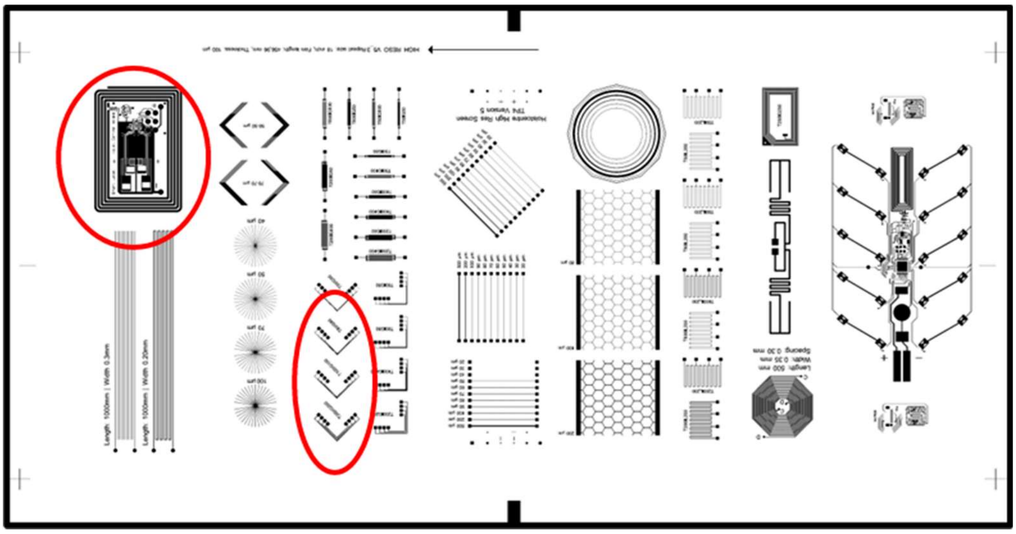


Figure 13: Print design for emulsion tests

Using the design from *Figure 13*, 5 different screens were made with 3 different emulsions. Table 1 gives an overview of the different screen specifications with the used emulsions.

Table 1: Mesh and emulsion combinations used for evaluation

Emulsion	Mesh	Open area [%]	Theoretical wet layer deposition [µm]	Theoretical print resolution [µm]
Rotacoat 326Q red	305	17	14	100
SCR100	305	17	14	100
Azocol Z177 FL	305	13	10	100
Azocol Z177 FL	215	25	20	125

All the screens were printed using a standard Silver paste. *Figure 14* shows the inside of a rotary mesh during printing. The squeegee is placed horizontally inside the screen and pressed with a certain force against the screen in contact with the substrate running against a counter roll. During the printing, the print pressure was varied in order to find the optimal setting.

Figure 14: Squeegee inside the rotary screen.

The printing results at different print pressures for the screen with the Rotacoat 326Q red emulsion are shown in *Figure 15*. The top row shows lines with 200µm width and 200µm spacing. The bottom row shows a corner of the antenna structures.

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 101003587

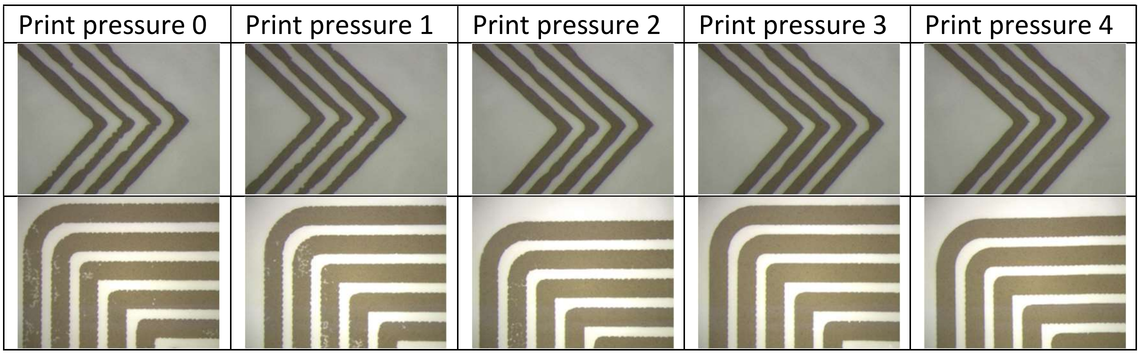


Figure 15: Print results at different print pressures for the screen with the Rotacoat 326Q red emulsion

Figure 15 shows that the ink throughput for the Rotacoat 326Q red emulsion is not so good at low print pressures. The line definition is poor and open areas can be seen in the antenna structures. At print pressure 3 and 4, the throughput is good, resulting in closed structures with better definition.

