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Development of a 3D-formed and thin-film backlit HMI

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Abstract

During three subsequent research projects in co-operation with industrial partners, thin printed touch sensors were developed and investigated. In the first project the touch sensors employing the capacitive or piezoelectric principle were screen-printed as thin-film sheets of transparent polycarbonate. In the second project, these thin-film sheets were 3D-formed through thermoforming and over-moulding process. In the third project, a thin-film light source was printed onto the backside of the transparent sensors. The backlighting was achieved using either electroluminescence or an innovative technique of micro-LEDs suspended in a printed varnish, a proprietary method developed by the company NthDegree.

Keywords: screen-printing; micro-LED lighting, touch sensors, Human Machine Interface (HMI), 3D forming

1. Introduction

In recent years, the interior design of cars has undergone significant changes. Mechanical switches have almost completely disappeared, replaced by smart controls with touch-sensitive activation. However, for simplicity, large TV-like touch screens currently dominate dashboards. To allow designers to return to curved shapes, touch controls implemented in thin 3D-formed parts would be desirable. This goal has been pursued through three consecutive research projects funded by the Ministry of Science and Culture of the federal state Baden-Württemberg under the “Innovative Projekte” (innovative projects) program.

Thus, at the Institut für Innovative Anwendungen der Drucktechnologien (IAD) in co-operation with industrial partners thin, printed touch sensors were fabricated and thoroughly investigated. In the first project, touch sensors operating on the capacitive principle, were produced as thin-films made of transparent polycarbonate using a screen-printing process. An attempt was made to provide haptic feedback to the user upon switch activation through vibration of a printed piezo element placed beneath the capacitive touch sensor. The printed piezo element was found to vibrate optimally at frequencies between 250 and 300 Hz, but the amplitude proved too be too low for user perception in a moving vehicle environment. However, the printed piezo stack itself demonstrated potential as a sensor, as it generates a detectable transient signal that can be detected easily and reliably by the evaluation software when pressed. This capability proved to be even more advantageous than that of a capacitive sensor, as the

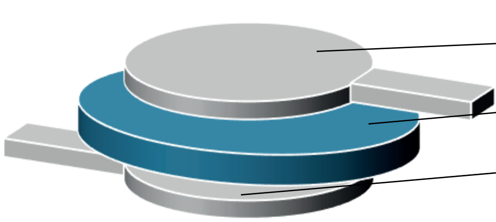

Figure 1: Schematic of the printed piezo-effect touch sensor

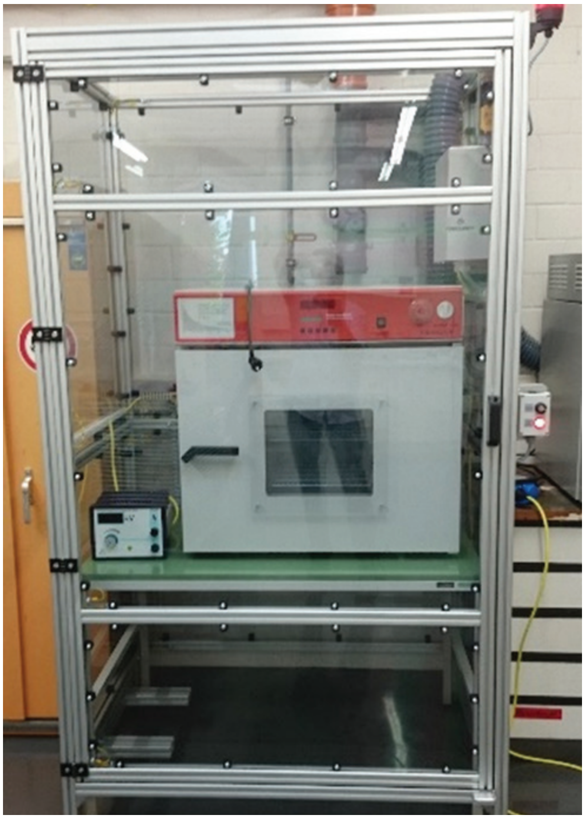

Figure 2: Safety housing around an oven to polarise the printed piezo-effect touch sensor permanently at elevated temperature and high electrical voltage

