Over-molding of two-dimensional curved shape using polyimide copper cladding foil

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Abstract— In many applications, including automotive, wearables, and health sectors, the over-molding of flexible electronics structures into plastics has been commonly used. A polyimide-copper (PI/Cu) electronic circuit embedded in a thermoplastic material using an injection molding process is the basis of this work. The electronic circuit is a PI substrate consisting of copper interconnections where lead-free solder and under-fill material are used to assemble the electronic components. In previous work, the integration of electronics using a mold with a two-dimensional (2D) flat shape and the optimization of materials, including the over-molding material and the type of PI/Cu foil used, were studied. In this study, a 2D curved mold with an arc length curvature of 205 mm is used to investigate its effect on the resistance of 0-ohm resistors. The circuit design and the component mounting place are considered to be the parameters in this study. Moreover, the data obtained before and after over-molding from the measurements of the assembled resistors showed the effect of the over-molding on the electronics in the curved mold.

Keywords: flexible electronics, over-molding, in-mold electronics

I. INTRODUCTION

Over the last 10 years, the interest in the integration of electronic circuits into plastics has been growing permanently and stimulated quite some research and development efforts, especially for the automotive industry[1]. The fundamental concept of producing plastic parts using injection molding made it a very good candidate for the development of such technology. With the growing demand for new inventive products, the continuous expansion of special injection molding techniques has become more critical. These techniques include the in-mold process, and over-molding process [2]. The field is now commonly referred to as "in-mold electronics (IME)" or "over-mold electronics (OME)". Both approaches can be used in many applications as they are diverse in electronic features, they can be used in the production of appliances, automotive industry, medical equipment, aerospace, and consumer electronics. These technologies are both cost and time-efficient with good dimensional accuracy for their products. As a general definition in-mold electronics processes (IME) are designed to form plastic products before or during the injection molding process [3]. On the other hand, over-mold electronics (OME) is designed to produce plastic products without forming step. Moreover, these technologies have more differences which mainly occur in their fabrication steps as describes in table 1.

TABLE I. Comparison between In-mold and Over-mold electronics

	In- mold electronics (IME)	**Over-mold electronics (OME)**
Foil used	Mainly polycarbonate (PC), polyethylene (PE) or Polyethylene terephthalate (PET) foils	Mainly polyimide (PI) foils but (PC) and (PET) could be used
Track material	Printed silver (Ag) tracks	Etched copper (Cu) tracks
Ways of assembly	Conductive adhesive	Lead-free solder
Outcome technology	Flexible hybrid electronics (FHE)	Flexible printed circuit board (FPCB)

Therefore, many intensive efforts were made to improve the ways of integration of the flexible circuits into plastic parts using injection molding. At which the flex electronic structure acts as the insert in the injection molding machine to perform over-mold structure. Nevertheless, as a film to be formed and over-molded to produce an in-molded structure. The most important parameter in this field of research is the material compatibility between the insert and the polymer injected or formed. Early approaches started to test injection molding with various films without electronics like presented in [4] where polycarbonate (PC) was the film and Acrylonitrile butadiene styrene (ABS) was the injected polymer and in [5] where polypropylene (PP) was used as both the film the injected polymer. Next efforts made researchers interested in improving the technology by presenting various functionalities in the plastic products. An overview is shown in table 2

TABLE II. Up to date approaches in IME and OME

Insert material	Plastic used	Functionality	Demonstrator	Reference
ITO-PET	PC	OLED	OLED	[6]
PC	PC	Sensor	Disposable health sensor	[6]
PET	TPU	LEDs	Wraplight	[7]
PP	PP	Solar cells	Solar cells as an energy harvesting system	[8]
PI	PA6	LEDs and NFc chips	Wireless control	[9]
PC	PC	LEDs	3D-shaped touch-user-interfaces	[10]

Moreover, a wide variety of promising approaches to realize the concept of such electronic structures including material combination, adhesion, and overall electronic performance were discussed in the following studies [9,11-13].
In our previous work[9], we studied the effect of over-molding on the components in a flat mold. Additionally, our motivation was to study what happens to electronics in various over-molding conditions. In this paper, we are investigating the same effect but in a curved mold as depicted in fig.1 and with different component sizes. In the first section, an overview of the literature study was discussed, then in the second section, the process flow is explained including the foil design, fabrication, in which the electronic structure is completed and tested, followed by the over-molding and simulation step. Then, a discussion on the results is in section III, and finally the conclusions and future work.

