R2R process for integrating LEDs on flexible substrate

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Abstract—Injection overmoulding enables cost-efficient and fully integrated manufacturing of sealed flexible electronics devices with complex optical and mechanical functionalities. Furthermore, the electrical performance of the system can be improved by adding inorganic components on printed, flexible foil before in mould integration of the structure. The development of such the manufacturing process combining hybrid integrated structures with injection overmoulding is introduced in this paper. Contrary to traditional process of overmoulding the electronics label in sheet format, the flexible foil is processed roll-to-roll throughout the full manufacturing chain providing high-efficiency manufacturing. The paper discusses the manufacturing process development and results with a manufacturing trial of demonstrator processed in roll-to-roll hybrid manufacturing with good yield.

Keywords—in mould, hybrid integration, printed electronics, injection over moulding, roll-to-roll, flexible electronics

I. INTRODUCTION

Printing refers to a reproduction process in which printing ink is applied to a substrate in a repeatable form using an image-carrying medium [1]. This technology revolutionized by the Johannes Gutenberg with his printing press in 1439 [2] is currently being transferred into the use of modern electronics industry. Printed electronics uses well known printing techniques such as rotary screen, flexography and gravure printing to create electrical circuitry on flexible, transparent foil [3]. In addition to simple passive structures like conductors, resistors and dielectrics, also active components like organic light emitting diodes (OLEDs) [4] and organic solar cells (OSCs) [5] can be realized by printing. However, attaining high-performance devices capable of operating near the performance of state-of-the-art inorganic devises is generally not feasible with current printed organic electronics, mainly due to limitations related to the efficiency and life time of the low-cost flexible organic electronics [6]. The system functionality can be further expanded by assembling inorganic components like LED chips [7] and microcontrollers on flexible foils that greatly enhances the possibilities of printed electronics to produce high-performance consumer electronic devices [8].

Combinations of printed electronics with inorganic components, referred as hybrid integrated structures, are thin, transparent elements that can be cut and bent to desired shape that is an attractive feature for wearables and lighting applications for example [9]. Flexible hybrid integrated structures are also compatible with injection overmoulding, that provides sealing and enables cost-efficient, fully integrated and automated manufacturing [10]. Injection moulding is a common manufacturing method of freeform shaped thermoplastic parts in mass production [11, 12]. The thermoplastic material is injected with heat and pressure into a mould cavity where it cools and solidifies to the shape of the cavity [13]. Overmoulding of hybrid integrated electronics is achieved by inserting the flexible foil inside the mould cavity. With the versatile 3D shape technology of injection overmoulding, there is great potential to deliver complex optical and mechanical functionalities on low cost printed electronic devices [14]. In this paper, injection overmoulded hybrid integrated manufacturing process is introduced. Commonly, the foil is inserted into the mould as a sheet. Consequently the method is sometimes referred as in-mould labelling [15]. Here, the flexible foil is in roll format through all the process steps providing high-efficiency manufacturing. The paper discusses the manufacturing process development and results with a manufacturing trial of demonstrator processed in roll-to-roll (R2R) hybrid manufacturing with good yield.

II. R2R HYBRID INTEGRATION PROCESS

A. In-Mould integration process

Injection moulding is an industrial cost-effective high mass manufacturing method in which a thermoplastic polymer is injection moulded with heat and pressure. There is a wide range of thermoplastic grades from soft thermoplastic elastomers to high stiff thermoplastic composites available commercially. In conventional in-mould process e.g. a metal part or graphics foil is inserted in the tooling and overmoulded as an integrated part. Here, a printed and hybrid integrated electronics foil is inserted in the tooling and overmoulded as a fully seamless and integrated plastics-electronics system. Combined effect of thermal shock, cavity pressure and shear stress are the critical stress factors of the overmoulding process. Chemical compatibility of the materials is essential to establish good adhesion between the foil and overmoulding material. System based in-mould concept creation process is shown in Figure 1.