Figure 3: Large sample printed piezo-effect touch sensor

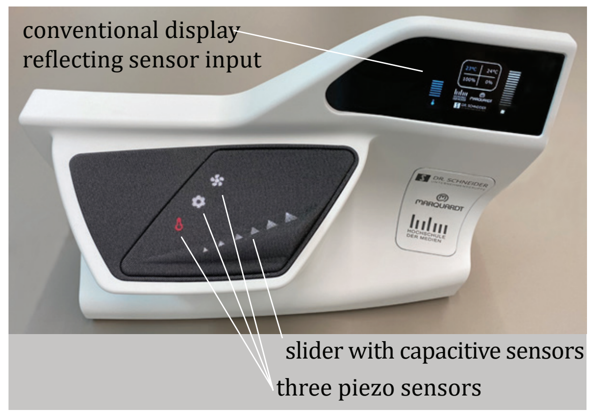

Figure 4: Demonstrator with three piezo sensors, a slider with capacitive sensors and a conventional display reflecting sensor input

piezo sensor's force requirement provides protection against unintentional activation.

The piezo sensor developed in the first two of these three projects was already reported on at the 2018 iarigai conference (Huebner, et al., 2018). Figure 1 illustrates the basic concept of the touch sensors based on the piezo-effect. The challenge was the layer of PVDF-TrFE (poly(vinylidene fluoride-co-trifluoroethylene)material. The solids content of the paste is very low and several successive prints (at least four print passes) were necessary to achieve a desired layer thickness of 16 to 20 μm while maintaining sufficient electrical dielectric strength.

After printing of the PVDF-TrFE layer (figure 3) with several print runs the layer must undergo polarization at elevated temperatures. High voltage (several thousand volts) is applied to the top and bottom electrodes during the stay in the oven. The oven therefore is placed in a safety housing (see Figure 2), with the voltage automatically disconnecting when the housing door is opened.

In the second project, the thin-film sheets were 3D-formed (thermoforming and subsequently over-moulding). The challenge is to maintain the function after the forming and over-moulding process. The result of this second step was a demonstrator (Figure 4). The sensors have conventional LED-lighting from behind. This demonstrator won the OE-A price at LOPEC 2023.

In the third project, which is the focus of this paper, a thin-film light source was printed onto the backside of the transparent sensors. In comparison to classical, rigid SMD-LED placements, the idea was to print light-emitting layers that are extremely thin in the range of a few microns (excluding substrates).

Two techniques for lighting up from behind were investigated. First, the well-known electroluminescence (EL) was employed and second, a proprietary technique of micro-LEDs suspended in a printed varnish (a method developed by the company NthDegree, Tempe AZ, USA).

Figure 5 shows sample light sources printed by NthDegree. Their process accommodates both screen-printing and flexography.

It can clearly be seen that the micro-LEDs are distributed randomly. The dimensions of the micro-LEDs are about 20 μm in diameter as can be seen on the SEM-photo (Figure 6) taken from US Patent 9,425,357 B2 (Lowenthal, et al., 2016).

Figure 5: Printed micro-LED lamps

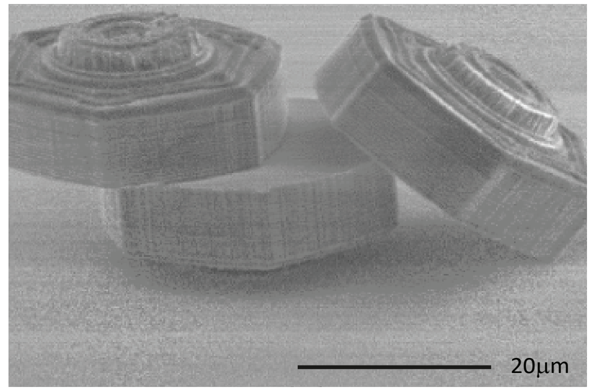

Figure 6: Micro-LED lamps (Lowenthal, et al., 2016)

