Vacuum thermoforming for packaging flexible electronics and sensors in e-textiles

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***Abstract*—Packaging of flexible electronics is essential for e-textile applications to reduce degradation of the performance caused by mechanical stress, environmental effects and to have increased durability. Conformal coatings for packaging have the advantage of reducing rigidity and can be seamlessly integrated into fabrics. Vacuum forming is a technique for packaging electronic devices with thermoplastic films of various thicknesses providing uniform coating. Polyurethane is a widely used thermoplastic material in e-textile and can be easily processed by vacuum forming for packaging. In this paper, a detailed explanation of the working of Formech 450DT vacuum former is discussed for packaging small electronic chip for e-textile application with thermoplastic polyurethane (TPU). Two types of flexible circuits were packaged; a Carbon monoxide gas sensor and a series of resistors on flexible PCB. The packaged CO flexible sensor and series resistors endured 5.3 times and 1.7 times respectively, more bending cycles than unpackaged flexible electronic filament samples. For the washing cycles, the packaged flexible strips with CO sensor and series resistors endured 1.5 times.**

***Index Terms*—Packaging, vacuum forming, thermoplastic films**

I. INTRODUCTION

Flexible electronics and sensor systems have been used in a wide range of e-textile applications such as measuring temperature, humidity, proximity or air quality monitoring [1][2][3]. Early examples of flexible electronics for e-textiles utilised single devices, such as light emitting diodes (LEDs) and radio frequency identification (RFID) [4][5] chips periodically spaced along a yarn. This approach has developed further with flexible filament circuits that include multiple components arranged in long thin flexible circuit layouts. The filament format facilitates integration within the channels formed within the fabric such within the knitted textile shown in fig 1(a) or within bespoke pockets in a woven textile structure shown in fig 1(b) [6] [7]. This approach can both hide the circuits invisibly within the fabric and enable circuits to be replaced or recycled at end of life. Minimising the size of the filament and the circuit components is important for ensuring the circuits remain unobtrusive. Once integrated within the fabric, these circuits must withstand the rigours of use such as the mechanical forces and exposure to chemicals experienced when machine washed. Mechanical stresses in particular limit the longevity of these circuits which often fail due to cracks in the circuit tracks and solder joint failures.

To improve the robustness of the electronic filament under mechanical loading and protect against exposure to harmful media, packaging approaches can provide additional protection. Traditional ways of packaging rigid electronics include glob top, dam and fill, casting and potting [8][9].

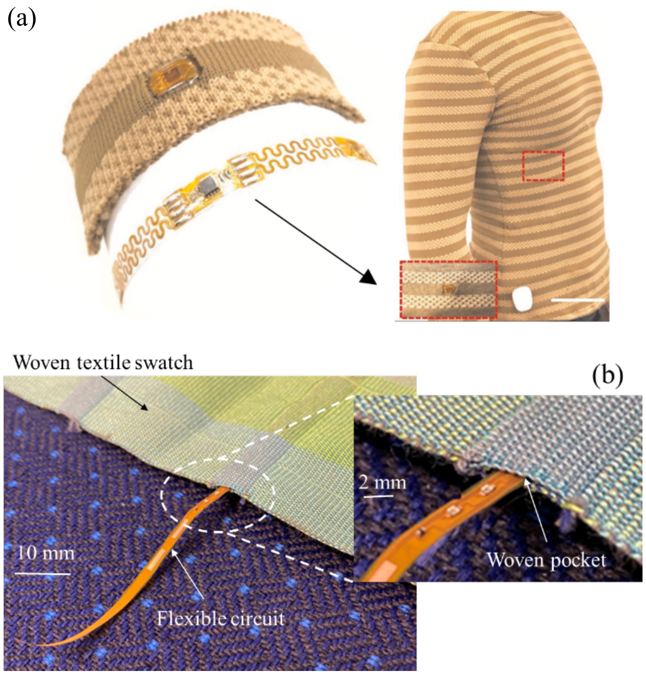


Fig. 1. (a) A knitted electronic textile (E-TeCS) for sensing temperature and acceleration (for heart beat and respiration) with the flexible circuit located within channels in the fabric (adapted from [6]); (b) Flexible filament mounted with surface mount LEDs and microcontrollers integrated in the woven textile pocket.

The dam and fill, casting and potting approaches are not suitable for flexible circuits and glob top encapsulation can be difficult to control repeatably, can result in crack formation in the copper tracks at the edge of the glob top and can significantly increase the bulk of the filament circuits.

Conformal (or uniform) coating is also routinely used for protecting rigid printed circuit boards (PCBs) by a applying thin layer of liquid polymer (e.g., acrylic, epoxy, silicone) by dip, brush, or spray coating [10] [11]. Such liquid coatings are typically applied in thin layers (25 – 125 µm) and provide some protection against solvents, moisture and abrasion, and can reduce thermal and mechanical stresses [12] on the electronic circuit. The conformal coating has a minimal effect on the flexibility and obtrusiveness of the circuits compared with, for example, glob top, therefore, helping in the seamless integration in textiles. Conformal coating can also be achieved by attaching solid films to the flexible substrate. For example, a polyimide film (Kapton) was used for conformally packaging flexible electronic strip circuits containing bare silicon test die. This packaging approach enabled the circuits to survive 45 machine wash cycles and 1470 bending test cycles [13]. For comparison, glob top encapsulation was also used in this work to protect the test chips using UV curable polymer EC-9519 supplied by Nagase. The glob top circuits typically failed after between 20 and 25 wash cycles [7] and this can fall to around 5 wash cycles on more complex circuits [13]. To achieve a conformal coating with Kapton, metal moulds were used to form the recess required at the location of the test die. The Kapton was moulded by placing the material between the male and female halves of the mould and was deformed by heating up the assembly to 360ºC for 60s. The moulded Kapton was then bonded to the circuit strip using a thin layer of polyimide-based adhesive. Whilst this approach was successful in improving the robustness of the flexible circuit, Kapton is a thermoset plastic and does not readily deform leading to variations in film thickness around the chip edges. Different metal moulds are required for different circuit layouts which adds complexity to the packaging process.

