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Flexible Microsystems Using Over-molding Technology

Mona Bakr [a]*, Frederick Bossuyt [a], Jan Vanfleteren [a], Yibo Su [b]

[a] *Center for Microsystems Technology, IMEC and Ghent University, 9052 Zwijnaarde-Gent, Belgium*
[b] *Brightlands Materials Center, 6167 RD Geleen, The Netherlands*

* Corresponding author. Tel.: +32-9-2646606; fax: +32-9-2645374. *E-mail address:* mona.bakr@ugent.be

Abstract

Today's world is full of intelligent electronics and with the development of flexible printed electronics technologies, different integration approaches are of high demand. The combination of electronics with polymer is a new technology platform as it integrates multiple functionalities into plastic products. This work shows preliminary results in the integration of electronic components (e.g. NFC chips and LEDs) using over-molding technology. A significant degree of freedom in product design is obtained resulting in a low-cost fabrication of flexible smart objects. The integration is achieved by using adhesion between flexible circuits and injection molded plastics. In order to check the adhesion performance between the flexible circuit and polymer injected, the polyimide foils with patterned copper cladding were over-molded with different engineering plastics into the form of peel test specimens. The technology was shown by the realization of a demonstrator, in which LEDs are wirelessly powered using an NFC antenna and a chip. The NFC antenna is executed in the copper layer and the LEDs and NFC chip are soldered on the foil. The antenna and NFC chip can harvest the energy from (e.g. a smartphone) in order to power the LEDs. This is a simple example of wireless energy transfer that could be used to power circuits and readout sensor values using NFC without the need of having an integrated battery.

Keywords: Flexible electronic circuits; Printed electronics; Injection over-molding process; Smart objects

1. Introduction

Flexible printed microsystems are emerging and achieving a great variety of applications [1]. The primary advantage of this technology is to reduce electronic device complexity with more design freedom. Moreover, flexible printed systems have high dimensional stability that makes them attractive to various aspects of daily life, leading to the rapid development of their integration approaches and related manufacturing technologies [2]. Such interest in flexible electronics has been driven by the huge demand for wearable, intelligent, and integrated electronics systems during the past decade.

Therefore, intensive efforts have been made to realize the integration methods of printed flexible microsystems and reduce the total fabrication cost. These efforts were mainly focused on polycarbonate (PC) foils with silver (Ag) metallic printed structures using in-mould structural integration where the PC/Ag foil is inserted in the mold, formed and then injection is applied [3]. In this paper, one process technique will be applied using different material combination of printed foils where they are embedded in a plastic material entitled "over-molding".

Over-molding (OVM) is a process of adding a layer of material

over an already existing object. The most important benefit of using over-molding technology is its low-cost, fast production, good dimensional control and good product consistency. This technology adapts conventional techniques of injection molding and printed electronics to achieve economic efficiency and manufacturing viability. Over-molded flexible printed electronics are receiving widespread attention as a type of innovative technology that will drastically change our daily lives. This technique was developed to bring advantages to different manufacturing sectors such as automotive, telecommunication, health care, and energy applications [4].
This paper highlights the findings derived from experiments undertaken to explore the factors in such technology including different variables as electronics interconnections, material selection, adhesion and molding process parameters. Furthermore, over-molding a flexible smart microsystem is presented.

2. Materials Selection

The fabrication of over-molded flexible microsystems usually involves many different materials and substrates. In this section, material screening is done and all polyimide (PI) copper (Cu) cladding foils are over-molded by commercially available thermoplastic materials. Thermoplastic injection molding compounds are also commercial products with a wide interest in various application fields such as automotive and consumer electronics. These thermoplastic injection molding compounds are:

a) Polypropylene (PP)
b) Polypropylene with 30% weight percentage of glass filling (30%GF-PP)
c) Polyamide-6 (PA6)
d) Polyamide-6 with 30% weight percentage of glass filling (30%GF-PA6)
e) Polyamide-6 with 50% weight percentage of glass filling (50%GF-PA6)
f) Polycarbonate (PC)
g) Polycarbonate with 10% weight percentage of glass filling (10%GF-PC)