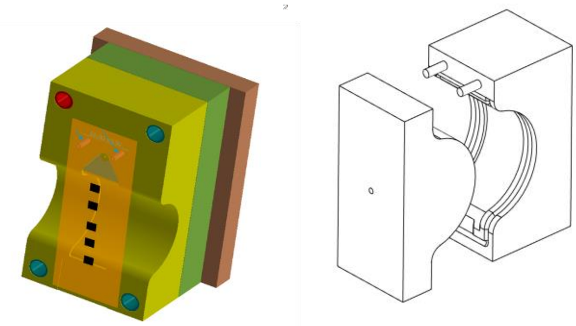

Fig. 1. Curved mold shape

II. Process Flow

The process flow of the electronic structured foil can be defined as a set of steps that must work together to have a reliable over-molded foil. Each step in the process flow could have a great influence on the other as depicted in fig.2

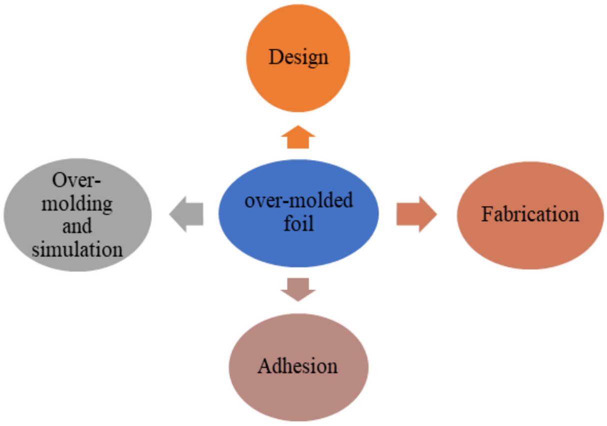

Fig. 2. Process flow of an over-molded foil

Fabrication starts using a dedicated design including 16 zero-ohm resistors in packages 1206 and 0402. The SMD components are assembled in 90° orientation. Another design was made using 10 zero-ohm resistors of different package sizes of 0603 and 0805. The components are mounted in 45 ° and 90 °. Using a commercially available polyimide FR9120, which was produced by Dupont. The circuit pattern was etched with a copper structure. In addition, the photoresist is removed and the copper is treated with an organic solder preservative (OSP) to protect it from oxidation. The thick film resistors-SMD components (zero-ohm resistors) purchased from (Yageo) are applied to the PI-Cu foil where the pads are soldered with conventional lead-free solder paste, and then the resistors are mounted on these pads. After that, the foils are heated until the solder particles solidify in a reflow oven. Followed by the application of an underfill material (Namics X58455-48). This underfill material offers the filling between the package (resistor) and the substrate (FR9120) that cures at 120°C for 20 mins. Furthermore, underfill materials enhance the reliability of the electronic structures. The choice of using the Dupont FR9120 as the base foil of flexible electronic was made due to the superior adhesion performance between the foil and the injection molding materials according to previous research [13]. In that research, the interfacial fracture energy of different PI foil–injection molding material systems measured by a tailored peel test system, was discussed as the adhesion evaluation criterion of different commercial PI foils. This foil showed the highest interfacial fracture energy when over-molding with polyamide-6 (PA6) injection molding material, which may be attributed to the chemical bonding between PA6 and the adhesive coated on FR9120. In the previous work [9], the applicability of injection over-molding FR9120 foil-based flexible circuits with PA6 injection molding material was demonstrated by fabricating flat over-molded structure as shown in fig.3. Moreover, the effect of the over-molding process on influencing the resistance of the components/tracks was evaluated.

Fig.3 Flat over-molded structure

In this work, different from the previous research samples with flat flexible foils, samples and experiments are performed with a new design using a curved shape mold as depicted in fig.1. The curvature of the sample is designed to be more significant than the common applications to demonstrate the flexibility of the foil and the shape of injection over-molded flexible electronics products. Real-life samples are depicted in figures 4 and 5.

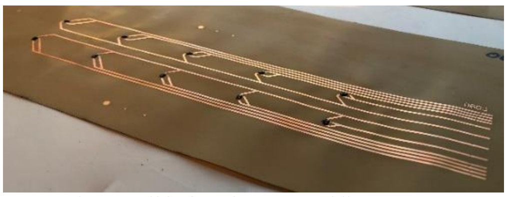

Fig. 4. Foil before the over-molding process

Fig. 5. Foils after the over-molding process

Moreover, numerical simulation is done to ensure that the entire mold cavity is uniformly filled with injecting polymer (PA6) at an appropriate time. The simulation is performed using commercial software Moldex3D and PA6 is selected as the reference material, with a melt temperature of 255 °C and a mold temperature of 65 °C (settings recommended by the material producer).