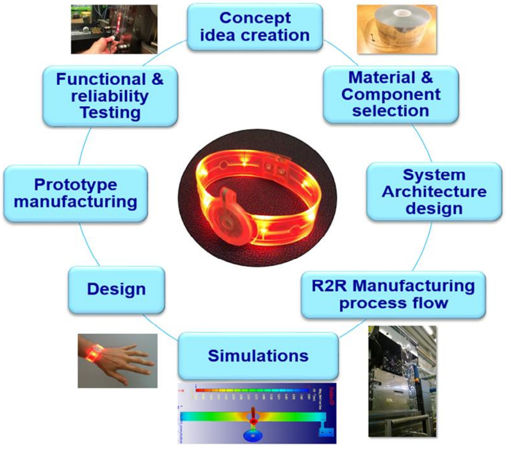

Fig. 1. System based in-mould concept creation process.

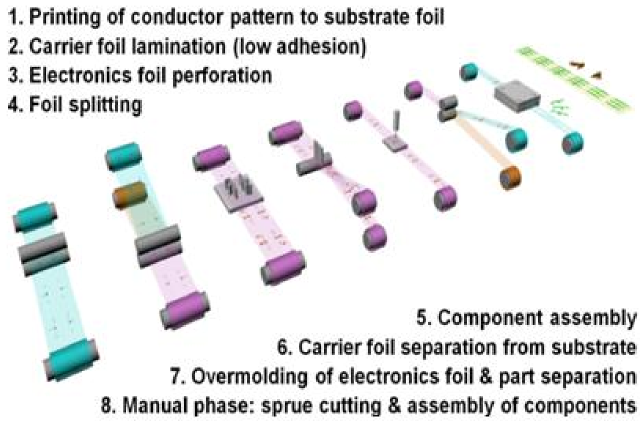

Fig. 2. R2R hybrid integration manufacturing process.

B. *Roll-to-roll hybrid integration*

The novelty of our hybrid integration manufacturing process is based on combining the technologies in a way that it allows roll-to-roll (R2R) processing through all the manufacturing steps. By using R2R processes a significant increase of the throughput and cost efficiency can be achieved compared to the standard sheet insert process because the separate sheet cutting manufacturing step is avoided. In addition, component handling is more simple with roll format, and inserting the foil in the moulding tool by a roll feeder system is less complex. This also enables better possibilities to fully automate the process. VTT's hybrid manufacturing line used in the process development and demonstrator manufacturing has commercially available manufacturing equipment that enable fast industrial implementation of manufacturing process without any need for developing totally new production machinery and process control systems.

The manufacturing process steps are shown in Figure 2. First the foil is patterned by printing. Then, a low adhesion carrier foil is laminated to support the substrate, and the foil is perforated and split if needed. Next, components are bonded to the foil with a conductive adhesive, after which the carrier foil can be delaminated . The flexible electronics foil is now in roll format ready to be overmoulded. Typically, in this phase the foil is cut into sheets for the sheet-insert injection overmoulding. However, here the final cut-out of the hybrid electronics foil is done simultaneously with the injection moulding by the moulding tool when the mould closes and electronics is overmoulded with the thermoplastics. The final assembly of discrete components (e.g. batteries) to the moulded part is the first phase where devices are not in roll format anymore. It has become clear during the process development, that it is extremely important to consider all the boundary conditions of processes at the product design phase in order to achieve true design for manufacturing (DFM).