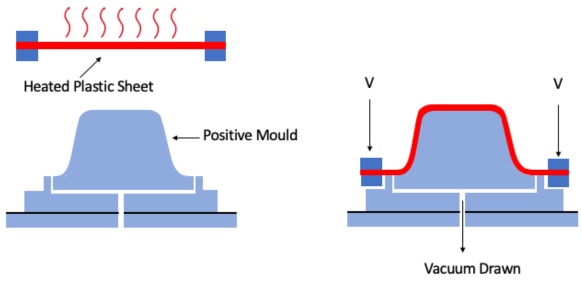
Thermoplastic materials become soft and moldable when heated and are therefore an attractive option for conformal film packaging. The flexible circuits shown in figure 1(a) were encapsulated on both sides with a 100µm thick thermoplastic polyurethane (TPU) film using a thermal lamination process at 150ºC [6]. An alternative to lamination is vacuum forming which is a thermoforming process whereby a vacuum is applied to obtain the desired mould shape. This process is used in various applications including general moulded plastic parts, in the packaging industry, for example, in manufacturing clamshell and blister packs and in the fabrication of microfluidics [14][15]. Thermoplastic materials are typically used for vacuum forming where the softening of the polymer film when heated above the glass transition temperature (T_g) enables it to become mouldable when the vacuum is applied and solidifies when cooled. In typical consumer packaging applications, the vacuum forming process uses a specifically designed mould to realise the geometries required for the application (for example, blister packs for pharmaceuticals) and is then sealed by bonding to cardboard backing or with aluminium foil.

In this work, the vacuum forming process has been applied to encapsulate the flexible circuit without a separate moulding step, i.e., the thermoplastic polyurethane (TPU) (Platilon U 4201 AU [16]) was moulded directly onto the target flexible circuit. This approach enables flexible filament circuits with any topology to be packaged without the use of bespoke moulds. The bonding process between the encapsulating film and the Kapton circuit substrate has been explored and the bond strength quantified. This paper applies the encapsulation process to two example flexible electronic circuits: a test circuit comprising five 1 kΩ surface mount (SMD) 1206 resistors in series and a MICS 5524 carbon monoxide (CO) sensor for air pollution sensing. The components for these circuits were soldered in place and Masterbond EP37- 3FLF underfill was used for additional mechanical strength. The reliability of the packaged circuits under cyclical mechanical bending stresses and machine washes has also been evaluated.

1 VACUUM FORMING

A. Type General principle of Vacuum forming

Vacuum forming is a process that transforms thermoplastic polymer sheets or films into three dimensional geometries, normally using a specifically fabricated mould. The working principle involves heating the thermoplastic film to reach a softened malleable state that is placed on top of the mould as shown in fig 2(a). The vacuum is formed by extracting the air from underneath the softened film causing atmospheric pressure to force the polymer against the mould as shown in fig 2 (b). In this case, the mould is replaced by the circuit to be coated and the thermoplastic film conformally coats the substrate and components directly.



(a) (b)

Fig. 2. (a) The thermoplastic film is initially heated until it softens (b) the vacuum is applied and atmospheric pressure forces the softened material on top of the target mould. Image adapted from [15]

For this work, a Formech 450DT desktop vacuum forming machine [17] has been used to encapsulate the flexible circuits. This equipment includes a Quartz infrared heater and has a maximum operating window of 450 x 300 mm. In this case the initial operating window was reduced to 150 x

150 mm using a machined aluminium top plate as shown in figure 3 to avoid material waste.

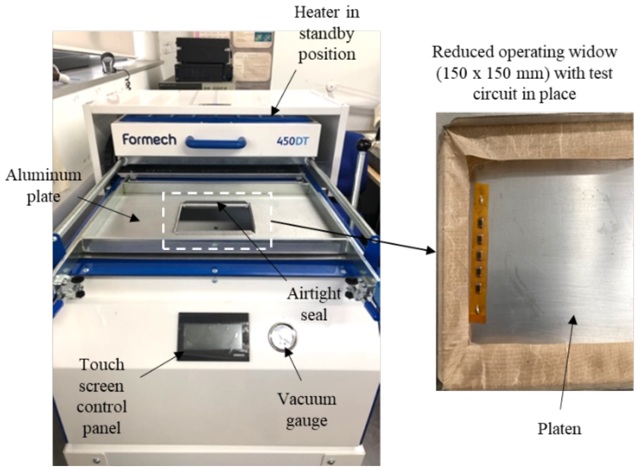


Fig. 3. Front view of Formech 450DT and reduced processing window is shown with flexible electronic test circuit with series resistors.

