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Adopting Hybrid Integrated Flexible Electronics in Products: Case—Personal Activity Meter

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ABSTRACT In this case study, the possibilities of hybrid integration of printed and flexible electronics in combination with conventional electronic components to create new types of product concepts is demonstrated. The final result is a personal activity meter demonstrator, which is realized by utilizing various flexible electronics manufacturing and integration techniques. Roll-to-roll printing was used to print the electronic backplane as well as co-planar electrochromic (EC) display. A pick-and-place assembled microcontroller unit and accelerometer, together with passive components, provided the brains for the system. Injection molding was then utilized to create a structural electronics system including an EC display. To validate the feasibility and scalability of the processes used, 100 pieces of the personal activity meter were fabricated. Modeling with continuum computational fluid dynamics and numerical heat transfer, using the high-performance finite volume method, showed that high filling pressure and shear-stress are the key factors causing broken devices. The stability of the devices in harsh environmental conditions as well as in bending seem to be slightly improved in the over molded samples.

INDEX TERMS Electrochromic displays, injection molding, hybrid integration, printed electronics, structural electronics.

I. INTRODUCTION

In recent years, flexible and printed electronics have gained much research and industrial interest. The possibilities of printing techniques such as gravure printing, flexography, and screen-printing have been widely exploited for the fabrication of functional films. To date, the printing of simple and passive components like conductors, dielectrics, and resistors can be already considered as mature technologies. As well, developments in printed active thin film devices such as organic light emitting diodes (OLEDs) [1], transistors [2] and organic solar cells (OSCs) [3] have also been progressed. In this paper, printed and volume-scale-producible electrochromic displays (ECs) are of particular interest. For these elements both vertical and inter-digitated/co-planar device architectures have been proposed for mass manufacturing [4].

However, the performance of state-of-the-art roll-to-roll (R2R) printed active components is not yet at the same level as their traditional electronic counterparts. This is mainly due to the larger area required, efficiency and the lifetime limitations of the printed and flexible organic electronics [5]. Therefore, for applications where printed electronics are lacking in performance, the required functionality has been achieved through combining printed and flexible technologies with conventional component technologies. For example, Keränen *et al.* [6] have demonstrated a plastic LED-illumination laminate where electrical conductors and vias are produced using screen- and stencil-printing, respectively, and the LED-chips are assembled using a roll-to-roll capable pick-and-place machine. In addition, Ynvisible, together with Quad Industries, have demonstrated a device where printed EC displays are combined with chip-based near field

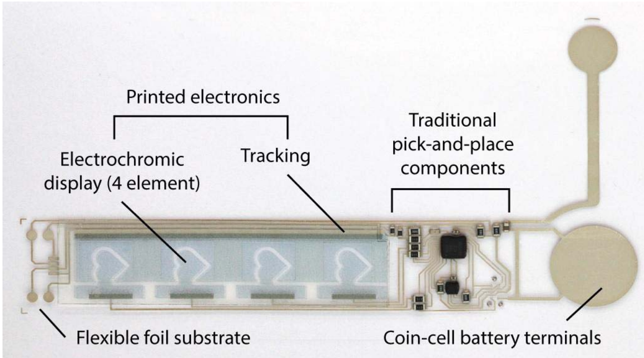

FIGURE 1. The assembled hybrid activity badge foil before the injection molding phase. Excluding the coin-cell holder assembly, the device dimensions are approximately 96 mm x 19 mm.

communication (NFC) electronics [7]. This combination of printed electronics and inorganic components is referred to as hybrid integration, the use of which can significantly enhance the functionality and performance of printed electronics products targeting consumer electronic applications [8].

As part of an end-user product, hybrid integrated electronics can be further incorporated with injection molding [9], [10]. During the injection molding process, a thermoplastic material is injected with heat and pressure into a mold cavity where it cools and solidifies to the shape of the cavity. In the over-molding of hybrid integrated electronics, the flexible foil is first inserted inside the mold cavity. The over-molding of such a structure provides an enhanced barrier against environmental stresses, as well as providing the possibility to add seamless 3D shapes and mechanical functionalities to the low-cost printed electronic devices.