The micro-LEDs feature electrodes at the top and bottom and the light is emitted upwards. The patented technology somehow makes it possible for the lower electrode of the LEDs to sink downwards and orientate itself to the conductive silver layer underneath. The dielectric layers are necessary so that the transparent top conductor layer does not get in touch with the bottom conductive layer. According to NthDegree, approximately 70 % of the LEDs can be illuminated using this method. The phosphor layer is applied to make the light of the blue micro-LEDs appear white (wavelength shifting with the help of YAG, yttrium-aluminium-garnet). NthDegree's innovative approach to printing the micro-LEDs also made it possible to print in reverse order, i.e. the transparent conductive electrode first and the Ag electrode last, so that the light is directed onto the substrate. This project utilized screen-printing in reverse order.

The visibility of the lighting is determined by the illuminance, which is specified in candelas per square metre (cd/m^2). Automotive applications typically require illuminance exceeding 500 cd/m^2, with 1 000 cd/m^2 representing ideal conditions. For night design applications, around 10 cd/m^2 is sufficient.

2. Research methods

The third step, implementing the light-emitting layer, utilized the same layout as previous steps due to the existing thermoforming and moulding tools, as creating new tools would be cost-prohibitive. The key difference now is that the function, i.e. the touch sensors and the illumination layers are printed on the same substrate, the illumination on the top side and the touch sensors on the bottom side. This substrate is referred to as the B-surface, i.e. the back of the side facing the user. Both, the sensors and the lighting, are printed on the B-surface, with the lighting being printed first. The decorative surface visible to the end user is called A-surface. To finalize the part, both foils (A-surface and B-surface) are placed into an injection moulding device, where the stiffening plastic is injected between the two substrates. This setup is depicted in Figure 8.

In this project, piezo sensors were not employed as capacitive touch sensors offer simpler manufacturing processes and more reliable functionality. Moreover, the forming capability of the piezo sensors was already shown in the second project step.

The investigation covered two thin-film illumination techniques: electroluminescence and the printed micro-LED approach.

2.1 Lighting with electroluminescence

This technique is well known, and it has been shown that the printed sheets can be thermoformed quite easily (e.g., Chang, 2019). Figure 9 shows the basic struc-

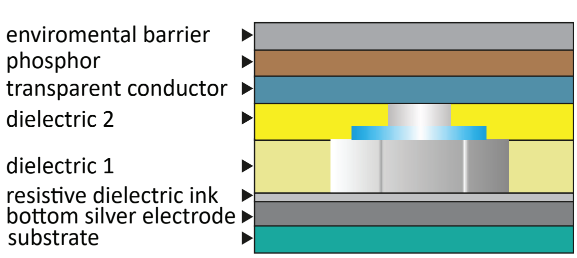

Figure 7: Sequence of printed layers with micro-LEDs (Claypole, 2019)

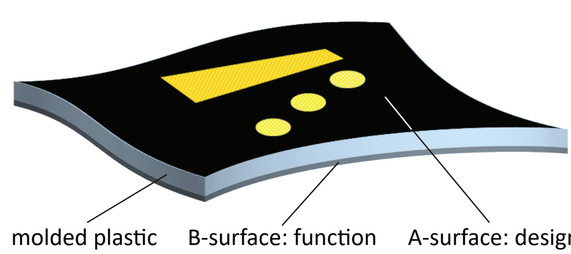

Figure 8: Basic design of the demonstrator with three buttons and a slider

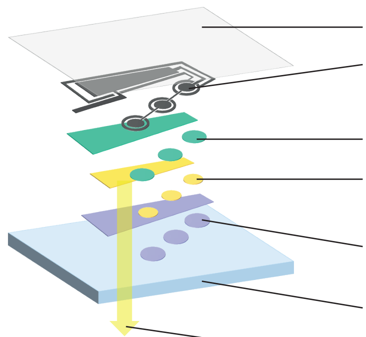

Figure 9: Layer sequence of printed electroluminescent lamp. PEDOT is the cationic species of poly(3,4-ethylenedioxythiophene)

ture of the screen-printed EL lamp used in this project, comprising substrate (polycarbonate, PC), transparent electrode, emitting layer (commonly referred to as 'phosphor', typically doped zinc sulphide), dielectric (insulating layer), electrode, and protective layer.