III. Process Demonstrator

A. *Demonstrator concept*

A simple LED bracelet, called the WrapLight, was designed to demonstrate the injection overmoulded R2R hybrid integration process. Figure 3 shows the general bracelet concept. The demonstrator is used to prove the feasibility of the full production chain. The WrapLight demonstrator is a simple band that wraps around the wrist and illuminates it with a row of LEDs. LEDs are turned on when the magnetic connector is locked as the loop is closed. The band material (TPU) is flexible and transparent to the light. A V-groove feature of the light guide couples the light emitted by the LEDs into the wristband spreading it to a wider illumination area. The main features demonstrated with the WrapLight demonstrator are a) R2R overmould tooling and processing of flexible electronics, b) integration of bare LED chips into a thin light guide structure and, c) moulding of mechanical features that are a simple connector and battery holder in this case. Battery holder demonstrates the "origami electronics" idea. In the mechanics 3D design, the battery holder with a uniform cavity and lid is modelled as a planar and open projected that enables a simple and low cost tooling structure (Figure 4). In the final assembly, the lid of the holder is folded on top of the holder cavity making 2-side battery contacts and the holder lid at the same time. This approach enables also 1-side foil printing.

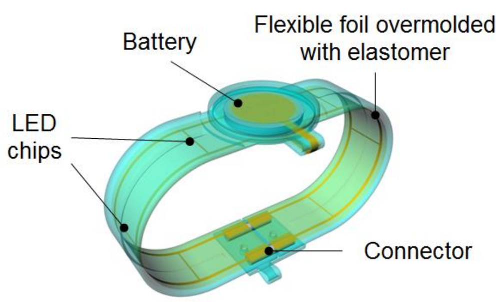

Fig. 3. WrapLight technology demonstrator concept.

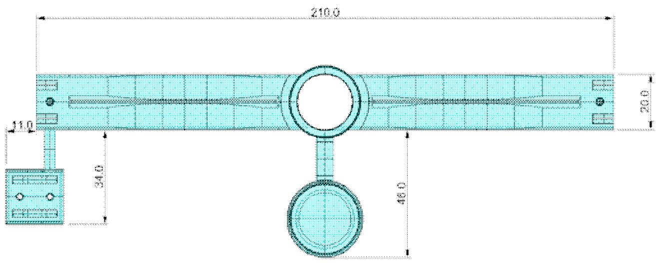

Fig. 4. "Origami"mechanics design enables 3D devices with low cost planar tooling and 1-layer printing.

B. In-Mould Process development

The demonstrator concept was first tested with vacuum casted prototypes and with two band materials that had different optical properties (white and transparent) and different hardness values (Shore A70 and A80) respectively. The injection moulding process was simulated with computational fluid dynamics by using Moldex3D software (**Error! Reference source not found.**5) in order to verify R2R moulding part geometry, runner and gate systems, and cooling channels of the tooling. In addition, critical stress factors of the inserted electronics foil, such as temperature, cavity pressure and shear stress, were estimated. The first moulding trials were made with foils without LEDs in order to test the functioning of the mould and the foil feeder system integrated to the injection moulding machine. The foil feeder setup in the injection moulding machine is shown in Figure 6. Several details of the design were modified based on these tests and simulations. For example, length of the wristband was set to 21cm in order to accommodate thicker wrists. In addition, it was found that the electronics substrates made of PET foils made the band much more rigid than what was estimated. This resulted to the lower hardness value (ShA 70) being used in the final over-moulding material.

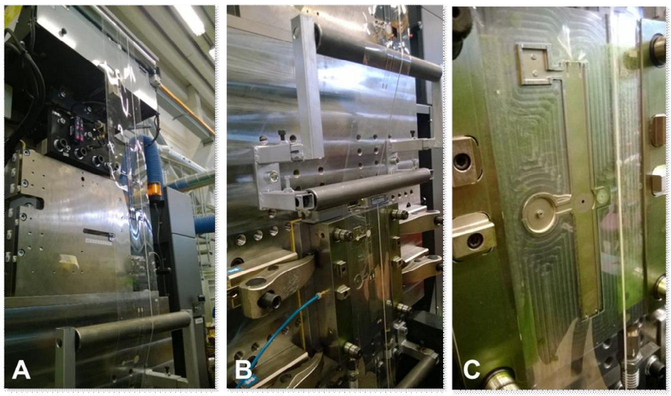

Fig. 6. Picture of the a) R2R foil feeder, b) foil moving to right position and c) fixed cavity side after ejection.