In-mold electronics (IME) technologies, are gaining increasing research and commercial interest. Commercial development of IME technologies is currently ongoing in several companies, e.g., TactoTek which may be considered the market driver, having a widespread global collaboration and research network [11], as well as Flexbright [12]. Other companies active in IME technologies are, for example, Sun Chemical, Eastprint, DuraTech, AlSentis and T+ink, who have collaborated in the development of IME solutions [13], Dupont are providing specialized printed electronics inks that tolerate relatively harsh process conditions, and PolyIC and Kurtz are applying IME technologies to the automotive industry [14]. In the research field, the potential of the technology has been demonstrated by VTT in several photonic over-molded flexible foil structures as OLED sub-assemblies [15], over-molded semiconductor electronics, LED lighting [16], and over-molded optical touch panels [15]. Considering their commercialization, it is commonly foreseen that the first IME technologies based applications will be based on capacitive sensors with LED lighting and NFC communication, followed by systems combining a wider range of flexible technologies. As part of flexible printed electronics end-user products, the integration of electrochromic (EC) display technologies provides interesting opportunities, as a flexible, low-energy output mechanism that benefits from synergies in the production process.

To investigate the possibilities for wide integration of the different technologies that have been proposed, as well as to understand in more detail the full process, from initial concept to end-user product, a case study was undertaken. The aim of the study, from the technology point of view, was to build an intelligent system combining printed and flexible components, including an EC display component, together with traditional pick-and-place components. Further, this hybrid integrated foil would then be seamlessly integrated in injection molded 3D mechanics to create an end-product-like demonstrator. To our understanding, this is the first time that electrochromic displays have been shown to be applicable to an over-molding process. From the product and concept creation point of view, by demonstrating these novel possibilities, we hope to spur the interest of the creative industries, and hence the uptake of these new technologies. As a contribution, we are the first to demonstrate a prototype production run, of approximately 100 pieces, that integrates hybrid integrated printed electronics film and electrochromic display elements as part of an injection molded end-user product.

II. PERSONAL ACTIVITY METER

A. CONCEPT, SPECIFICATIONS AND DESIGN

Based on use-case concepting and technology possibilities, a personal activity meter badge was selected as a suitable example case, and further specified as follows:

1) *Outer casting:* Flexible injection-molded (using an existing wristband mold).
2) *Electronics:* Implemented on a flexible substrate, utilizing roll-to-roll printing technologies as well as hybrid integration of traditional electronics components. The device includes a CPU, accelerometer for activity sensing an LED element and 13 passive elements, such as capacitors and resistors. The integration is implemented using VTT's roll-to-roll capable pick-and-place facility.

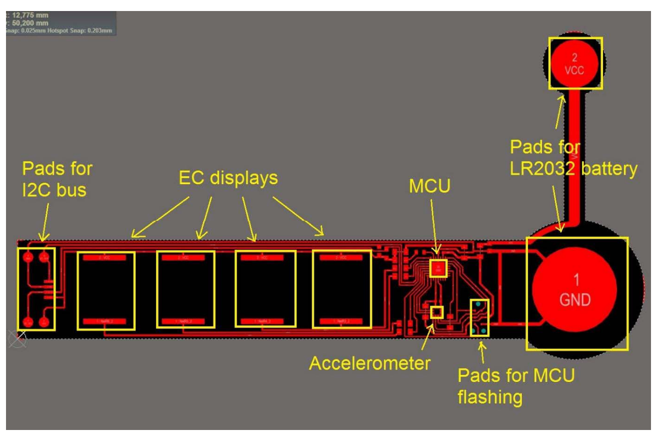

FIGURE 2. Technical layout for the demonstrator.

3) *Visual interface:* The device's visual interface is a row of four heart-shaped graphical elements, activated by the badge's movement. The interface will be realized using electrochromic display technology provided by Ynvisible [17].
4) *Power requirements:* The electronics are powered by a 3 V coin-cell battery with a targeted power consumption of less than 50 μW. The potential lifetime with a standard 210 mAh battery is up to one year.

Firstly, the demo layout and first electric schematics were created. The schematics were based on VTT's previous wristwatch prototype layout and existing injection molding tool, which created the physical boundaries for the electronics. The EC display size was optimized and the electronics were designed to enable manufacture using rotary screen printing. The layout was designed to have only a single printed silver wiring layer The technical layout and main functions are introduced in Figure 2.

Prior to proceeding to the roll-to-roll manufacturing process, the demo functionality was tested in a rigid FR4 version. Based on the tests, some minor electrical faults were corrected to obtain proper functionality. The electric schematics were updated and layouts for the printing trials were drawn.