In this research, utilizing adhesion to integrate flexible microsystems with thermoplastic parts is more of an interest due to the requirement of maintaining structural integrity in long-term applications. If the adhesion between the flexible microsystem and thermoplastic is not optimized, crack propagation can be facilitated through the interface between flexible printed foils and thermoplastics resulting in loss of functionality of the microsystems. Therefore, the adhesion performance between electronic foils and thermoplastics should be evaluated to seek for a suitable material combination for the OVM process. In this paper, fracture energy based peeling test methods [5, 6], characterizing the interfacial fracture energy as the energy required for crack propagation between foils and thermoplastics, are employed to evaluate the adhesion between dissimilar materials which is affected by different fundamental adhesion mechanisms such as physical attraction, chemical bonding and mechanical interlocking [7]. In this method, ISO 8510 standard 90° peeling test is initially performed to measure the peel force, afterwards, the interfacial fracture energy can be calculated based on the following parameters:

- External work G, obtained by measured peel force divided by bond width.
- Plastic deformation energy during peeling test G_P, obtained by ISO 527 tensile test on a flexible microsystem.
- Interfacial thermal residual strain energy G_{RS}, calculated based on the methodology presented in ref [6] by considering the over-molded flexible electronics as a hybrid bi-material system comprising a polyimide copper cladding foil and a thermoplastic part. The thermal residual stresses in the foil and the thermoplastic could be solved by using a strain compatibility equation which includes the free contraction of the materials and the mechanical component necessary to compensate for the free contraction. The approach of this method is shown in the following equations:

$$\alpha_f \Delta T_f + \frac{\sigma_f}{E_f} = \alpha_t \Delta T_t + \frac{\sigma_t}{E_t} \qquad \text{(Eq.1)}$$

$$\alpha_f t_f + \alpha_t t_t = 0 \qquad \text{(Eq.2)}$$

Where α is the thermal expansion coefficient (CTE), subscript f and t refers to foil and thermoplastic. ΔT is the temperature difference between room temperature and material processing temperature. The processing temperature of foil is considered as the temperature of the mold and the processing temperature of thermoplastic is considered as the temperature of the thermoplastic melt. σ, E and t refer to thermal residual stress, elastic modulus, and thickness of foil and thermoplastic. Thermal residual stresses can be calculated by solving Eq. 1 and Eq.2, which are used to further calculate the value of G_{RS}. Therefore, the interfacial fracture energy is calculated as:

$$G_i = G - G_P + G_{RS} \qquad \text{(Eq.3)}$$

The test sample is fabricated through a typical injection molding process. The product of injection molding is trimmed into the shape of the peeling test sample as shown in Fig. 1 with a 10 mm bonded width. The thermoplastic melt temperature and the mold temperature used in sample fabrication are:

- PP and 30% GF-PP:
  - Melt temperature 240 °C, mold temperature 50 °C.
- PA6, 30% GF-PA6 and 50% GF-PA6:
  - Melt temperature 270 °C, mold temperature 80 °C.
- PC and 10% GF-PC:
  - Melt temperature 300 °C, mold temperature 90 °C.

Figure 1: Over-molded sample (top), Trimmed peeling test sample (bottom)

After testing five specimens of each combination, the average peel force and average interfacial fracture energy are shown in table 1:

Table 1: Measured peel force and calculated interfacial fracture energy.

Microsystem	**Commercial polyimide flexible foil with copper cladding (CTE = 18 $\cdot 10^{-6}$/K)**						
Thermoplastics	**a**	**b**	**c**	**d**	**e**	**f**	**g**
CTE of thermoplastics (10^{-6}/K)	90	5	100	20	10	70	40
Measured peel force (N)	0	0	1.34	0.19	0.29	0	0
Plastic deformation energy G_P (J/M^2)	0	0	49	0	0	0	0
Thermal residual strain energy G_{RS} (J/M^2)	86	0	149	0	1	75	14
Interfacial fracture energy G_I (J/M^2)	<86	0	234	19	29	<75	<14

In table 1, a zero peel force represents an immediate failure of the over-molded product taken out of the mold without the subjection of any external force. Therefore, the interfacial fracture energy of those combinations is considered to be lower than the interfacial thermal residual strain energy. It can be observed from table 1 that PI film only naturally bonds with PA6 thermoplastic. Besides, the adhesion between PA6 and PI significantly outperforms the adhesion between GF-PA6 and PI, a much higher peel force is shown in PA6-PI sample with the presence of a much larger interfacial thermal residual strain energy.

After screening tests, it can be seen that PA6 thermoplastic is the most suitable material for over-molding with a PI-based microsystem. However, it should be noted that although interfacial fracture energy of 234 J/m^2 is capable to maintain the structural integrity of the over-molded microsystem, it is always noteworthy to attempt an optimized adhesion performance between PA6 and PI printed flexible microsystem. In the following chapter, some efforts regarding adhesion optimization are introduced.