Figure 6 represents the cavity model, mesh, and boundary conditions. The cavity is discretized with about 1000000 elements, after performing mesh convergence models. The simulation results not only show that the filling time of the cavity is about 1.43 sec as depicted in fig.7 what remains acceptable, and indicates that the predefined over-molding cavity is a suitable design, but also such processing temperature can maintain the functionality of electronics during and after injection over-molding process.

Fig. 6. Mold cavity model and the discretized geometry

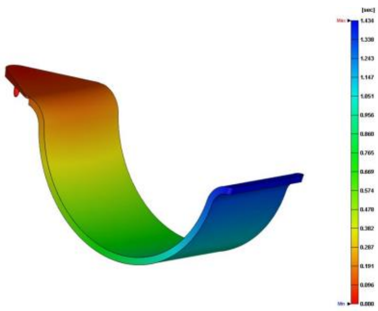

Fig. 7. Filling time of the mold cavity

III. Results and Discussions

Measurements were taken as an average of two foils for each package size and were also measured before over-molding acting as reference values and after over-molding to check the influence of the process on the resistance.

A. *Before over-molding*

The measured resistance is the sum of the resistance of the used component, the resistance of the copper track, the resistance of the soldered connection, and the probes' contact resistance. In other words,

$$R_{measured} = R_{initial} + R_{track\ length} + R_{solder\ connection} + R_{contact}$$

To know the tolerance variation of the resistors, ten 0-ohm resistors were measured acting as $R_{initial}$ of the component, which is 0.1 Ω before assembling the resistors on the foil. After assembly, the resistance of the assembled component was measured as follows:

For the 1206 and 0402 resistor package

The distance between the copper pad and the components from set 1 [R1-R8] and set 2 [R9-R16] is equal as depicted in fig.8 Accordingly, we can check the measurements of one of the sets for each package size.

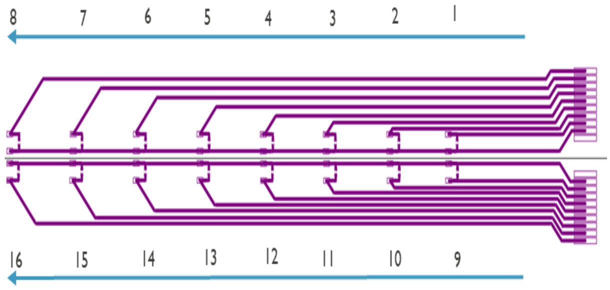

Fig. 8. Foil assembled with 1206 and 0402 resistors

To get an overview between $R_{measured}$ and $R_{theoretical}$, we calculated $R_{theoretical}$ for all 8 resistors. We had to put into account $R_{initial}$=0.1 Ω, the resistivity (ρ) of copper= 1.7×10^{-8} mΩ, the thickness of the track= 35 µm and the track width= 0.0005 m. The calculations showed no significant difference between the measured and the calculated resistance as presented in Table III

Table III. Resistance values for assembled 1206 and 0402 resistors before over-molding

	R measured		**R theoretical**
	1206	**0402**	**1206 & 0402**
R1	0.2 Ω	0.2 Ω	0.1667 Ω
R2	0.2 Ω	0.2 Ω	0.199 Ω
R3	0.3 Ω	0.3 Ω	0.23 Ω
R4	0.3 Ω	0.3 Ω	0.26 Ω
R5	0.3 Ω	0.3 Ω	0.303 Ω

R6	0.4 Ω	0.4 Ω	0.33 Ω
R7	0.4 Ω	0.4 Ω	0.37 Ω
R8	0.5 Ω	0.5 Ω	0.408 Ω

For the 0805 and 0603 resistor package

As the measurement was taken in the previous design, the distance between the copper pad and the components from set 1 [R1-R5] and set 2 [R6-R10] is equal as depicted in fig.9

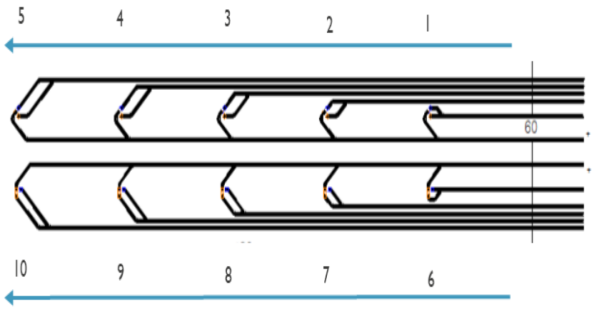

Fig. 9. Foil assembled with 0805 and 0603 resistors

The difference here is the track width which is equal to 0.0007m. The calculations again showed no significant difference between the measured and the calculated resistance.