B. PRINTING PROCESS, COMPONENT ASSEMBLY AND DISPLAY FABRICATION

VTT's ROKO pilot line was used for printing the electrical wirings and Ynvisible PEDOT:PSS electrochromic inks on a 125 μm thick PET substrate. For both functional layers a rotary-screen printing method was used. Prior to printing, the substrate was run through ovens, 4 × 1 m at 140 °C, at 5 m/min, to minimize substrate shrinkage during the printing trials. Electrical wirings were printed with Asahi LS411AW silver ink and a Rotaplate 215V screen. The printing speed was 2 m/min and the Web was run two times through the ovens, 4 × 1 m at 140 °C. The PEDOT:PSS film for the co-planar electrochromic display structure was printed using a screen-printable formulation of PEDOT:PSS supplied by Ynvisible. A Rotaplate 305V screen was used for the PEDOT:PSS printing. The printing speed was 2 m/min and the curing temperature was 130 °C, 3 × 1 m ovens.

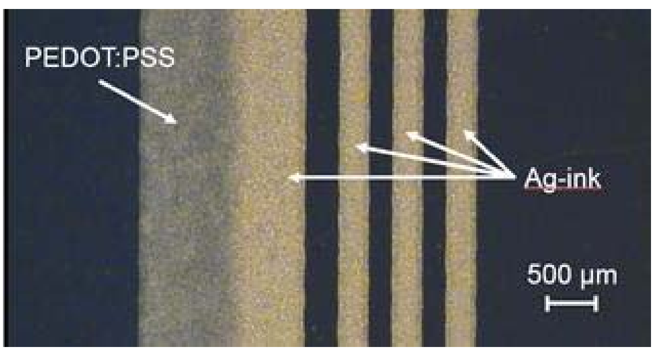

FIGURE 3. **Smartscope picture of printed electrical wirings and PEDOT:PSS on Ag-ink.**

In Figure 3, printed electrical wirings and printed PEDOT:PSS on printed Ag-ink are shown. As can be seen, good quality electrical wirings were produced. The average line width of the three narrow lines was 325 μm showing only a light spreading, from the nominal line width of 300 μm. The PEDOT:PSS also showed a good printability. However, there were some variation in the thickness of printed PEDOT:PSS being between 400 nm and 600 nm. The thickness of printed Ag-ink, on the other hand was fairly constant being around 13.6 μm.

After the printing process, discrete components were assembled. VTT's R2R-capable pick-and-place machine, EVO Datacon 2200, was used for the component assembly. However, at this point the roll was divided into sheets to ease the machine programming. Firstly, conductive adhesives were applied to the foil. Anisotropically conductive adhesive (ACA) Delomonopox AC350 was used for the accelerometer and MCU whereas for other components isotropically conductive adhesive (ICA) EPO-TEK H20E was applied. After that, the components were pick-and-placed on the foil, followed by curing the adhesive. The working order was so that first passive components were assembled with ICA followed by ACA bonded active components. To achieve the required mechanical stability of the assembled components, a support glue was dispensed and cured. UV-curable non-conductive adhesive (NCA), Dymax 9008, was used for this purpose. Altogether 13 passive discrete electronic components were assembled together with the CPU and accelerometer.

The electrochromic display stack was fabricated offline, on top of the previously printed PEDOT:PSS. First, a spacer foil of pressure sensitive adhesive (PSA), was attached on the electronics foil. Then, UV-curable electrolyte from Ynvisible was dispensed and UV-cured. In the final step a covering PET foil was assembled and the functionality of the display was tested.

C. PROGRAMMING

The embedded software was created in the C language by using the Codesvision AVR compiler. Microcontroller flash programming was done via an ISP programming interface and an AVRisp flashing device. The implemented software functionality detected activity using the 3D acceleration sensor and displayed its level on the 4-segment electrochromic display.