3. Adhesion optimization

Various techniques have been used to and optimize adhesion and this variety is highlighted by the fact that many theoretical mechanisms of adhesion have been proposed. It is reported in previous studies that the adhesion mechanisms between dissimilar materials are mechanical interlocking, physical and chemical bonding [7]. Therefore, the following approaches are employed in this research to attempt promoting adhesion mechanisms between PI and PA6:

- PI foil without Cu cladding as a reference sample.
- Cu cladding perpendicular to peeling direction as shown in figure 2a to evaluate mechanical interlocking mechanism. The location of the over-molded part is schematically shown in figure 2a, which is corresponded with figure 1.
- Effect of Cu cladding diagonal to peeling direction as shown in figure 2b to evaluate mechanical interlocking.
- Applying polyurethane (PU) coating on PI film to promote secondary chemical bonding provided by PU coating, since polyurethanes are widely applied in bonding with PA6.

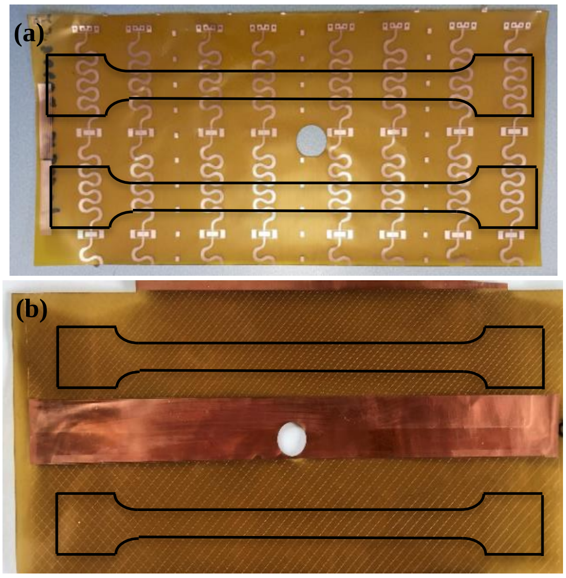

Figure 2: Mechanical interlock effect for perpendicular Cu lines (a) and diagonal Cu lines (b)

Regarding the copper cladding structure, it is observed that the layer thickness of both perpendicular direction and diagonal direction are identical, and the overall area of copper cladding layers of both textures are similar. Indeed, by comparing the adhesion performance between two textures, the mechanical interlocking effect between large texture size with loose texture distribution (perpendicular) and small texture size with dense texture distribution (diagonal) are studied. Figure 3 schematically shows a cross-section view of the peel specimen to indicate the difference between the two textures.

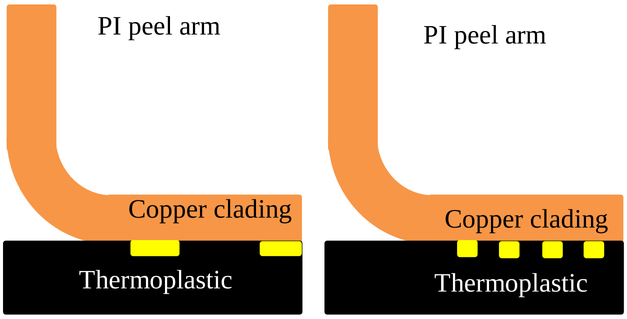

Figure 3: Schematically view of the difference between perpendicular Cu lines (left: large texture size with loose texture distribution) and diagonal Cu lines (right: small texture size with dense texture distribution).

The measured peel force and calculated interfacial fracture energy of over-molded PA6-PI microsystems with different mechanisms are shown in table 2:

Table 2: Measured peel force and interfacial fracture energy of over-molded microsystems with different approaches promoting adhesion.

Foil type	PI without copper	PI/Cu perpendicular	Pi/Cu diagonal	PI + PU
Measured peel force (N)	0.26 ± 0.10	1.34 ± 0.21	0.08 ± 0.04	0.63 ± 0.05
Plastic deformation energy G_P (j/m^2)	0	49	0	7.3
Thermal residual strain energy G_{RS} (j/m^2)	149	149	149	149
Interfacial fracture energy G_I (j/m^2)	175 ± 10	234 ± 21	157 ± 4	205 ± 5