During testing, forming process challenges led to cracking of printed layer, compromising lamp functionality. A protective coating from the ink manufacturer Pröll, which was specially developed for in-mould electronics (IME), showed better results, particularly when applied as a double layer, but could not guarantee 100 % yield. Figure 10 (a) shows such a crack that occurs after thermoforming. The cracks occur where the conductor track merges into the slider. To overcome the cracking issue, the design was modified by trying to avoid the hump and thus, some working lamps could be produced. However, the achieved illuminance was only around 50 cd/m^2, which is not sufficient for the desired application. In addition to the project partner Dr Schneider GmbH (now Motherson DRSC Deutschland GmbH), a further industrial partnership was established with Niebling GmbH during the project. Niebling has developed a forming method called high pressure forming (HPF), which is somewhat 'gentler' than the classic 'vacuum forming' at Dr Schneider, as the preheating temperature of the film is significantly lower, while the temperature of the forming tool is quite similar. Ten EL lamp prints were formed using Niebling's HPF process and remained functional but achieved illuminance no higher than 70 cd/m^2. Niebling reported successful EL forming in previous industrial trials (unpublished).

2.2 Lighting with micro-LEDs

The most challenging part of the research is the 3D forming and overmoulding of the printed structures, especially as the suspension of the micro-LEDs in a printing paste is quite expensive and the risk of damage during the forming and moulding tests is high. Preliminary testing of printing ink stretchability and formability was therefore conducted. Various silver pastes marketed for in-mould electronics were evaluated using a test moulding tool featuring 0.5 and 1 mm wide lines with increasing stretch factors (1 to 2.5) and defined edge radii. Figure 11 shows the printing layout (a) and the moulded plastic part (b).

Another aim of the test prints was to find out whether PET could be used instead of PC, as NthDegree had better experience with PET than PC for its products, but PC is used almost exclusively in the automotive industry.

As the silver print has direct contact with the moulding tool, a protective lacquer is also used, which is applied in a second printing process and is intended to further support successful forming. For this purpose, both the varnishes corresponding to the respective paste and two different varnishes from Pröll GmbH were tested, namely the solvent-based varnishes Noriphan HTR N 093/444 (one-component) and Noriphan N2K (two-component).

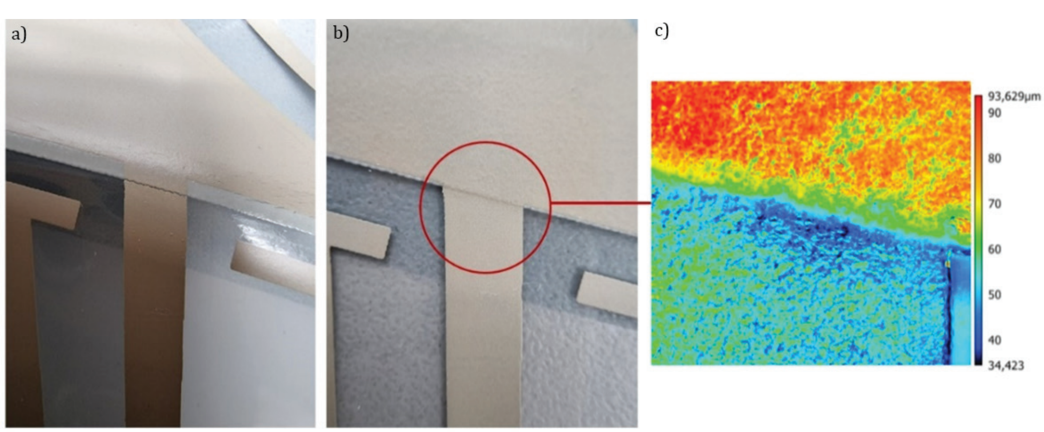

Figure 10: a) Crack after forming; b) enlarged before forming; c) height profile of the print before forming (ranging from 34.423 to 93.629 µm)