In table 2, the measured resistance values for the antenna structures are shown. The samples printed at pressure 1, 2 and 3 had so many openings that no resistance value could be measured. At print pressure 3 and 4 the print quality was good and the resistance could be measured.

Table 2: Resistance of printed antenna structures using Rotacoat 326Q red emulsion

	After printing		After oven post cure	
Print pressure	**Resistance Ω**			
	1000 mm long 300 µm wide	**Antenna**	**1000 mm long 300 µm wide**	**Antenna**
0	-	-	-	
1	-	-	-	
2	-	-	-	
3	273	63	245	59
4	204	54	191	50

All combinations of screen and emulsion were evaluated in a similar way as described above. The summarized optimized results for each combination are shown in *Figure 16*.

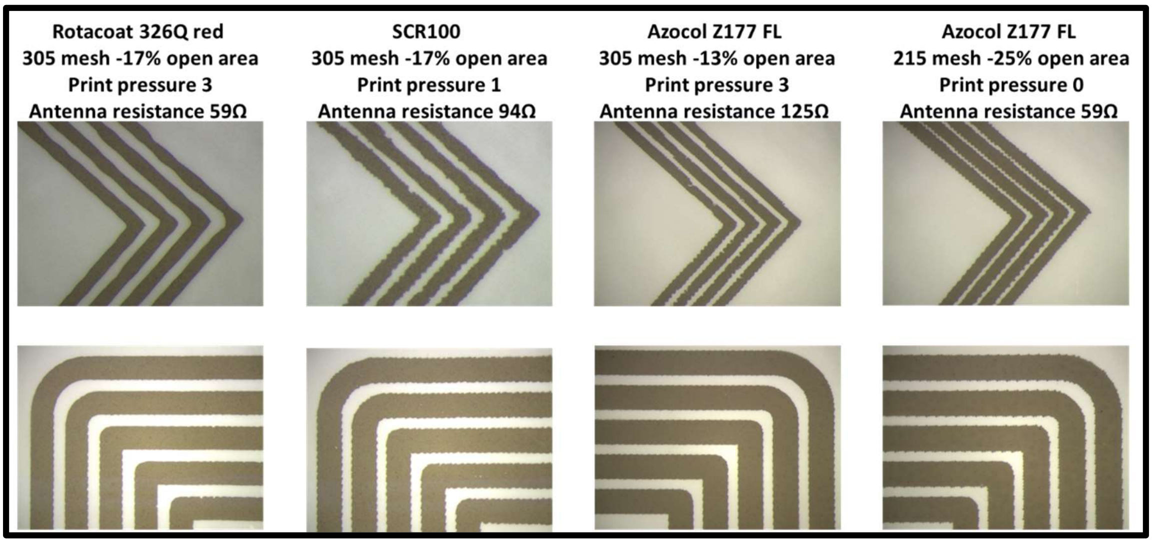


Figure 16: Summary optimized print results for screen-emulsion combinations.

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 101003587

Overall results Rotacoat 326Q red:

- Poor ink throughput at print pressure 0, 1 and 2
- Good throughput at pressure 3 and 4
- With pressure increase, the ink spreads more on the substrate
- 200-200µm lines-gap possible; 100-100µm lines-gap also possible but challenging

Overall results SCR 100:

- Poor ink throughput at print pressure 0
- Good throughput at print pressure 1 and higher
- Quite strong spreading of the ink at all pressures
- 200-200µm lines-gap are possible, higher resolution is not possible

Overall results Azocol Z177 FL – RM305 – 13% open area:

- Little ink throughput due to low open area
    - Printed structures not fully filled at pressure 0, 1 and 2
    - At pressure 3 and 4 stuctures are filled
- 200-200µm lines-gap possible, higher resolution is challenging

Overall results Azocol Z177 FL – RM215 – 25% open area:

- High ink throughput, even at pressure 0
- 200-200µm lines-gap are possible, higher resolution is not possible

Comparing all the results we can conclude that the Rotacoat 326Q red gives the best results with respect to print quality and resistance.