It can be observed from table 2 that all of the approaches are capable of promoting adhesion between PI foil and PA6 apart from the diagonal copper cladding. The latter deteriorates the adhesion since the dense texture creates a significant number of localized stress concentrations which may cause a readily crack propagation. Moreover, the mechanical interlocking mechanism was successful with perpendicular copper cladding due to the larger volume of PA6 penetrated the larger gaps between copper cladding texture, those PA6 will cause extra deformation energy during peeling, thus higher interfacial fracture energy is obtained. In addition, the stress concentration in perpendicular texture is relatively milder due to a relatively smoother geometrical transition in comparison with diagonal texture (Figure 2c). The PU coating does not dramatically improve the adhesion, since the PU adhesive may decompose in course of the injection molding process as the thermoplastic melt temperature is 270 °C, while the decomposition temperature of PU is around 150 °C. Based on the aforementioned knowledge, the over-molded flexible printed microsystems are fabricated by using polyimide flexible foil with a patterned copper cladding that is perpendicular to peeling direction, with a surface cleaning by isopropyl alcohol (IPA) done before the injection molding process.

4. Manufacturing methods for over-molded flexible printed foils

The concept of over-molding integration is based on the combination of flexible printed electronic foils, electronic components assembly, and injection molding manufacturing process. The idea is to assemble components on flexible substrates or circuit boards, and use the former as an insert in a conventional injection molding machine.

4.1 Foil fabrication

To fabricate the foil, a commercially available polyimide flexible foil with patterned copper cladding is used. The process flow for flexible printed electronic includes patterning the copper structure on a flexible polyimide (PI) substrate via lithography and wet etching. PI is ideal as carrier material because of its high thermal resistance, excellent mechanical properties, and stable dielectric properties over the temperature and frequency ranges. An organic solderability preservative (OSP) treatment is applied to protect the patterned copper from oxidation and laser ablation is used to cut the foil into two parts as well as cut an opening to act as a gate for the polymer to flow during the over-molding process. Finally, to assemble the components, conventional lead-free solder paste is applied onto the pads of the copper traces, the components are placed on these solder pads and then heated in a reflow oven until the solder particles solidify [8] as shown in fig.4.

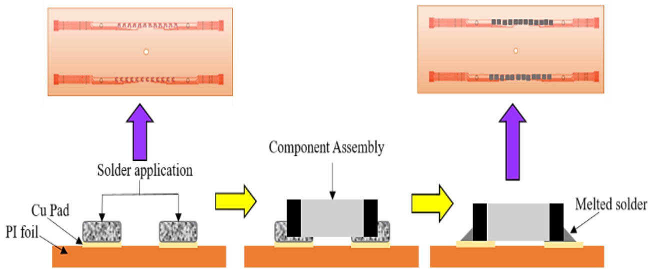

Figure 4: Flexible printed foils assembly process

4.2 Over-molding process

Polyamide(PA6) as the over-molding plastic is considered to be a hygroscopic polymer which is affected by moisture content in the air, so it is advisable to dry it in a convection oven before using to eliminate the occurrence of air bubbles that may affect the adhesion [9]. Before starting injection molding, all of the PI foils are cleaned with IPA. During over-molding as schematically presented in fig.5. The integrated foil is clamped in the mold cavity. The over-molding polymer is heated beyond its melting temperature. After the desired temperature is achieved, the mold is closed on the foil. Once the polymer is melted the pressure moves the injection screw to push the thermoplastic material towards the mold. The polymer starts to flow into the cavity, thus flowing on the foil and achieving the desired product shape. Cooling down happens and the shape solidifies quickly, the mold opens again and ejects the foil out from the machine. The result is a dogbone shaped plastic with integrated components as shown in fig.6 in a very short injection time.

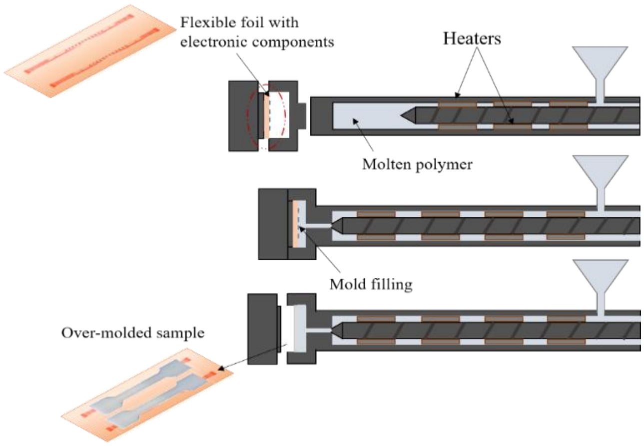

Figure 5: Schematic for over-molding process

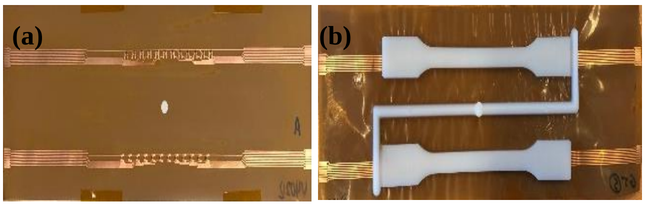

Figure 6: Real-life samples before (a) and after OVM (b)