Different moulding process parameters were experimented in order to find a good setup. The target was to ensure adequate mould filling without flash and any failure of the electronic conductors. Temperature of the melt was at 215 °C, but the mould temperature was varied between 20 - 50 °C. Injection rate was varied between 1.4 – 15 mm/s (∅40mm screw) with a flat profile resulting to the hydraulic pressure of 55 – 178 bar. It was found that with higher injection rate the conductors near the injection gate could easily break due to the high shear stress. Some flash also appeared in the parting line. With lower injection rate the cavity was not completely filled. Based on these experiments, the optimum process parameters could be determined although setting the parameters between the shots required relatively long time. That caused long residence time of the melt in a barrel resulting to inconsistent melt viscosity.

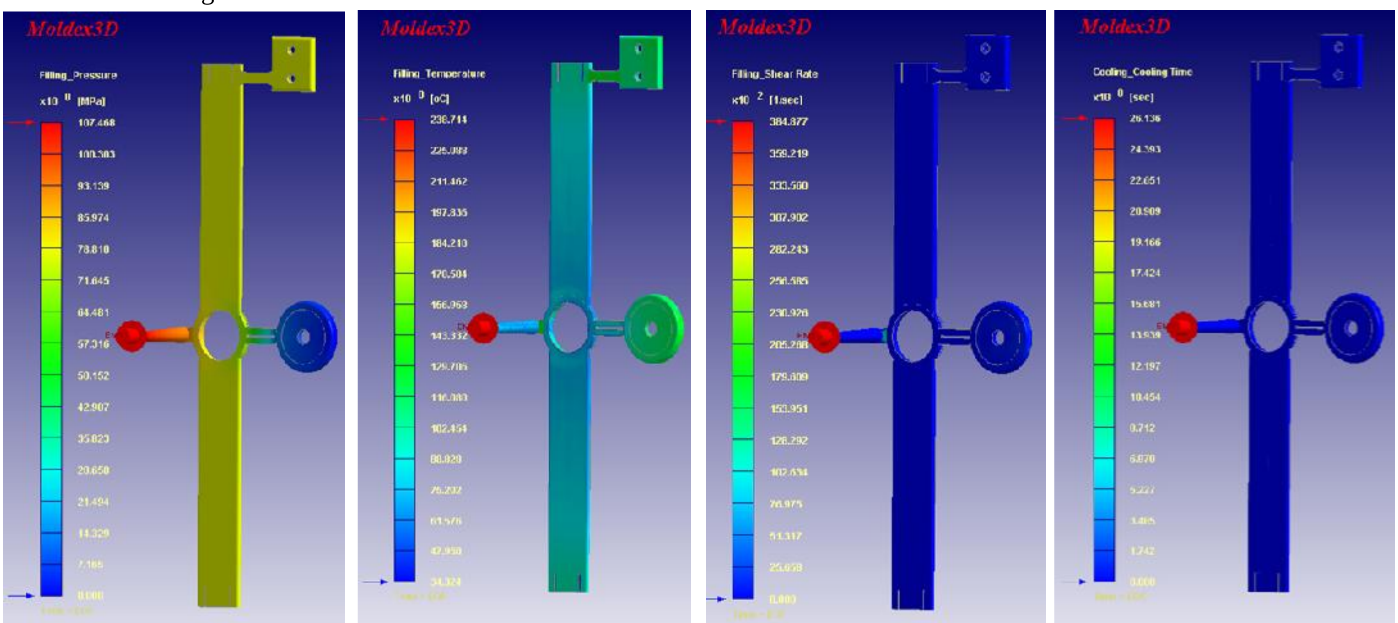

Fig. 5 Results of the mould cavity Moldex3D simulations.