Each encapsulating material has a specific T_g at which it softens and becomes malleable and ready to mould. The Formech 450 DT vacuum former defines the heating power in terms of percentage and therefore the equipment was characterised to find the approximate temperature for different heating power percentages from 5 to 100%. An infrared thermometer (Etekcity Lasergrip 1080, range -50°C ~ 550°C) with a response time of less than 0.5 seconds was used to measure the temperature at the centre of the area under the heater at the standby position. The correlation between temperature and the heating percentage is shown in fig 4.

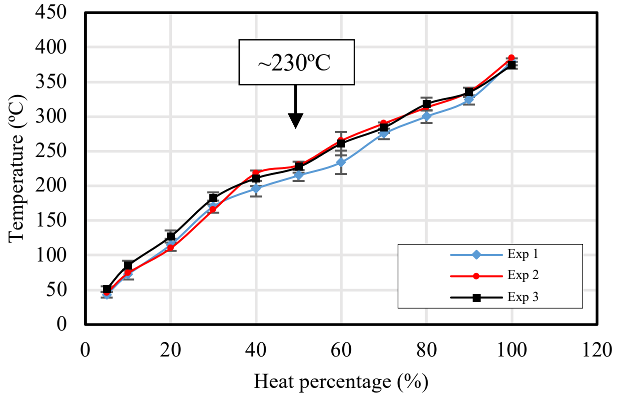


Fig. 4. Temperature measurement for different heat powers (3 separate measurements)

The TPU encapsulant Platilon U 4201 AU [16] used is a breathable and waterproof film of thickness 100µm. The vacuum forming process with the TPU film is as follows.

Step 1: The circuit is placed onto a platen mounted on a mesh located under the operating window. The mesh allows the application of the vacuum and is initially in the lower position ~ 10 cm below the bottom plate. The TPU film is sandwiched between the top and bottom plates with an airtight seal around the operating window to form the vacuum in step 4. The heater is in the standby position as shown in figure 5(a) with the heat power set at 50% power corresponding to ~230 ºC which is above the T_g for the TPU film and results in a soft pliable film.

Step 2: The heater is bought forward to be located and lowered over the TPU film which is heated for 50s as shown in figure 5 (b).

Step 3: The machine has an interlock system that does not allow heating and vacuum forming simultaneously. Hence the heater returned to the standby position and the mesh and platen containing the circuit is raised. This forms a seal between the edge of the mesh and the bottom plate, figure 5(c). A vacuum of -0.8 bar is applied and atmospheric pressure forces the TPU film down over the circuit, figure 5(d).

Step 4: After the process, the clamps can be released to remove the encapsulated circuit from the platen. Excess material around the circuit is removed.

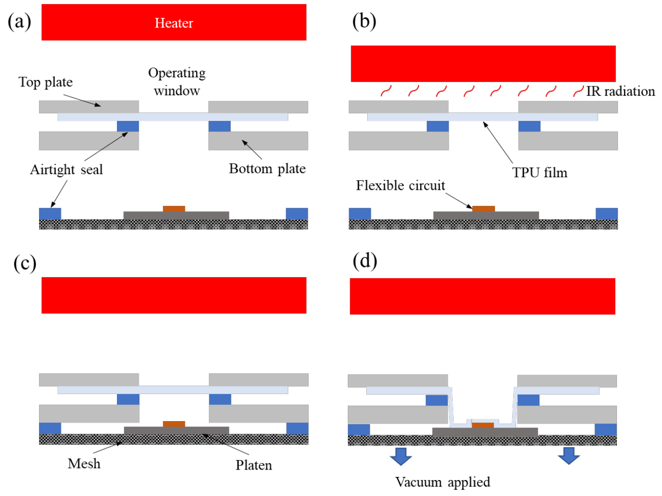


Fig. 5. Schematic diagram of vacuum forming process using Formech 450DT for moulding with Platilon U 4201 AU. (a) The heater is at the standby position and the sample is placed on the table below the clamped TPU film under the window; (b) the heater is moved forward to the front end from standby position to heat the TPU material; (c) the heater is moved back to the standby position and mesh and platen are raised towards the softened TPU forming a seal around the mesh; (d) vacuum is applied to force the softened material over the circuit.

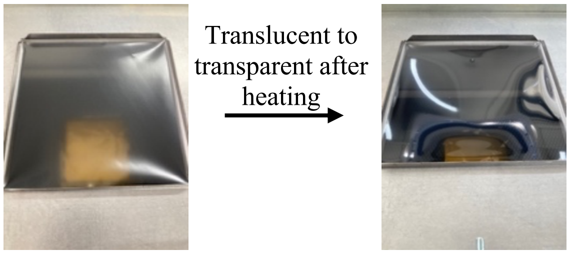


Fig. 6. Material changes from translucent to transparent after heating at 50% heat power setting for 50s

An iterative approach was used to identify the optimum heater power for the TPU film. The TPU changes appearance after heating as shown in figure 6 transforming from being translucent when cold to transparent when heated. This visible change in appearance indicates the film has achieved the required soft and malleable phase and is ready to be vacuum formed. Since the heater cannot be used at the same time as the vacuum is being applied the TPU film will cool, and it is desirable to apply the vacuum as soon as possible. However, when the mesh and platen are raised and the seal formed with the bottom plate, the trapped air is heated by the raised temperature of the plates and the pressure rises causing the TPU film to bulge as shown in figure 7. This can introduce undesirable bubbles in the final vacuum formed encapsulating films. This is minimised by gradually raising the mesh and platen but there is a trade-off with the cooling of the TPU film. Optimising the vacuum forming process is desirable to minimise the formation of bubbles and avoid tenting of the encapsulating film around components. Where components have right angled edges, tenting can occur resulting in bubbles around each component. The position of the circuit on the platen was also found to be a factor in the quality of the encapsulation. The circuit placed at the edge of the platen had reduced tenting around the components compared with circuits located at the centre. Additional heating and vacuum steps can be repeated to further reduce this (see section 2.3).

