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A Substrateless Process for Sustainable Manufacture of Electronic Assemblies

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Abstract

The exponential growth in worldwide production and consumption of electronics, and the short operational lifespan of many products, has resulted in increasing amounts of electronics waste. There is enormous pressure on electronic product manufacturers to reduce the consumption of materials and their subsequent impact on the environment, especially at the end-of-life, through such measures as the EU Directive on Waste Electrical and Electronic Equipment (WEEE). Ideally any product should be separable into its constituent parts at end of life for subsequent reuse, recycling or disposal. However separation of a typical electronic assembly into its constituent parts is problematic because of the intimate nature of the bonding between the glass fibre/thermoset composite laminate, the laminated and embedded copper conductor layers and the soldered electronic components.

To address these problems, an alternative processing route for manufacture of electronics assemblies is proposed, in which the electronic components and metal content can be easily separated out from the organic content at end-of-life. No separate printed circuit board is used to interconnect the components so the process may be termed as "substrateless". The route has the additional advantage that standard electronic assembly equipment can be used. In this work the process route is described and the implications of adoption for the electronics manufacturing industry considered. The results of initial proof of principle trials are described, and conclusions are drawn as to the development work required to allow adoption of the process by the industry.

Introduction

As one of the largest industrial sectors, there is enormous pressure on electronic product manufacturers to reduce the consumption of materials and their subsequent impact on the environment, especially at the end-of-life. Within the EU, this has recently become even more significant with the implementation of the Waste in Electronic and Electrical Equipment (WEEE) and the Restriction of Hazardous Substances (RoHS) Directives [1]. A key aspect of the new legislation is the requirement for the manufacturers to take back products at the end of their life and to dispose of them in a responsible manner that will limit the amount of waste to landfill and maximise the amount of material recycled. The directive mandates recovery of up to 80% of electrical and electronic products sold by manufacturers or distributors at end-of-life. The directive also mandates that at least 50% of the collected WEEE should be reused or recycled. Manufacturers must therefore now consider more

environmentally friendly and sustainable methods of manufacture, while still working within the bounds of a highly competitive, cost conscious marketplace. An extensive WEEE recovery system is already in place in Japan [2], while within the UK the Valpak scheme has been set up to allow distributors of electronic goods to meet their WEEE take-back obligations.

In the specific area of the populated printed circuit board (PCB), which amounts to 40,000 tonnes per annum of waste in the UK alone [3], the issue of reducing waste and minimising environmental impact is particularly difficult. One of the major challenges is the separation of the highly dispersed metallic and other materials (copper tracks, solder alloys, silicon components) from the glass fibre reinforced epoxy laminate substrate, which in many cases are inextricably intermixed as a result of the manufacture of multilayer boards. Furthermore, recent advances, such as integrated passives, have further increased the range of materials present within the substrate. Previously, the separation of these has not been considered cost effective due to the limited amount and mixed nature of the metallic materials and the inherent non-recyclability of the thermosetting epoxy laminate. As a result of this, much of this waste has simply been disposed of into landfill sites, leading to fears of land and ground water contamination due to the leaching of heavy metals and other chemicals. However, the EC has acted by implementing the Landfill Directive [4] which requires the reduction of municipal landfill sites by 65% by the year 2020 and the segregation of PCBs from non-hazardous waste streams.

To address these problems, an alternative processing route for manufacture of electronics assemblies is proposed involving insert moulding with thermoplastics, in which the electronic components and metal content can be easily separated out from the organic content at end-of-life. The route reverses the normal order of surface mount technology (SMT) assembly steps in that components are assembled before the interconnection pattern is created. No separate printed circuit board is used to interconnect the components so the process may be termed as "substrateless". In this work the process route is described and the implications of adoption for the electronics manufacturing industry considered. The results of initial proof of principle trials are described, and conclusions are drawn as to the development work required to allow adoption of the process by the industry.

Process Route

One embodiment of the processing route is illustrated in Figure 1.

- a) Conventional pick and place machines would be used to position components onto a carrier film that would secure them using an adhesive.
- b) The carrier film with components would then be overmoulded with a thermoplastic polymer using an injection moulding process.
- c) The moulding would be removed from the mould tool.
- d) The carrier film would be removed, revealing the undersides of the component leads. The component leads would be set flush with the surface of the moulding, facilitating the electrical interconnection step.
- e) A circuit pattern would then be produced using established processes such as electroless copper metallisation or printing conducting inks / pastes. The circuit pattern would act to interconnect the components directly, without requiring soldering.

For multilayer circuit manufacture, a further dielectric layer could be added to the underside of the structure by injection moulding or another suitable process, into which vias may be formed and onto which additional tracks added.

Component recovery at end of life can be enhanced through judicious choice of overmoulding polymer. For a biodegradable polymer the assembly can be composted and the components sieved out at the end of breakdown. Alternatively a water or other solvent soluble polymer could be used, especially where the solution has commercial value. If a water soluble polymer is used a protective coating may be required to prevent premature attack by moisture during the working life of the electronic assembly.

The advantages of the substrateless manufacturing route for electronic assemblies are:

- Separation of the components and metals from the polymer at end of life, thereby generating two streams of material for recycling or further processing;
- The requirement for solder interconnection would be removed, leading to reduced material and energy costs, avoiding additional process steps and the reliability issues associated with solder joints;
- The product packaging and mechanical structure would be produced at the same time as the electronic circuit;
- The process is a combination of many existing technologies and uses legacy electronic manufacturing equipment.

Variations on the processing route outlined in Figure 1 are conceivable. For example components could be soldered to a copper sheet and overmoulded, with the

copper sheet being subsequently etched. Registration features would be required to align the etch mask with the components hidden underneath the foil.

Figure 1. One embodiment of the substrateless process for manufacture of electronic assemblies.