3.3. Ink benchmark

For many screen-printing applications, it is desired to have a as low as possible resistance at an as high as possible resolution. To achieve this, inks with a high conductivity and a high solid loading are preferred. In addition, when going to high resolution printing, it is desired to have small (sub-micron) particle sizes for the solids for better definition of the printed structures. The evaluation of three inks and a reference was done using sheet-to-sheet screen printing as this is done easier compared to roll-to-roll printing. Table 3 gives an overview of the most important properties of our reference ink and three potentially interesting inks.

Table 3: Benchmark results of 4 conductive Silver inks

Ink	resistance 1 meter long tracks (Ohm)			sheet resistance / mil (mΩ/□/mil)			avreage height (micron)		
	line width (micron)			line width (micron)			line width (micron)		
	200	500	1000	200	500	1000	200	500	1000
Reference ink	236	74,7	37,7	14	12,2	10,8	5,6	7,6	7
Silver ink 1	101,3	36,3	21,4	4,2	4,2	4,4	3,6	5	4,8
Silver ink 2	128	48,0	23,8	11,5	11,5	11,0	10,5	11,6	11,7
Silver ink 3	29,4	8,9	4,5	2,1	1,9	1,8	8,6	10,7	10,7

In Table 3 can be seen that all 3 Silver inks have a lower resistivity compared to our reference ink. In addition, ink 3 and 4 also have a higher solid load resulting in a higher print thickness. For

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 101003587

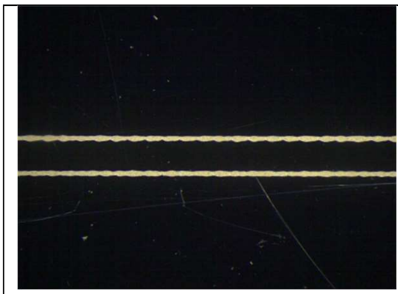
Silver ink 2 this means that using the same screen, a >35 % lower track resistance is obtained and for Silver ink 3 even a >85% lower track resistance is obtained.

3.4. Roll-to-roll print optimization

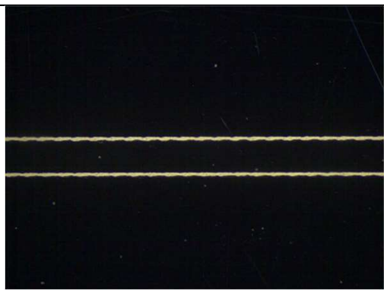
To optimize the R2R printing process, two main parameters were investigated. First is the influence of the Conductive ink. For this we use the information obtained in the S2S ink benchmark. Secondly, the influence of the screen type on the resolution and resistance is evaluated.

3.4.1. R2R conductive ink comparison

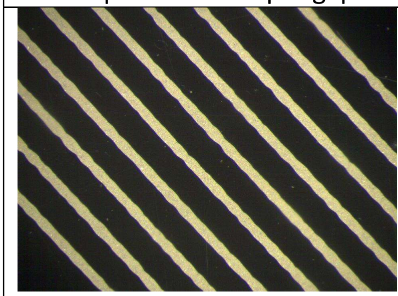
Using the outcome of the S2S ink benchmark, a R2R comparison was made using Silver ink 2 (although Silver ink 3 gave even better results, there was not sufficient ink available to perform a R2R experiment) and the reference ink. A screen with a 305 mesh, 17% open area and the Azocol Z177 FL emulsion was used. In order to compare the results, the print quality of fine features was compared. *Figure 17* shows the R2R results of the reference ink and Silver ink 2.