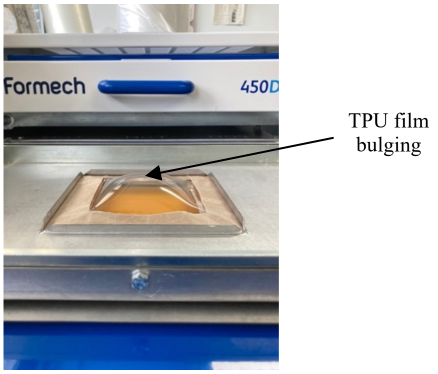
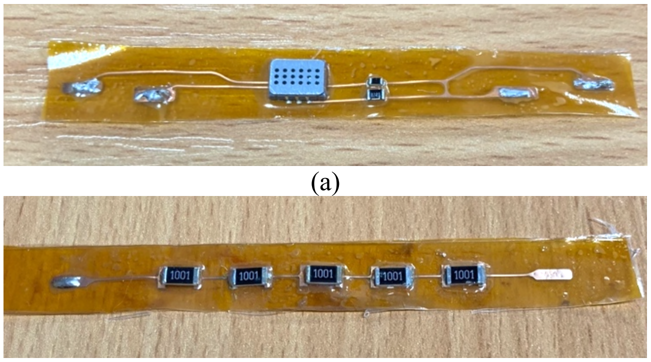


Fig. 7. TPU film deforming due to the trapped air pressure prior to the application of the vacuum. This can cause uneven bonding of the TPU film to the flexible circuit substrate.

The two flexible electronic circuits were encapsulated using the optimised settings. The flexible CO gas sensor strip shown in figure 8 (a) and SMD resistors (each 1KΩ) in series is shown in figure 8 (b). The carbon monoxide sensor is relatively large (5 x 7 x 1.55 mm) and has been successfully encapsulated with minimal tenting around it. The wires can be subsequently attached to the contact pads by melting the TPU with the soldering iron at the location of each pad.



(a)

(b)

Fig. 8. TPU Vacuum formed (a) flexible CO gas sensor and (b) flexible strip with series resist

B. Bonding process for TPU film on Kapton substrates

The flexible circuits are fabricated from copper coated Kapton substrates (GTS7800, supplied by GTS Flexible Materials Ltd) that are patterned using standard photolithography followed by a copper etching step [7]. The copper is bonded to the Kapton using a thin (17 µm) epoxy adhesive layer. The copper etching process removes the copper where it is exposed to the etchant but does not attack the adhesive which remains on the surface of the Kapton film. This remaining epoxy film is used to bond the TPU film with the Kapton substrate and means no additional adhesives, such as hot melt films or pressure sensitive adhesives, are required. In order to achieve the maximum bond strength, the encapsulated circuit must be subsequently heated to 230-240ºC using a hot air gun positioned around 2cm above the circuit. The quality of the bond can be visually confirmed by the transparent appearance of the TPU film and the absence of voids across the substrate. The surface of the Kapton after etching i.e., with the epoxy (denoted Kapton E) has been compared with standard non coated Kapton (Kapton N) in figure 9. Figure 9(a) shows the smooth surface of the Kapton N whereas the adhesive is clearly visible in figure 9(b). The appearance of the Kapton is also different as shown in the inserts in figure 9 with the Kapton N being shiny and the Kapton E being dull. It should also be noted that the epoxy is not always distributed uniformly across the Kapton with variations in thickness as shown in figure 9(c). This may affect the bond quality between the TPU and Kapton films. The use of the remaining epoxy means the circuit should be designed such that sufficient copper is etched away from the substrate to maximise the area of the exposed epoxy. There should also be a sufficient gap between the edge of the die and the edge of the strip, the size of this gap depends upon the thickness of the die. The MICS 5524 CO sensor is 1.55 mm thick and requires a gap of 2 mm around it to effectively bond the TPU film.