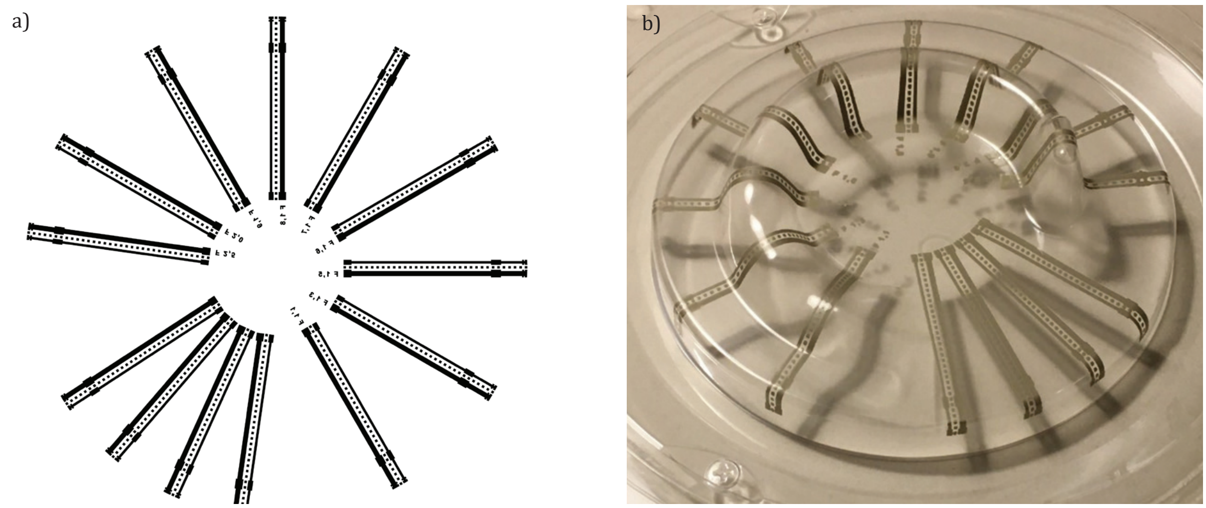

Figure 11: Printed test pattern (a); formed polycarbonate sheet (b)

Some prints were produced at NthDegree and some at the HdM in order to subsequently carry out the forming tests at Niebling (HPF) and also at Dr Schneider (vacuum thermoforming process). With HPF, it is possible to work with comparatively low film-forming temperatures. The results show that there are virtually no differences between the various silver pastes in terms of electrical performance and visual inspection before thermoforming, regardless of whether PET or PC was used.

After thermoforming, the picture is different:

- The printed lines on PET are interrupted at significantly lower stretch factors and therefore lose conductivity.
- When comparing the varnishes recommended by the manufacturer with those from Pröll, the Pröll HTR N 093/444 is particularly favourable.
- All silver pastes showed comparable conductivity when using Pröll varnish.
- Visual inspection of the forming with the HPF technology shows always better results than with the classical vacuum forming.

As the B-surface is also to be printed with silver paste on the front and then over-moulded with plastic in the further course of the project, adhesion to the injection moulding material is crucial. Peeling tests were carried out for this purpose. Peeling tests identified the Elantas silver layer (Bectron CP 6680) with Pröll protective coating (HTR N 093/444) as the best-performing combination, which was adopted for subsequent work.

As the micro-LEDs emit blue light (450nm), but a white colour is desired, a phosphor layer is “phosphor“ is necessary. The term “phosphor” refers to cerium-doped yttrium aluminium garnet (YAG), which functions as a wavelength shifter similar to standard white LED production. Tests were carried out whether this phosphor layer is also formable without defects. The phosphor is supplied as a powder and is stirred into the clear lacquer HTR N 093/444 from Pröll GmbH for printing. The forming tests showed no cracks, and a homogenous layer was maintained. Without illumination with blue light, the print appears yellowish as shown in Figure 12. NthDegree has some experience and provided empirical values for the recommended CIE b^*-values. They were measured with a spectrophotometer and showed sufficiently high values.