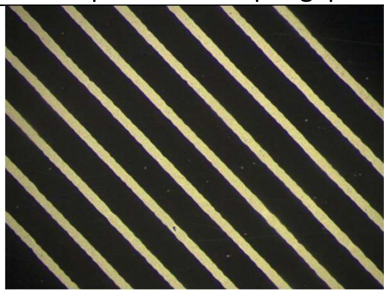
100µm line – 500µm gap



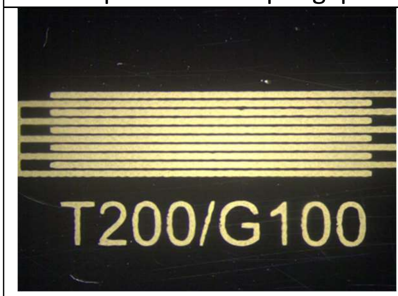
100µm line – 500µm gap



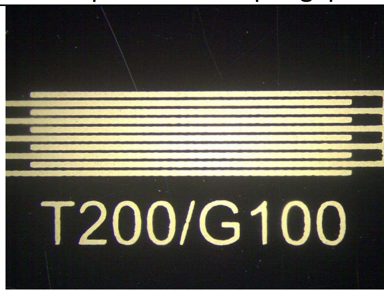
150µm line – 500µm gap



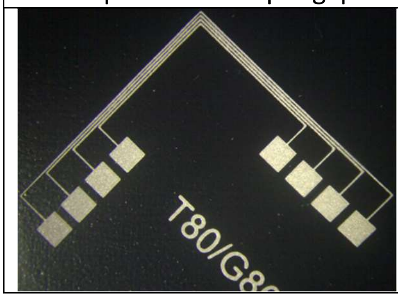
150µm line – 500µm gap

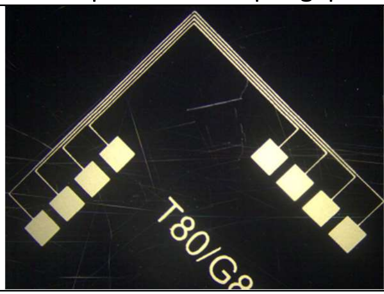


200µm line – 100µm gap



200µm line – 100µm gap





This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 101003587

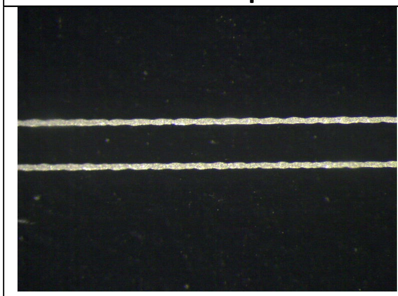
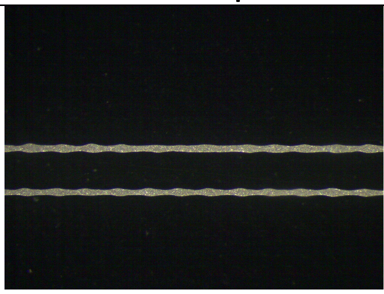
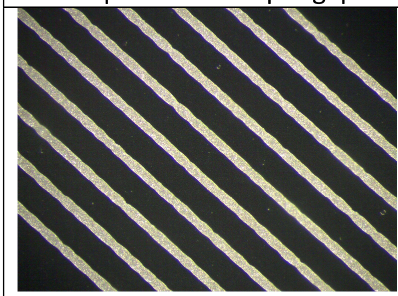
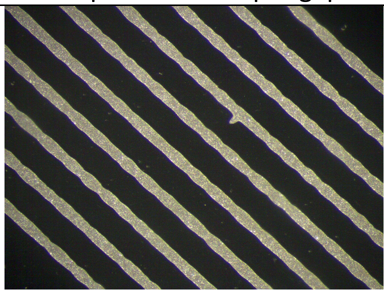
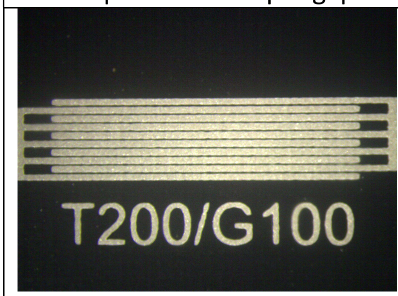
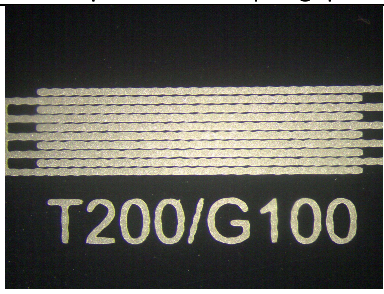
80µm line – 80µm gap	80µm line – 80µm gap

Figure 17: Comparison of fine R2R printed structures using a reference ink and Silver ink 2.