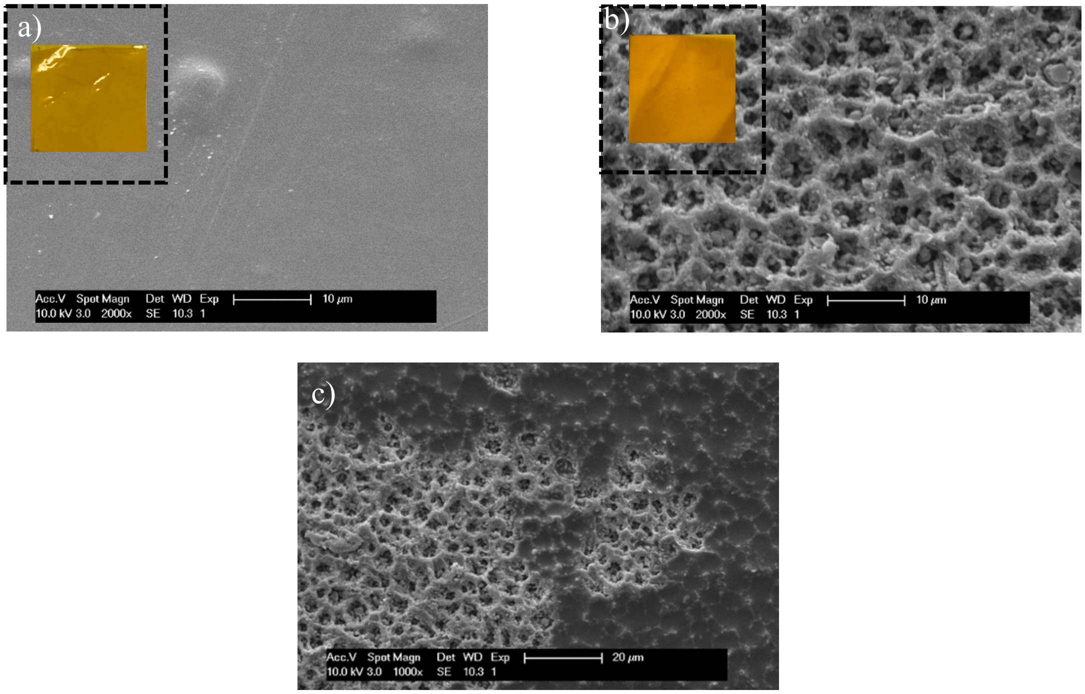


Fig. 9. Scanning Electron Microscope images of (a) Kapton N; (b) Kapton E and (c) Kapton E with a non-uniform coating of epoxy

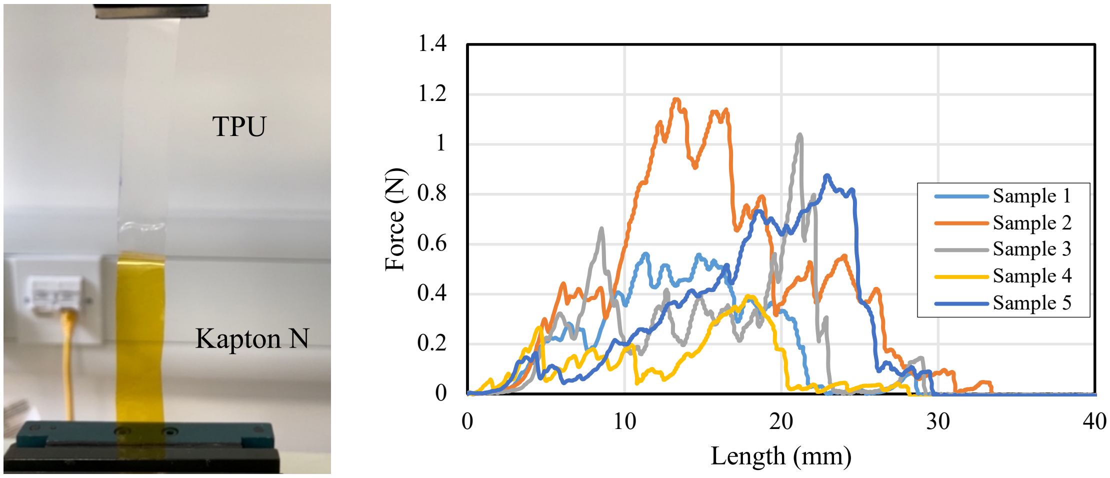


Fig. 10. Peel strength for Platilon U 4201 AU on Kapton N after vacuum forming and hot air gun at 230ºC. Uneven peaks indicate non-uniform bonding

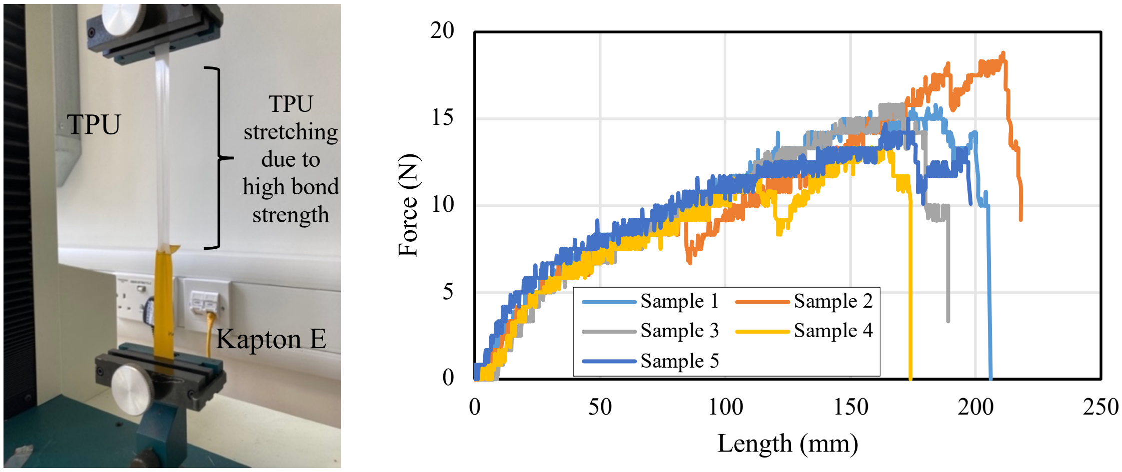


Fig. 11. Peeling test of Platilon U 4201 AU on Kapton E after vacuum forming and hot air gun at 230ºC for bonding