Table IV. Resistance values for assembled 0805 and 0603 resistors before over-molding

	$R_{measured}$		$R_{theoretical}$
	0.805	**0603**	**0.805 & 0603**
R1	0.2 Ω	0.2 Ω	0.147 Ω
R2	0.2 Ω	0.2 Ω	0.188 Ω
R3	0.3 Ω	0.3 Ω	0.229 Ω
R4	0.3 Ω	0.3 Ω	0.267 Ω
R5	0.4 Ω	0.4 Ω	0.305 Ω

This comparison also proves that the major contribution in $R_{measured}$ is the change in resistance of the copper track length, both solder connection and probe contacts have a negligible contribution to the measured resistance.

B. *After over-molding*

The foils were clamped in the mold and the over-molding process was performed using PA6 including over-molding pressure, which is 576 bars. Over-molding slightly influenced the measured resistance as shown in Table V

Table V. Average resistance values after over-molding with PA6

	$R_{measured}$			
	1206	**0402**	**0805**	**0603**
R1	0.2 Ω	0.2 Ω	0.25 Ω	0.3 Ω
R2	0.3 Ω	0.3 Ω	0.3 Ω	0.4 Ω
R3	0.3 Ω	0.3 Ω	0.35 Ω	0.4 Ω
R4	0.35 Ω	0.4 Ω	0.4 Ω	0.4 Ω
R5	0.4 Ω	0.4 Ω	0.4 Ω	0.45 Ω
R6	0.4 Ω	0.45 Ω		
R7	0.5 Ω	0.5 Ω		
R8	0.5 Ω	0.5 Ω		

After over-molding, we observed for some components a slight increase in resistance. For resistance change in foils with 1206 resistors, the change was shown in resistors R2, R4, R5, R7 and change in resistance in R2, R5, R6, R7 in foils with 0402 packages as presented in fig.10

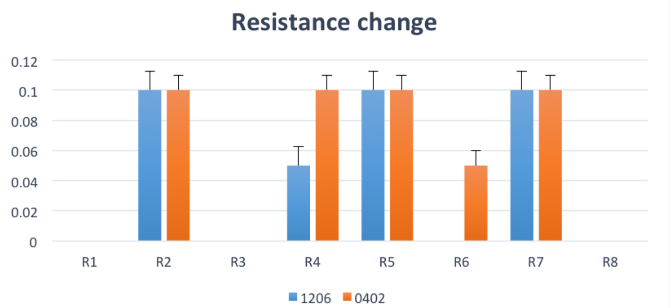

Fig. 10. Resistance change after Over-molding for 1206 and 0402 resistors

On the other hand, in fig. 11 the increased resistors are R1, R2, R3, R4 in 0805 foils, and the change in foils with 0603 packages was shown in all assembled resistors.

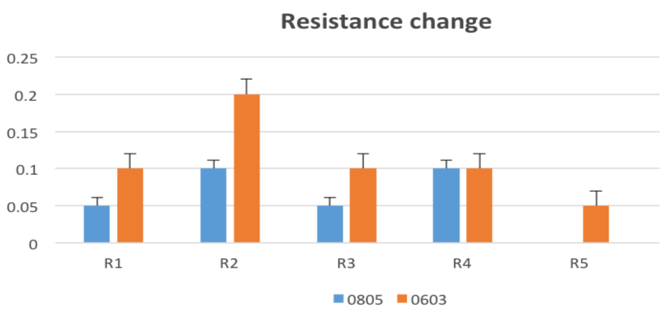

Fig. 11. Resistance change after Over-molding for 0805and 0603 resistors

Typically, an increase of 0.1 Ω is the major change in resistance measurements which is the same change as discussed in previous work with the use of the flat mold. The data were limited, but it seems that both a mold shape with curvature and difference in resistors packages used does not influence the electrical measurements. Moreover, The data shows the possibility to use different mold shapes and still have functional electronics on PI-Cu foils.

IV. CONCLUSIONS AND OUTLOOK

In this work, a mold with curvature was studied to check the performance of electronics after over-molding. Generally, the circuit including the components can withstand the over-molding conditions using PA6 material. As shown in the previous section, mold shape did not influence the components assembled on the used PI/Cu foil. Moreover, it showed us the PI/Cu foil can be slightly formed within a curvature mold without the need for a thermoforming step. We also observed a slight increase in resistance for most of the components. As the whole system is embedded in an opaque polymer (PA6), it is sometimes difficult to obtain the failure mechanism. However, using a transparent polymer instead of PA6 is highly recommended. Different electronics still need to be studied. In addition to this, a fully integrated over-molded part is highly recommended to end up with a foil inserted in two layers of injected molded material (e.g: PA6).

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