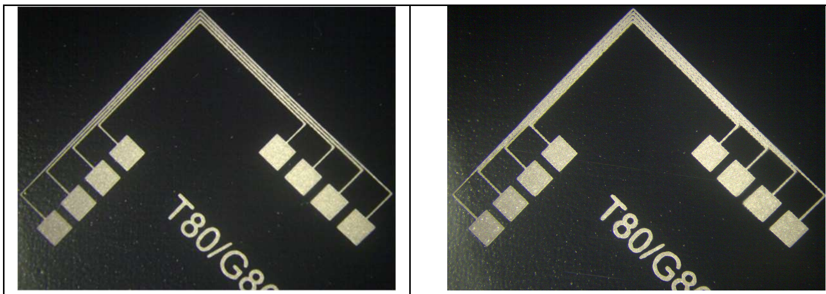
Figure 17 shows that Silver ink 2 prints slightly better defined structures compared to the reference ink. The resistance of 1 mm wide lines is for the reference ink the reference ink 48 Ω/m compared to 28 Ω/m for Silver ink 2, which is >40% lower which is quite in line with the results found in the S2S evaluation.

3.4.2. R2R screen type comparison

The influence of the screen type on the resolution and the resistance of printed structures was compared using the reference Silver ink and two different screen types. The first screen has a 305 mesh, 17% open area, a wet layer thickness of 14 µm and a theoretical print resolution of 100 µm. The second screen has a 215 mesh, 25% open area, a wet layer thickness of 20 µm and a theoretical resolution of 120 µm. In figure 7, images comparing the result using the 2 screens are shown.

Screen: **RM305 – 17% open area**	**Screen:** **RM215 – 25% open area**
 100µm line – 500µm gap	 100µm line – 500µm gap
 150µm line – 500µm gap	 150µm line – 500µm gap
 200µm line – 100µm gap	 200µm line – 100µm gap

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 101003587



80µm line – 80µm gap	80µm line – 80µm gap

Figure 18: Comparison of fine R2R printed structures using the reference Silver ink printed with two different screens.

Figure 18 shows that the printed structures using a RM215 mesh compared to the RM305 mesh leads to lower resolution in the printed structures. Narrow lines of <100µm can still be printed with the RM215 screen, however, the line definition is worse compared to lines printed with the RM305 screen. As a result, the spacing between printed structures should be at least <200µm to avoid short circuits. Benefit of the RM215 screen over the RM305 screen is the increased wet layer deposition (from 14 to 20 µm), which leads to a decrease in the resistance for 1 mm wide lines from 48 Ω/m for the RM305 mesh to 31 Ω/m for the RM215 mesh.

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 101003587

4. Pre-pilot line development of Treasure demonstrator

4.1. Demonstrator design

Activities using the pre-pilot line were carried out in work packages 5 and 6 in the EU Treasure project. WP5 tasks concerned simulation of IME processing using the pre-pilot line and optimization of the printing. WP6 tasks concerned prototyping automotive parts in collaboration with Walter Pack. These developments have not been concluded and are scheduled to be completed before the end of the project.