The bond strength was experimentally validated using a Tinius Oslen model H25KS tensile tester with a 25 kN loadcell. Blank (i.e., no tracks or components) Kapton and TPU samples were cut into 15 mm wide strips, 100 mm in length and were bonded as described above using the vacuum former and heat gun. Each sample was bonded partway along its length leaving both films accessible at one end of the strip. The Kapton was mounted on the bottom fixed position clamp and the TPU was attached to the top clamp as shown in figures 10 and 11. The tensile test was run following the ASTM F88 standard with a pull speed of 250 mm/min. Five samples of each of the standard Kapton (Kapton N) and Kapton with epoxy (Kapton E) were evaluated. The results for the Kapton N shown in figure 10 indicate a weak and variable peel strength with the films separating at a force typically less than 1 N. The bond strength of the Kapton E with the TPU is significantly higher with an average maximum peel force of 15.86 N and average peel strength of 10.5 N along the bonded length of each sample. The length scale in the x axis is longer for the Kapton E substrate compared with the Kapton N substrate due to the high force required to peel the bond which caused the TPU film to stretch as shown in figure 11.

C. Influence of platen position and repeated vacuum forming steps

Due to factors such as the bulging of the TPU film prior to vacuum forming and cooling of the TPU, the location of the circuits on the platen plays a role in the quality of the encapsulation. This was investigated by placing three samples with the MICS 5524 CO sensor die on Kapton E substrates of 1 cm width and 9 cm length at different positions on the platen (one on the left edge, one in the center and one on the right edge) as shown in figure 12.

Fig. 12. Samples are positioned at left, centre and right edge of the platen under the operating window for vacuum forming. The samples on the left and right have reduced tenting in comparison with the sample at the centre.

The test samples were subject to vacuum forming with the TPU film heated at 230ºC for 50 seconds. As shown in figure 12, the degree of tenting around the sensor die is less for the samples located on the sides of the platen compared to the sample positioned at the center.

(a) (b)

Fig. 13. Showing (a) vacuum formed using PU with tenting around the die (b) reduced tenting due to the use of a heat gun and applying the vacuum again.

The tenting around the sensor can be reduced by the additional heating step using the heat gun and a second application of the vacuum. This is shown in figure 13 (a) where the tenting around the die is clear and the considerable reduction in tenting is shown in figure 13 (b). The heat gun can be applied with the circuits in place on the platen to enable the rapid application of the second vacuum step. The additional heating and vacuum step can be repeated if required.

D. Carbon monoxide sensor response before and after TPU encapsulation

The encapsulation process could affect the sensor performance depending upon the sensor type and application. Inertial sensors, for example, would be unaffected by this approach whereas pressure and gas sensors, such as the CO sensor used here, may not be suitable despite the TPU film being classified as breathable. The actual permeability of the TPU film to different gases is not known and therefore this was investigated. To explore the effect on the gas sensor performance, the CO circuit was tested when exposed to a premixed concentration of 1000 ppm CO connected with a constant flow regulator (0.5 l/min) to a small gas chamber containing ambient air and a fan for distributing the gas inside the chamber. The gas was introduced with increasing dose durations (10s, 20s, 30s and 40s) to increase the CO concentrations (19 ppm, 34 ppm, 45 ppm and 65 ppm).

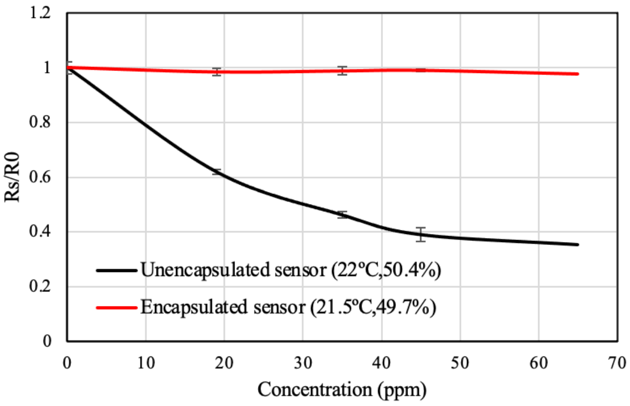


Fig. 14: Comparison between CO sensor response for encapsulated versus unencapsulated circuits with temperature and humidity readings at the time of testing.

The sensor response is given by R_s/R_0 where R_s is the sensor resistance in presence of CO and R_0 is the sensor response in presence of air. R_s decreases with increasing concentration of CO. It is observed that the response of the unencapsulated filaments decreases as expected with an increase in the concentration of CO gas. The TPU encapsulated circuits, however, exhibit a negligible change in the sensor response in the presence of the gas. This is shown in figure 14 and indicates that the Platilon U 4201 AU film acts as a gas barrier to CO molecules and the bond is gas tight. This indicates the TPU encapsulation is unsuitable for gas sensors.