5. Technology check

A preliminary test circuit was designed to check the whole mechanism. The circuit was produced using a 247 by 96 mm foil of UBE Upisel-N SR-1220 (UBEEXSYMO Co., Ltd., Tokyo, Japan) with Cu tracks thickness of 18µm on 50µm of polyimide, followed by the assembly of SMD passive components (zero-ohm resistors in 0402 package). After the circuit fabrication and component assembly, the circuit was over-molded. The results' analysis of this experiment was addressed in an earlier study [9], where different test conditions were discussed including the process temperature, foil type; with adhesive or without adhesive layer and different build-ups like the influence of underfill and glob-top materials. The presence of underfill material (Namics X58455-48) with curing at 120°C for 10 minutes showed better results in resistance values and no clear influence for glob-top material (EPO-TEK®) was noticed according to our design. Generally, these tests showed that over-molding a PI/Cu circuit with assembled components is a feasible technology to integrate electrical functionality inside a thermoplastic polymer. It also showed that the number of embedded SMD components can be relatively high and still functional during the over-molding process without the risk to be unsoldered. It also proved that Cu metallic structures were not damaged when exposed to the high temperatures of the over-molding process as Cu is capable of withstanding temperatures of 1000°C. All of these prior experiments could be a motivation to test more electronic packages such as capacitive touch, sensors, microcontrollers, and LEDs.

5.1 Over-molded smart system

A demonstrator was designed to power circuits and readout sensor values using NFC, without the need of having an integrated battery. The components include a thin FR4 board of 0.2 mm thickness having an NFC chip package with dimensions of 18.75 by 4 mm, mounted on PI/Cu foil, in addition to 5 LEDs of 0402 format which are directly assembled on the foil using conventional lead-free solder paste. The NFC antenna coil is composed of 15 lines with a line spacing of 0.2 mm and is directly realized in the copper as shown in fig.7

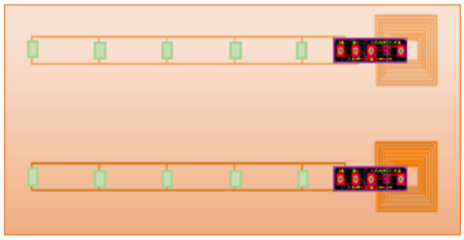

Figure 7: Schematic of NFC antenna design

Furthermore, assembled foils are over-molded and with applying the same process conditions used in the previous study [8], components are successfully embedded into PA6 thermoplastic material as shown in fig.8, with one sample as transparent just for more clarification on where it is located after over-molding.

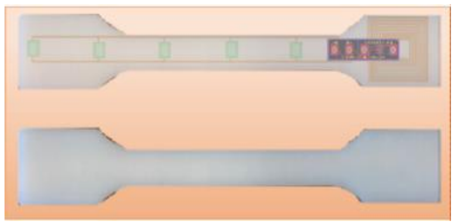

Figure 8: Schematic over-molded smart system

This attempt showed a successful simple example of wireless energy transfer in which the flexible printed microsystem could harvest the energy from e.g. a smartphone to drive the LEDs as depicted in fig.9

Figure 9: Real-life demonstration

6. Conclusions and outlook

In this paper, preliminary work has been made to report the possibility of using the over-molding technique as a manufacturing process for integration of electronics in plastic-based products. The process used facilitates the development and the realization with low fabrication cost. Adhesion between the electronic foil and the injected polymer is a very important parameter in our work. Therefore, considerable work has been done to improve the adhesion between these different materials.

Functional test circuits including components such as resistors, LEDs and NFC chips proved that their electronic interconnections can withstand both thermal and mechanical stresses provided from the injection-molding process. Accordingly, our experiments clearly showed the feasibility of the over-molding technique. However, some extra work is still needed to finalize the technology before introducing it to various industries and be used in different applications. We will work on having the optimized values for adhesion that ensure stability over time as well as achieving sufficient reliability of these test structures. Moreover, an important challenge is also to over-mold circuit designs with more complex shapes and be able to use different electronic packages.

Acknowledgments

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