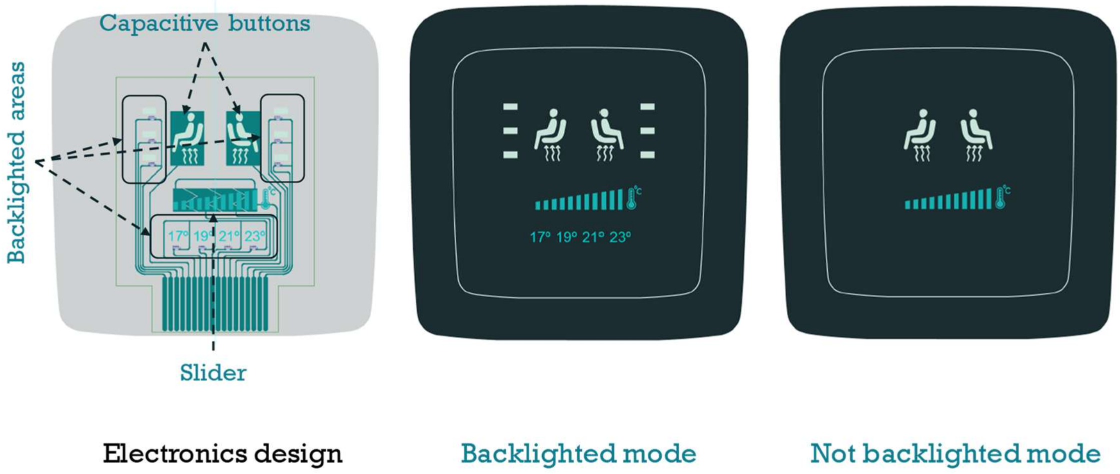


Figure 19:design of decorative foil A

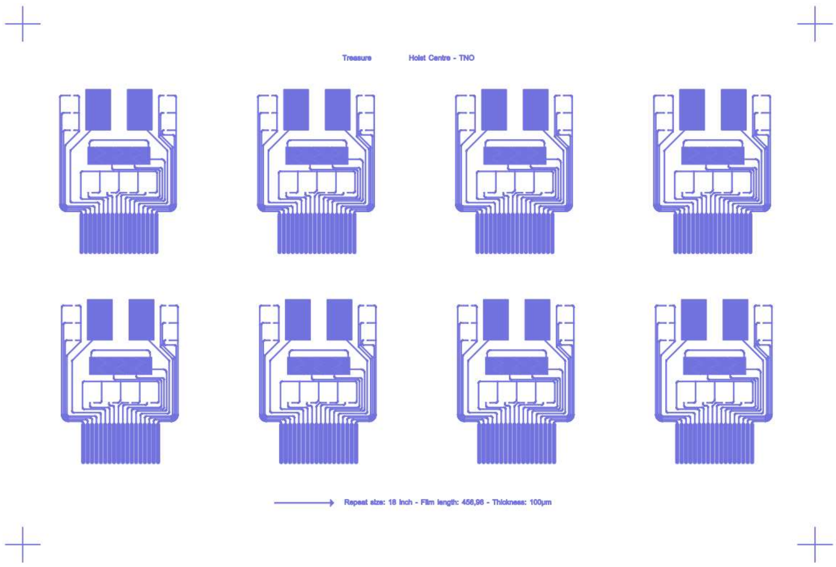


Figure 20: design for rotary screen of Ag circuitry on functional foil B

The designs of the decorative foil A and functional foil B are provided in *Figure 19* and *Figure 20*. *Figure 21* shows the process flow with a multitude of printing and curing steps to deposit the functional and decorative coatings onto each foil using the R2R line. These two foils, of which foil A is thermoformed to provide a curve shape, are then combined into a single IME device using injection molding.

4.2. Demonstrator process flow

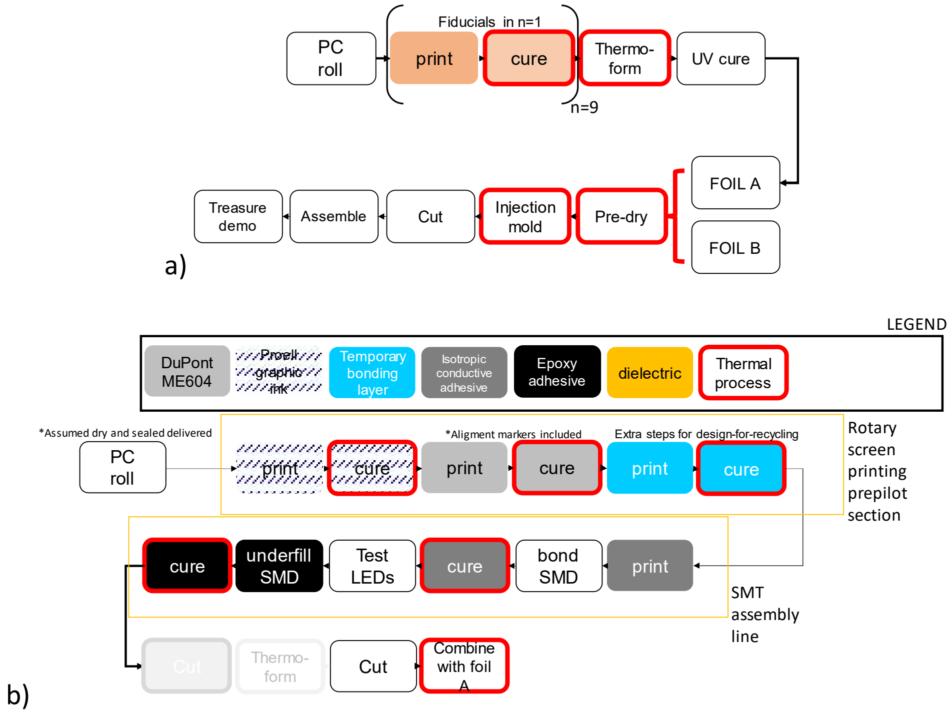


Figure 21: process flow for the Treasure IME demonstrator: a) Foil A and IJM of Foil A+B, b) process flow for foil B