2 BENDING TEST AND WASHING TEST

Textiles, by their very nature, are flexible materials with the woven/knitted construction enabling fabrics to shear which results in the ability to drape. The integration approach shown in figure 1 whereby the circuits are inserted into pockets has a negligible effect on these characteristics of the textile. Any bending of the fabric due to folding or machine washing will be transmitted to the flexible circuit, and it is important the TPU encapsulation process protects the circuits against the resulting mechanical stresses. This was evaluated by subjecting the circuits with the SMD resistors in series and the CO sensor circuits to a combination of bending and wash tests. The bending test setup is shown in figure 15 with the circuit under test located in a pocket woven into a cotton swatch. The textile swatch is clamped at each end with the top clamp being mounted on a stage that moves back and forth horizontally via motorised drive belt. The bottom clamp moves vertically up and down and has a 200 g weight attached placing the textile in tension during the experiment. As the top clamp moves back and forth, the textile swatch, and therefore the circuit, is repeatedly bent 90 degrees around the mandrel, which has a diameter of 5 mm.

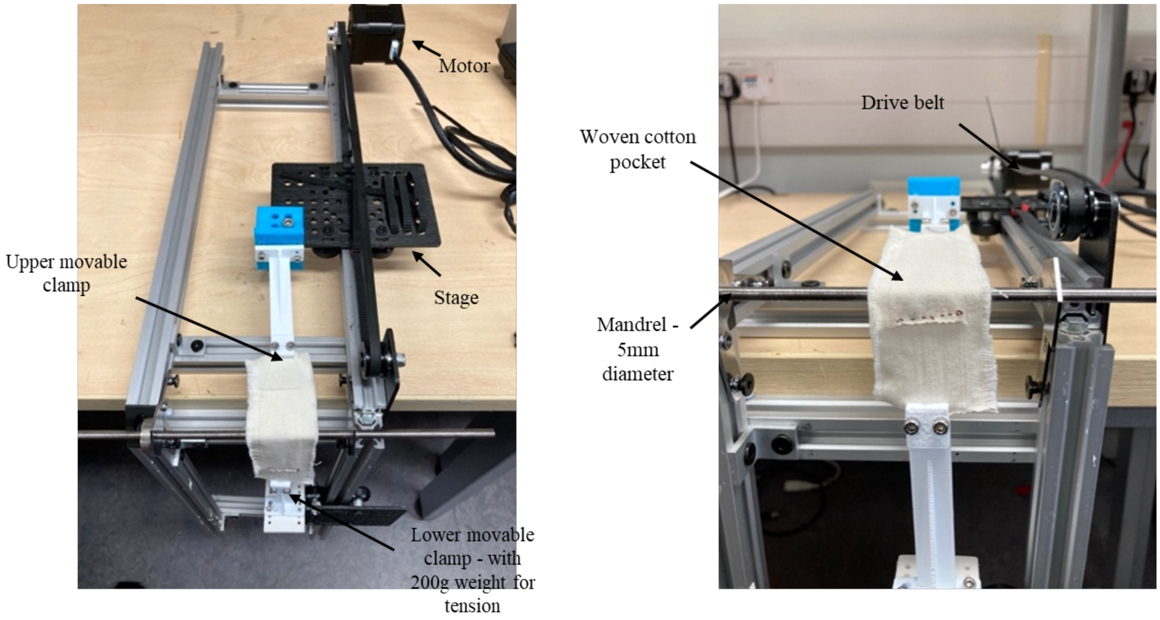


Fig. 15: Bending rig for the cyclical bending test. Connected to a microcontroller for setting number of cycles, stroke, and speed.

The resistance across both circuits was periodically measured and the number of cycles obtained until the resistance becomes open circuit (i.e., fails) was recorded. The results for the encapsulated and unencapsulated circuits are shown in figure 16 with the average being obtained from 3 circuits in each case. The packaged CO flexible circuit withstands an average of 46667 bending cycles which is 5.3 times more than the unpackaged CO circuits. The packaged SMD resistors in the series circuit achieved an average of 20667 which was 1.7 times more than the unpackaged circuits.

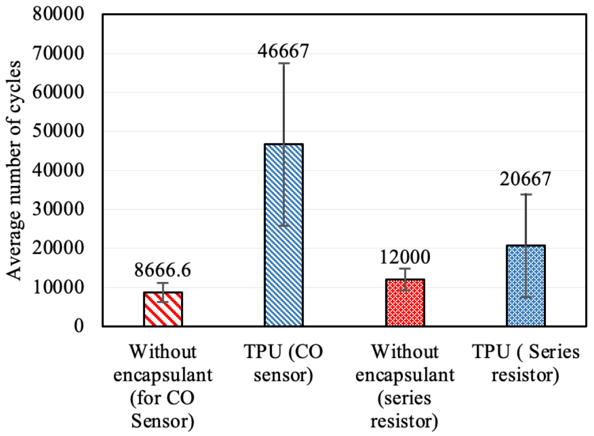


Fig. 16: Average number of bending cycles survived by unpackaged and packaged flexible CO and series resistors filaments

When the circuits fail this is typically due to the copper track in the electronic circuits cracking under the stress caused by bending (as shown in figure 18 in the case of washing). The underlying mechanism by which the TPU film improves bendability lies with the position of the copper tracks of the electronic circuit in relation to the neutral axis where the stress is zero during bending. The use of the TPU layer moves the copper tracks towards the neutral axis and therefore improves bendability and durability. The position of the neutral axis can be calculated by [18]

$$\mathrm{NA} = \frac{\sum_{i=1}^{n} E_i t_i \left(2\sum_{j=1}^{i} t_j - t_i\right)}{2\sum_{i=1}^{n} E_i t_i} \qquad (1)$$

Where E is the Young's modulus and t is the thickness of the materials. From equation 1, the NA for the TPU packaged electronics was calculated to be 48.5μm which is located within the copper track.