In the measurement loop, the acceleration sensor was configured to low-power activity detection mode where it informs the microcontroller by an IO signal when movement is detected. The acceleration sensor operated in AC filtered mode to exclude the effect of gravity and orientation. The microcontroller used a low power timer running at 1 Hz to periodically wake up from the sleep state, register movements from the sensor and calculate the corresponding activity level. For the activity level calculation, a 30 second rolling

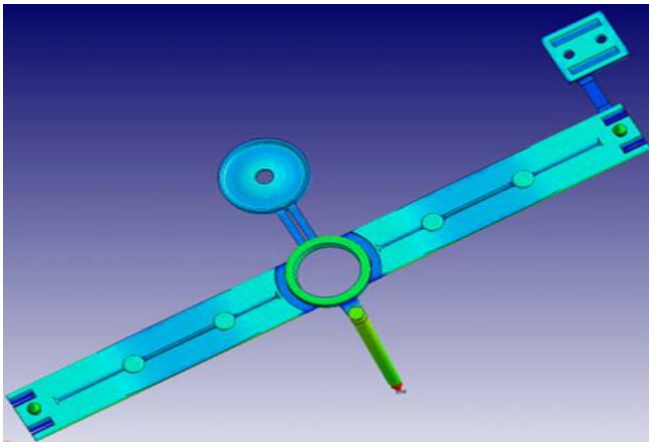

FIGURE 4. The schematic figure of the mold used for the over-molding process.

FIGURE 5. Finalized personal activity meters.

time window containing active and inactive periods of time was used. The resulting activity was based on the sum of detected movements over the time window, and thresholding them to 4 different levels.

The microcontroller's I2C bus provided an interface to collect activity related data afterwards through a specific reader device and a PC. The microcontroller is able to report power-on-time, total time when activity was detected, and the number of seconds spent at each activity level.

D. INJECTION MOULDING

Prior to injection molding, the foil inserts were cut from the sheet using a UV-laser. The mold design, including a process simulation, has been already described in detail in Ihme *et al.* [18] and is shown in Figure 4. The original application of the mold was a thin and flexible wristband. Thus, the wall thickness was not optimal for this activity badge application. From the over-molding process point of view, especially the local thinner cross-sections, required to increase flexibility, may in some extent affect the molding process and device reliability. The thinner cross sections can be seen as darker blue areas in the wristband shown in Figure 4.

The over-molding of the hybrid integrated electronic foil was realized with an Engel Victory 120 hydraulic injection molding machine. Thermoplastic urethane elastomer (TPU) was used for the over-molding. The TPU grade for the demo was Lubrizol Pearlthane D91T80. This grade, although not optimally transparent, was selected due to the requirements set by the battery cover; with the softer but clearer grade the battery cover would not remain closed reliably. The optimal molding conditions were determined experimentally by testing the devices immediately after the molding process to find the correct process parameters. Injection time, melt temperature and mold temperature were varied. To better understand the inherent parameters affecting to the device functionality, process simulation was performed. Process simulation and the obtained result are described in the following chapter.

According to the experimental results obtained, the process parameters for successful over-molding of the electronic foils were found. Once over-molded and finalized, the residual was removed and a graphic label attached to the rear of the device to finalize the demonstrator, see Figure 5.

The obtained process yield was approximately 60 %. However, from simulations (see the following chapter), it can be seen that the mold design was not optimal for the process and thus we believe that the yield can be greatly improved by a more specific and dedicated mold design as well as through optimized process parameters. For the non-functional devices, the main failure mechanism was the disruption of the electrolyte layer in the electrochromic display. This failure can be concluded to be dependent on the cavity pressure, melt temperature and shear-stress: 1) high melt temperature and 2) high shear stress, break the spacer in the electrochromic display allowing the electrolyte to be squeezed out by the cavity pressure of the TPU melt.

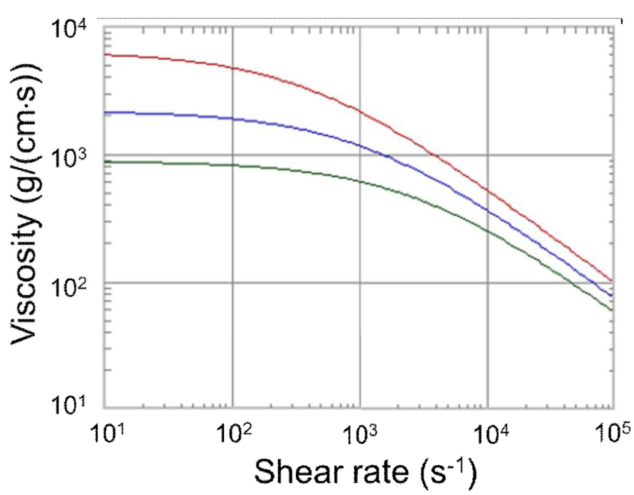

FIGURE 6. Viscosity curves of Covestro Desmopax DP 9370 as a function of shear rate in different temperatures: red 190 °C, blue 205 °C, and green 220 °C. Data is taken from the Moldex 3D database.