Process flow in *Figure 21* shows in a) the flow for the decorative foil, including the merging of foils A and B by injection molding, and in b) the flow for the functional foil. The process for foil A consists of the application of 9 coatings, but is more complicated than shown, as the final part contains haptics by surface textures, a unique feature added to the part by Walter Pack. This allows the user to feel where the slider is located and provides an intuitive interaction to adapt the air temperature using the slider. The materials used for the decorative foil are also not as easily summarized as for Foil B, as some layers may be achieved by a combination of materials. A legend is therefore omitted. Foil B includes the application of semiconductor components (LEDs) by pick & place technology. P&P is followed by application of structural adhesive and curing thereof. In the final stage of assembly, foils A and B are brought together in an injection molding tool and bonded together by the solidification of the injected hot polycarbonate.

Currently, further processing of the foils using the pre-pilot line is underway and will be reported on in a later deliverable.

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 101003587

4.3. Impact of NADL

Treasure methodology to disassemble the IME devices is incorporated in the demonstrator by an additional printing and curing step of the NADL and a pre-drying step just before injection molding. The added possibility of disassembly comes at a minor cost:

- Bill of material: we estimate that the addition of the NADL to a device would cost roughly 1-10 Eurocents, depending of the size of the part and the costs of the NADL. This price is based on a low-volume offer for a 1 kg purchase.
- Manufacturing: additional costs should be included, related to electricity use, as a result of an additional single printing step, followed by a drying step in a conveyor reflow oven set at 45°C (5 min). An additional pre-drying step just before injection molding: 10 min at 90-100°C. Early samples took 2 print/curing steps, but later samples only once (16 vs 8 micron thickness).
- Aesthetics: a thin colorless and fully transparent layer is hardly noticeable. Moreover, the film is especially meant to allow removal of foil B from the assembly. Typically, foil A provides the front aesthetics of the part and obscures view to foil B with the NADL.
- Reliability: initial life time testing, especially for 1000 hours at 85% RH, 85°C, revealed significantly fewer issues than expected thanks to several curing during processing and an additional pre-curing step just before injection molding (shown in *Figure 21*).
- Environmental impact (elaborately described in ref [2]): The NADL covers the circuitry and is intended to enable dismantling of the part at end-of-life. Dissolution of the NADL is believed to be necessary to fully access the Ag during a subsequent hydrometallurgic processing step. The NADL is a water-soluble, but quite possibly not made of a fully biodegradable material, which was the intention. A biodegradable material could reduce the impact of a rinsing step water. On the other hand: a solvent-based material would likely cause a larger impact through the use of volatile and/or hazardous solvents. We also speculate that the NADL may dissolve in the same mixture used to leach Ag from the printed circuitry.

For further information regarding the use of this water-based non-adhering dismantling layer, see Harkema *et al.*[2].

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 101003587

5. Abbreviations

IME	In-mold Structural Electronics
Ag	Silver
NADL	Non-adhering dismantling layer
PCB	Printed circuitry board (conventional electronics)
R2R	Roll-to-roll
S2S	Sheet-to-sheet
UV	Ultra-violet
NIR	Near-infrared
SMT	Surface-mounted technology
SMD	Surface-mounted device
IJM	Injection molding

6. Abbreviations

The content on the design-for-recycling for printed electronics was recently published in Journal of Cleaner Production, which is available via (gold) open access.

Texts with relevant references are best found in this article:

Stephan Harkema, Peter A. Rensing, Sanne M.D.C. Domensino, Joris M. Vermeijlen, Diana E. Godoi Bizarro, Antoinette van Schaik, "Disassembly of in-plastic embedded printed electronics",

Journal of Cleaner Production, Volume 450, 2024, 141837, ISSN 0959-6526, https://doi.org/10.1016/j.jclepro.2024.141837.
(https://www.sciencedirect.com/science/article/pii/S095965262401285X)