For the washing test, the flexible circuits were inserted into pockets within a larger textile swatch and the pocket openings were sewn up. All the samples were washed with 2 kg of clothing using a non-biological laundry detergent in a Beko WME7247W washing machine running a 58 minute wash programme at a temperature of 40 °C with a 1000 rpm spin dry cycle (similar to ISO 6330:2000-6A standard for domestic washing and drying procedures for textile testing [19]). The resistance across each circuit was measured after each wash cycle and the number of cycles until failure was recorded as an average from 3 samples for each circuit type.

The unencapsulated CO circuit survived an average of 10 wash cycles with all 3 circuits failing after a maximum of 12 cycles. The TPU encapsulated CO circuit survived an average of 16 wash cycles with the best performing circuit surviving 22 wash cycles as shown in figure 17.

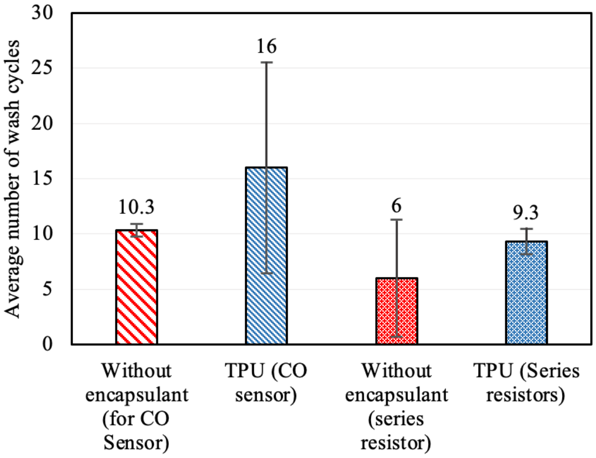


Fig. 17. Average number of wash cycles survived by unpackaged and packaged flexible CO and series resistors filaments

The results for the SMD resistors in series reflect these results with the TPU encapsulated circuit surviving longer than the unencapsulated circuits. The test circuit did not survive as long as the CO sensor circuit which may be due to the larger number of components mounted on the circuit providing more opportunity for failure. The unencapsulated CO filament failed due to the fracturing of the soldering joints causing detachment of the chip from the filament. The other circuits failed with the copper tracks typically cracking at the interface between the flexible circuit and the rigid component (see figure 18 (a), (b) and (c)). It can also be noticed that in the TPU encapsulated CO filament, the film appearance is altered by repeated exposure to the detergent which changes the colour of the film from transparent to almost white as shown in figure 18 (a).

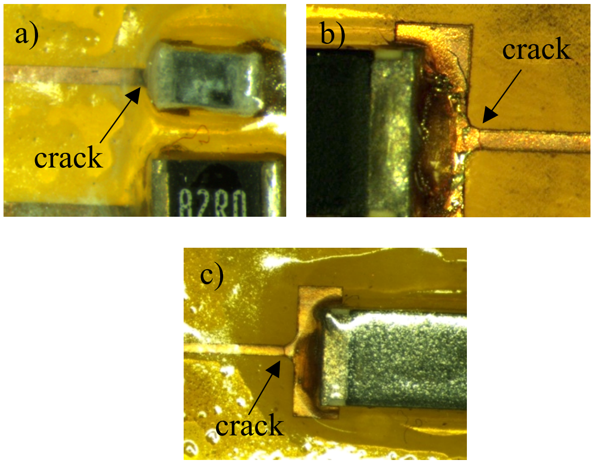


Fig. 18. Showing filaments after washing for a) TPU encapsulated CO filament, before washing of b) 5k series resistor and after washing of c) TPU encapsulated 5k series resistor

The improved reliability offered by the TPU encapsulation process is consistent with previously reported results although other test circuits with smaller components have survived up to 45 washes [13].

3 CONCLUSION

These results demonstrate the ability of vacuum forming to quickly and efficiently conformally package any flexible circuit without requiring specifically designed moulds. The TPU encapsulating film does improve the circuit robustness and increase the number of bending and wash cycles circuits can withstand before failure. The TPU films used in this work (Platilon U 4201 AU) is readily deformable and with correct processing parameters effectively covers all components, even the large CO sensor used in these tests. However, this form of coating with this TPU material does prevent the gas sensor from functioning and therefore alternative thermoplastic films that are porous to the particular target gas molecules must be identified for such applications. The TPU film is bonded to the Kapton substrate using the exposed epoxy adhesive after the copper has been removed in the fabrication of the circuit. If the circuit design results in insufficient copper being removed (e.g., because a ground plane is required), an alternative TPU film that includes a thin layer of hot melt adhesive (Platilon HL9007 can be used). Circuit failure is typically due to the copper track cracking at the interface between the rigid and flexible sections of the circuit and no components became unattached during these experiments. Circuit design is therefore also important for maximising the robustness of the circuits. This process is now routinely used in the fabrication of flexible circuits at Southampton and is the subject of a patent application [20] .

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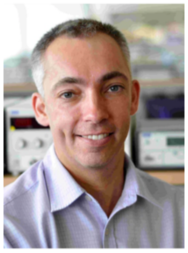

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