The electronics elements withstood the over-molding process well. This was already known from our previous studies where the process parameters and materials for the component assembly have been well exploited [18].

E. INJECTION MOLDING, PROCESS SIMULATION

To better understand the boundary conditions, critical stress factors, e.g., cavity pressure, shear rate, shear stress, and temperature, were simulated. The simulation was made with an exact 3D model of the molding part and electronics foil insert. The injection molding simulation was based on continuum computational fluid dynamics (CFD) and numerical heat transfer (NHT) using high performance finite volume method (HPFVM). The software used was Moldex3D using 3D solid solver.

Two different sets of experimented process parameters were run with the solver. The first set of parameters were from the process that functional devices with a high yield and the second set from the harsher process that resulted in broken displays. The process parameters in the first set of parameters had a longer injection time together with a higher melt and mold temperature. In the second set of process parameters a shorter injection time was used with lower temperatures. Accordingly, the injection pressure needed to be higher for the second set, as the viscosity of the thermoplastic melt increases with decreasing temperature, as shown in Figure 6.

According to the simulation results, the filling pressure and the shear stress are much higher for the process with shorter injection time and with lower temperatures. For both of these critical parameters, the maximum values are located on the thinner cross-section of the mold, as can be seen in Figure 7 and Figure 8. These parameters result in a low yield. The maximum melt temperature was slightly higher, 190 °C, for the process with better yield than for the process resulting in disruption of the electrolyte, 180 °C.

The obtained results are somehow unexpected but logical. It could be easily assumed that higher temperature would result more broken devices than lower pressure. However, this was not the case observed in our study. Instead, lower temperature resulted in higher shear-stress and filling pressure which induce high horizontal stress to the vertical layer constructed EC display device. At a critical point, the adhesion between the layers is exceeded and the shear strain from the flowing Melt causes the layers to slide, resulting in a broken device. Experiments for better understanding the limiting factors in both device as well as mold design enabling wider range of monolithically integrated structural

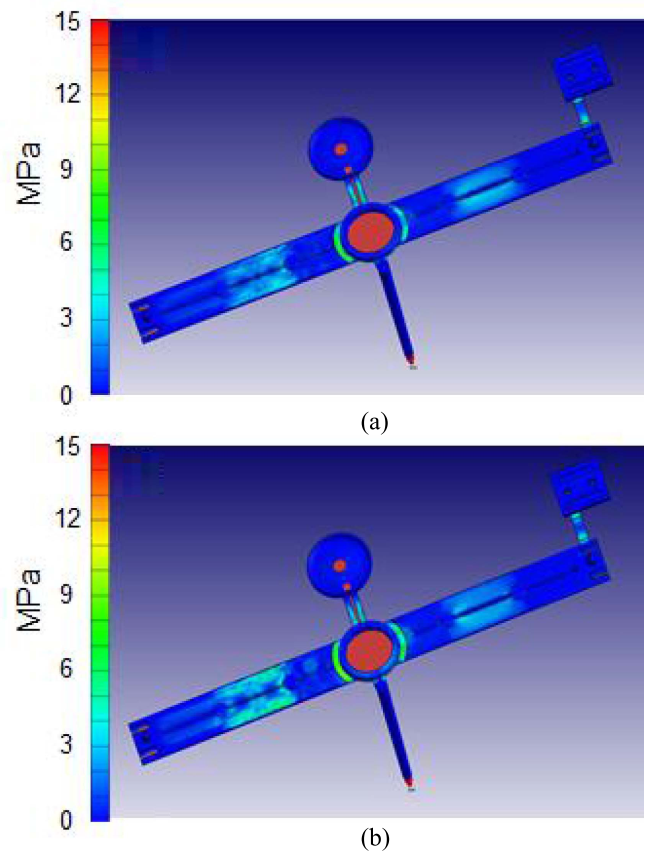

FIGURE 7. Filling pressure distribution in the injection molding process: a) higher temperature and shorter injection time process with high yield, b) process with lower yield.