Based on these preliminary tests the layout of the B-surface was fixed as shown in Figure 13.

Figure 14 details the layout and specifies screen–printing form mesh counts (threads per cm) in the legend. The structure resembles that of the electroluminescent lamp, with the micro-LED-containing layer replacing the electroluminescent layer.

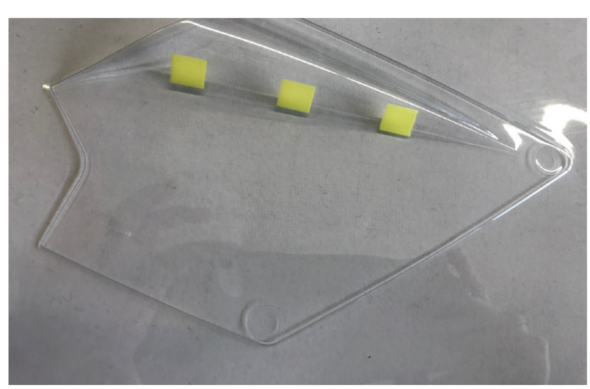

Figure 12: Test prints with phosphor layer after forming

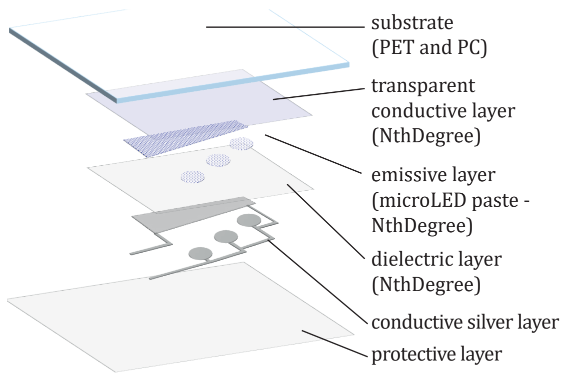

Figure 13: Printing of the illumination part onto the B-surface

Figure 15 depicts how the B-surface is finished by adding the layer with the capacitive switch pattern and the phosphor layer. NthDegree's special proprietary know-how is that during and immediately after the printing process, most of the micro-LEDs align themselves in such a way that the upper contact of the LEDs points downwards towards the transparent conductive layer (e.g. PEDOT/PSS) and the upward-facing opposite pole is not 100 % covered by the surrounding insulating paste. If the entire surface is then covered with a conductive layer (not transparent) applied on top, a sufficiently high percentage of the LEDs start to light up, which resembles a kind of starry sky. Figure 16 shows an example of the glowing blue background of the slider. To achieve white illumination with improved homogeneity, the phosphor was applied at HdM to the film's front alongside the capacitive sensor and final transparent protective coating. Figure 17 shows the required printing steps.

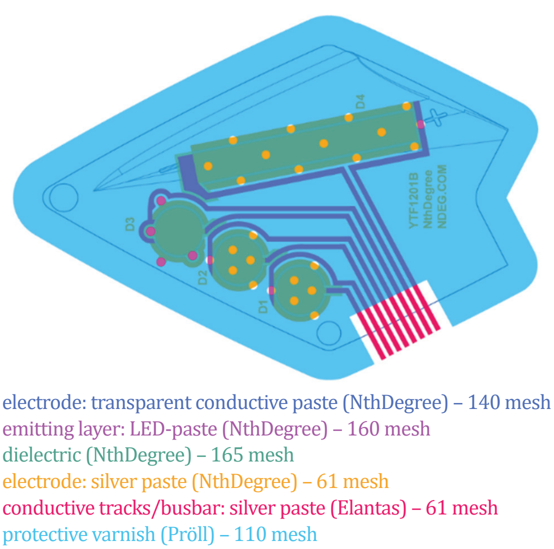

Figure 14: Layout (top view) of the B-surface foil showing which layer is printed by NthDegree and which by HdM including mesh count specifications. Some circular spots left open for measurement purposes