C. *Demonstrator manufacturing*

A set of WrapLight demonstrators was manufactured to test the developed roll-to-roll hybrid manufacturing process. Flexible plastic foil (PET 125µm) was printed with silver ink. Total length of the foil was 1190m with ~2900 bracelet layout patterns (Figure 7a). Red bare die LEDs (Epistar ES-AEHRAX12) were bonded on the foil using the automated bonding machine Datacon 2200 Evo with anisotropic conductive adhesive (Delo Delomonopox AC365). A bonded LED is shown in Figure 7b. The bonding process was operated roll-to-roll in a stop-and-go fashion. Feeders were used to move the foil to the work area with vacuum holder. The pressure dispenser in a gantry dispensed the conductive adhesive on the contact areas and the LEDs were picked and flipped upside down in the following pick and place process step. A thermode tool was used to apply pressure and heat on the chip curing the adhesive below. Force applied was 140 g for 20 seconds and temperatures of the substrate holder and thermode tool were 65 °C and 240 °C respectively. The process has been studied previously in [16]. Generally, the bonding process is comparable to RFID manufacturing.

Engel Victory 120 injection moulding machine was used for the overmoulding with thermoplastic urethane elastomer (TPU, ShA 70). Altogether 34 demonstrators were realized and tested before and after the moulding (Figure 7c). The testing was done by switching on the LEDs with correct drive current and voltage. The sample was considered functional if all the LEDs could be lighted. A total number of 184 LEDs were embedded into the plastic and 100% of these survived the over moulding process. In addition, two non-functional LEDs became operational after over moulding. The applied heat and pressure of the TPU in filling phase most likely improved the contact between the chip and conductors allowing current to pass through the component.

IV. CONCLUSIONS

Hybrid integration manufacturing process combining printed electronics with organic components and injection overmoulding was introduced in this paper. Contrary to traditional process of overmoulding the electronics label in sheet format, the flexible foil is processed roll-to-roll throughout the full manufacturing chain. By using R2R processes a significant increase of the throughput and cost efficiency can be achieved compared to the standard sheet insert process, as the separate sheet cutting manufacturing step is avoided. In addition, component handling is simpler in roll format and inserting the foil in the moulding tool by a foil feeder is less complex providing better possibilities to fully automate the process. A LED bracelet was manufactured to demonstrate the developed manufacturing process. Totally 34 demonstrators with 184 LEDs were realized and tested before and after the processing resulting 100% yield in overmoulding. Consequently, the work described in this paper indicates good possibility to produce high-performance, innovative consumer electronic devices with low cost printable electronics. In future, more work is still needed to optimize the moulding process further such as to shorten cycle time and verify the positioning accuracy.

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The work was carried out in Horizon2020 funded Optintegral project that develops in-mould hybrid integration process for advanced TOLAE LED displays. The OptIntegral approach is to combine printed, flexible electronics substrates with inorganic LEDs and injection overmoulded optics to realize innovative, energy efficient, and high performance LED displays.

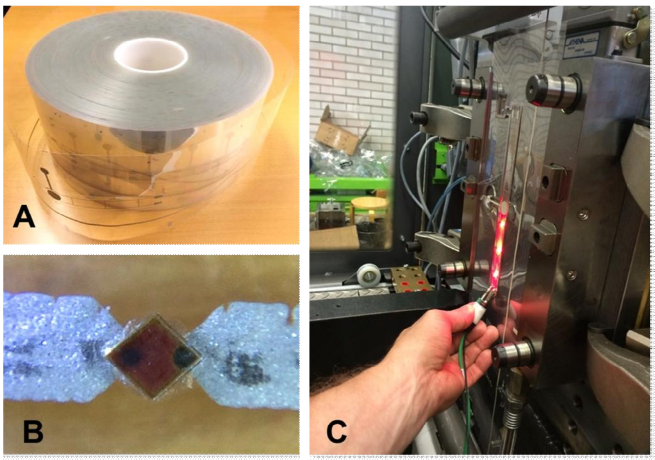

Fig. 7. a) Printed electronics foil b) a microscope image of a LED bonded to the conductor on a foil, and c) testing assembled electronics before overmoulding.

Fig. 8. the WrapLight demonstrator manufactured by R2R hydrid in mould integration.

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