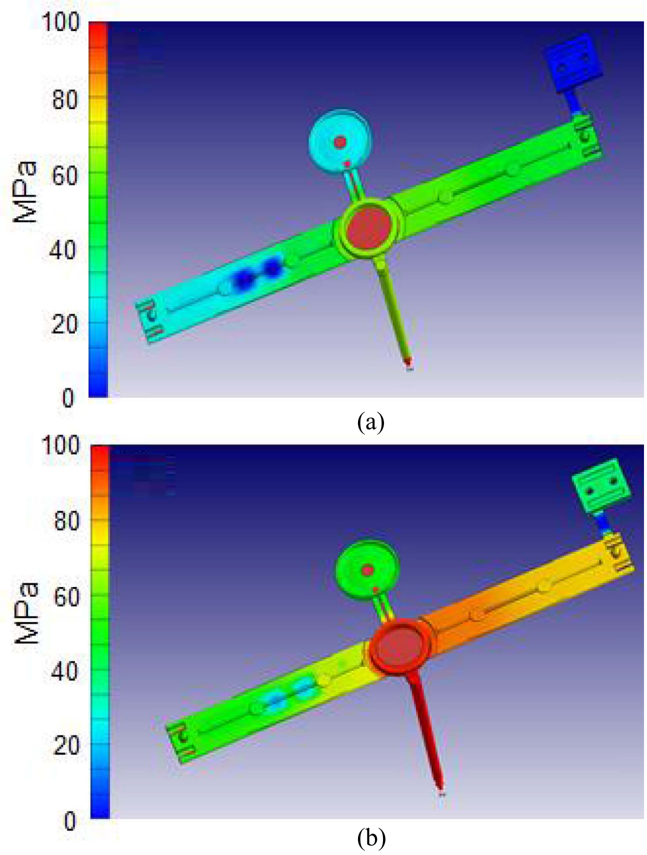

FIGURE 8. Shear-stress distribution in the injection molding process: a) higher temperature and shorter injection time process with high yield, b) process withlower yield.

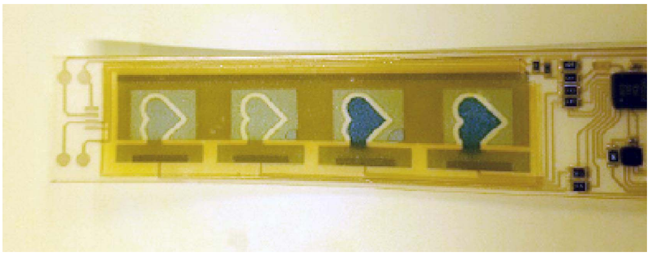

FIGURE 9. Coloring of the spacer foil during the environmental stability test.

electronics components are currently under our intensive study.

III. STABILITY STUDIES

The effect of the over-molded thermoplastic polyurethane (TPU) encapsulation on the device reliability was investigated by performing a set of reliability tests, which included thermal testing and mechanical bend testing. The performance of two types of samples were compared, bare electronics foil without over-molding and a fully over-molded device. Following the conditioning, the functionality and degradation of the electronics and the display area in both sample types was examined.

To investigate the stability of the device against environmental stresses, testing was made according to the JEDEC standard JESD-22 A101 Steady State Temperature Humidity Bias Life Test. Altogether, 6 samples, 3 foil-only and 3 with over-molding, were placed in a test chamber, which maintained a constant 85 °C temperature and 85 % relative humidity. The test duration was 14 days, during which the samples were unpowered whilst in the chamber, but were removed daily for functionality testing and visual inspection.

Following the test, all the foil-only samples showed similar degradation - the assembled LED was non-operational. Also, the active color of the electrochromic display element had become noticeably dimmer and the change between the states appeared slower. The latter, however, was not examined in detail. With the over-molded samples, it was found that one sample failed completely after 12 days exposure. Of the remaining 2 over-molded samples, one completed the test without degradation, whilst in the other sample some dimming of one electrochromic heart element was observed. Thus, we conclude that the over-molding, at least to some degree, protects the on-foil electronics. We postulate that, for the electrochromic display, the effect of moisture can be minimized by over-molding. Although this was experimentally demonstrated, more intense testing would be needed for a complete evaluation. For the assembled electronic components, the malfunction of LEDs can also be avoided by using over-molding.

The most visible degradation in all samples was to the PSA foil, which turned brown during the 85 °C temperature and 85 % relative humidity testing, see Figure 9. To understand the origin of the coloration, the behavior was also tested with the used PSA spacer alone, by placing it in the chamber with similar conditions. The spacer alone showed similar degradation. Hence, the coloring of the PSA is not due to the electrochromic display but due to the PSA characteristics.