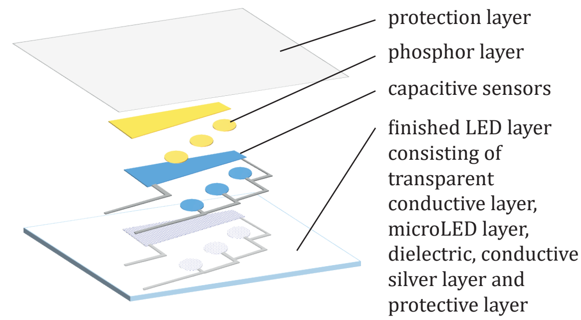

Figure 15: Adding capacitive switch and phosphor layer to the B-surface foil

3. Results

In the following the results are shown for both EL and micro-LED illumination.

3.1 Lighting with electroluminescence

3.2 Figure 18 shows the result with the EL technique. With the HPF technique from Niebling GmbH it was possible to thermoform the foil while maintaining the function.

Beyond the disadvantageous EL driving requirements (approximately 400 Hz with 100 V AC current), electroluminescence's primary limitation remains its low lumi-

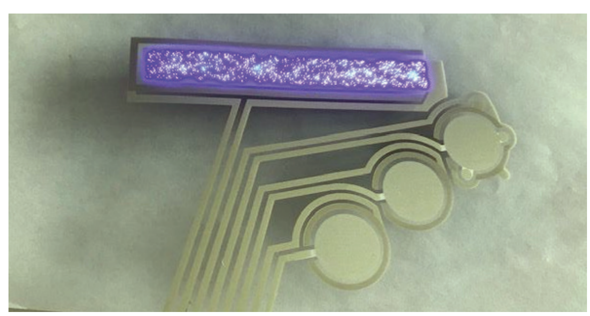

Figure 16: Background illumination of the slider area printed with micro-LEDs by NthDegree

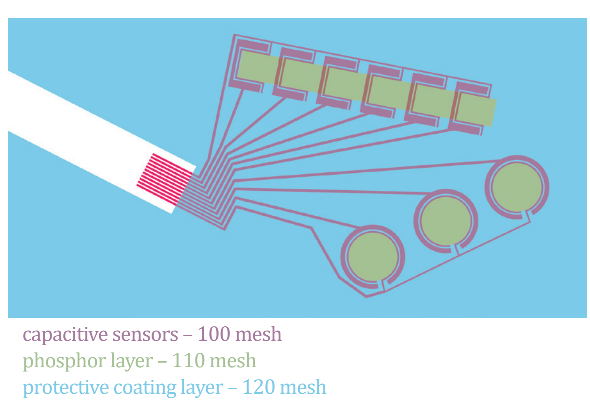

Figure 17: Printing steps to finalize the B-surface foil

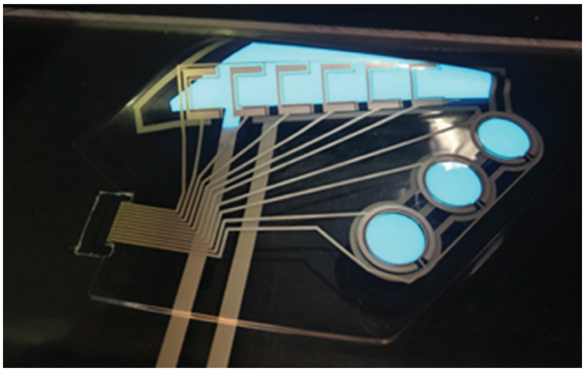

Figure 18: Fully functioning 3D-formed EL illumination and capacitive sensors (6 on slider and 3 buttons)

nous efficacy of approximately 70 cd/m^2. This inadequate brightness for automotive applications led to discontinuing EL investigation within this project, omitting overmoulding to focus on the more promising micro-LED technology. While superior EL materials may exist currently, their investigation fell outside this project's scope.