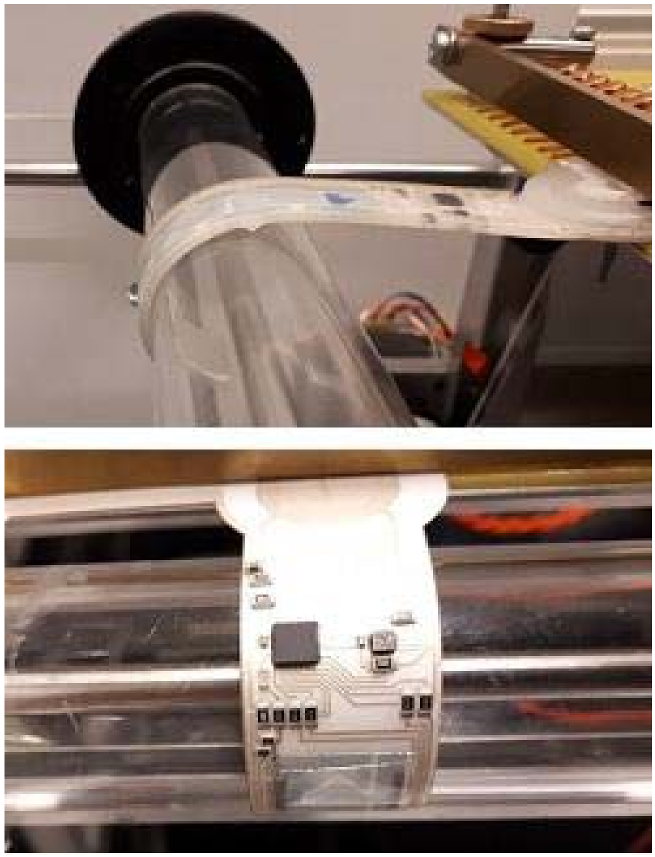

FIGURE 10. Two types of set-ups to test the functionality of the personal activity meter: upper picture, testing of the display, and below, testing of the electronics.

To test the performance of the samples under cyclic mechanical loading, three foil-only samples and three over-molded samples, were subjected to cyclic bending tests at the University of Oulu's test facilities. The custom constructed test apparatus repeatedly rolled the test samples over a cylinder with a 15 mm radius [19]. Due to the design of the personal activity meter, two different attachment positions were used, the first to focus the manipulation on the display element and the second on the electronic part, see Figure 10.

During the first 500 cycles the functionality of the samples was analyzed after every 10 cycles, and following that, after every 100 cycles. The testing ended at 1000 cycles. Following the testing, no failures in the electronics was observed in either sample type. However, when powered down, in some samples the display part of the device showed some degradation. In particular, the switching order was incorrect during the decoloring phase of the heart display element from colored to transparent form. In addition, some delamination of the top cover in the foil-only samples was observed. In the over-molded samples, some cracking/splintering of the TPU was seen. As already mentioned, one reason for the cracking and splintering arises from the usage of the harder TPU grade, required by the battery closing mechanism. With more careful mechanical design, such a compromise in material selection could be avoided and likely result in better bending stability.

As a conclusion from the stability testing, we found the display part of the personal activity meter to be more sensitive to both thermal and mechanical stress than the electronics part. The origin of these failures, however, seemed to be in the mechanical design and material interfaces rather than in the electrochromic display element itself. From the end-product usability point of view the coloration of the spacer PSA film was clearly the weak point. However, this can be remedied, for example, by masking the spacer layer with graphic printing. Whilst both foil-only and over-molded samples degraded during the environmental testing, there is evidence that the over-molding has potential to improve the devices resilience to such conditioning. To identify any differences in mechanical performance caused by the over-molding, more prolonged or rigorous testing would be required.

IV. CONCLUSION

Manufacturing of a hybrid-integrated, flexible and printable electronics based end-user product, starting from concept creation and ending with an over-molding process have been demonstrated. For the build-up of the personal activity meter demonstrator, roll-to-roll printing, discrete component assembly, laser processing and injection molding technologies were applied. Even though some process steps still required manual handwork, 100 pieces of personal activity meters were fabricated to demonstrate the feasibility and scalability of the technologies used. In our understanding, this is the first time that an electrochromic display has been integrated in an injection molded structure. Furthermore, the capability to produce such a structure would potentially enable the integration of other types of components requiring a liquid or semi-solid electrolyte, such as batteries and supercapacitors, in injection molded hybrid electronics structures.

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