3.3 Lighting with Micro-LEDs

Figure 19 shows the result with the micro-LED technique.

Following functional testing of B-surface foil sensors and micro-LED illumination at Marquardt GmbH, the PC films (B-surface) were successfully bonded to the decorative film (A-surface) through intermediate injection moulding at Dr Schneider.

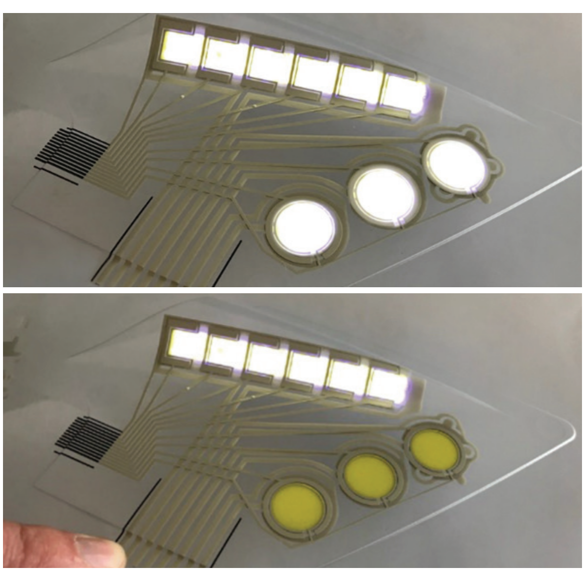

Figure 19: Fully functioning 3D-formed micro-LED illumination and capacitive sensors (six sensors on the slider and three buttons) left: all fields illuminated, right only slider illuminated. The yellow phosphor can be well observed

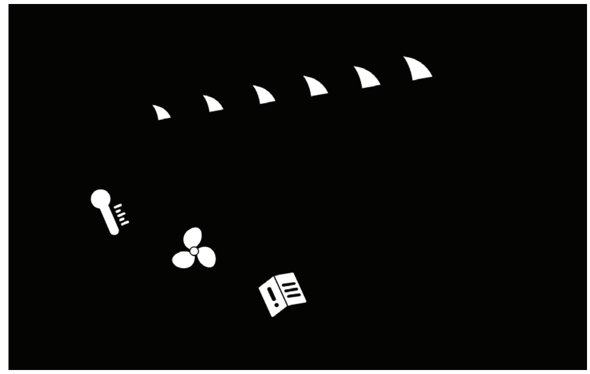

Figure 20: Decorative layout for A-surface

Figure 21: Final result of the injection moulding action

Figure 22: Final demonstrator with micro-LED illumination

The final goal of the project, however, is a demonstrator showing the fully functioning stiffened part by intermediate plastic injection and having a nice-looking surface, the A-surface. For the final demonstrator assembly, the 3D-formed, functional B-Surface has been bonded to the decorative film (A-Surface) by Dr Schneider using intermediate injection moulding. The decor features a black negative print displaying button symbols and descending-sized ‘claws’ for the slider (Figure 20).

The film joining process involves vertical insertion of both films into the injection moulding machine’s mould, followed by injection of polycarbonate melted at approximately 280°C between the films. Figure 21 shows the final injection moulding result.

For the dissemination of the results a demonstrator has been built by the industrial partners with slightly modified icons on the A-surface. The final demonstrator is shown in Figure 22.

4. Conclusions

Although the EL technique has some decisive drawbacks it could be shown that in general the technique works, and fully functional 3D formed parts can be produced. The micro-LED system can definitely be considered a success. The deformation of the micro-LED paste used had never been tested before, so subsequent functionality was not guaranteed. It is therefore even more pleasing that sensors with extremely thin-film-like backlighting are now available for the further process after the injection moulding process and connection to the A-Surface. The industrial project partners now have the opportunity and the challenge of bringing this innovative technology to the market. However, the stability and longevity of the system must now be checked in further investigations.

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