Background

Thermoplastics are attracting increasing interest for electronics packaging and interconnection as an alternative to thermosets [5]. In addition to the end-of-life advantages outlined above, thermoplastics can provide far shorter cycle times than thermoset processing because no cross-linking reaction is required for solidification. However, direct replacement of epoxy composites with thermoplastic materials for printed circuit boards is problematic because of the high temperatures seen by substrates during soldering. While high temperature thermoplastics are available, they are relatively costly. One way of avoiding soldering is to use an electrically conductive adhesive (ECA) for the electrical joint. For example Wickham et al. [6] investigated reliability of electronic assemblies using ECAs with a polyetherimide (PEI) substrate.

The use of plant based materials as alternatives to thermosets for circuit boards have also been investigated, for example lignin based resins [7]. These can be biodegraded with fungi, and feeding the biodegraded material back into the environment produces a closed loop system.

Where thermoplastics have been extensively used historically in electronic products is for the housing. The insertion of the electronic assembly into the housing represents a significant part of the manufacturing costs. Largely this has been achieved by locating the PCB within the housing using mechanical fixings to support the device and to seal the casing. In addition to providing aesthetic qualities (e.g. a mobile phone case), the casing must protect the electronics from moisture, vibration and impact. In the area of automotive devices, where harsh operating environments are experienced, this requirement of the packaging has become increasingly critical, such that it is quite common to encapsulate the electronics with a thermoset to provide protection during its service life. Recent research projects have utilised thermoplastics and injection moulding processes to allow the integration of electronics within thermoplastic components [8] and to increase the throughput and recyclability of such assemblies [9].

Use of a carrier film is also a central feature of the Occam process currently in development [10], in which the main advantage claimed is avoidance of the need to solder. The major differences to the substrateless process presented here are that the components are encapsulated with a thermoset and access to component metallisations is achieved by selective removal of the carrier film, for example by laser drilling, followed by interconnection by plating. The element of separation at end-of-life is not one of the advantages envisaged.

One area of electronics manufacture which has already seen extensive use of thermoplastics as the circuit substrate are moulded interconnect devices (MIDs) [11]. These are 3-dimensional circuit carriers formed by injection moulding and subsequent selective plating, and have a number of limitations including the inability to produce multilayered circuitry or use embedded components. In addition, high temperature resins must

generally be used to form the substrates, as components are attached using solder or conductive adhesives that require elevated temperatures for reflow or cure.

Development Challenges

In order to implement the technology successfully a number of core development challenges can be identified. Suitable materials for the carrier film and the adhesive system are required. The film must be temperature stable enough to withstand the temperatures seen during injection moulding. However, as the film is in contact with the mould this may be much lower than the temperature of the polymer melt. The adhesive system must hold the components firmly during injection moulding so that they are not displaced by the highly viscous melt flow, but allow the film to be easily removed from the moulding on solidification. Ideally the adhesive will not contaminate the contact surfaces of the electronic components, but this may not be critical as it is anticipated that a polish and desmear step may be applied after moulding. The polymer melt should wet the components and contact surfaces well. This is particularly important for fine pitch leaded IC components to ensure that electrical contact can be made to them. Finally suitable circuit patterning techniques are required that provide strong bonding to the moulding surface and reliable electrical connection to the component metallisations.

Injection Moulding Trials

Trials were carried out to scope these issues and provide proof-of-principle for the substrateless process. Initial proof-of-principle trials were carried out on a low pressure (0.5 MPa maximum injection pressure) injection moulding machine so that the injection mould tools could be made from a rapid prototyping resin. This meant the cavity design could easily be changed if necessary. However, it was found that a simple plaque 4 mm in thickness with an end gate was adequate. A simple flasher circuit was implemented, comprising a surface mount LED, chip resistors and capacitors, a surface mount transistor and a SO8 package IC (8 pins, j-leads, 1.27 mm pitch). A conventional phototool was produced for the circuit and the pattern transferred onto the surface of the mould tool cavity to aid in aligning the components. The transparent release film was placed in the cavity over the pattern and the components were assembled by hand as shown in Figure 2.

Two adhesives were required as shown in Figure 3. Adhesive 1 held the carrier film in the mould tool cavity, while adhesive 2 held the components. Kapton (polyimide) high temperature adhesive tape rated for use in a solder reflow oven was chosen as the carrier film. Initially the adhesive layer on the film was used as adhesive 2 to secure the components, while adhesive 1 holding the tape to the mould was a spray adhesive (3M Spraymount repositionable). The adhesive layer on the film was partially successful in holding components during injection, but the higher form factor capacitors were swept away.

Figure 2. Components assembled onto Kapton tape carrier film in a rapid prototyped mould tool.

Figure 3. Arrangement of carrier film and adhesives.

Figure 4. Electronic components overmoulded in ABS. The oval features surrounding some of the chip components are the SMT adhesive.

Subsequently an SMT adhesive was used as adhesive 2 to secure the components, while the Kapton tape was held to the mould by its own adhesive. The SMT adhesive is usually used for holding SMT components to a PCB during reflow, and required a curing step of 150°C for 10 minutes before moulding. This arrangement successfully held components in place during injection for a number of mouldings and the carrier film could be removed from the moulding leaving the components in place. An example is shown in Figure 4. As can be seen the SMT adhesive was left exposed on the underside of the components which plated poorly in the metallisation trials described below. Mouldings were successfully manufactured in ABS, a 30% glass filled liquid crystal polymer (LCP) and in a biodegradable polymer.

Following the proof-of-principle mouldings a second set of mouldings was produced on a production grade injection moulding machine (Boy15S, maximum clamp force 15 tonnes). The purpose of these trials was to investigate choice and performance of release film and adhesives in a manufacturing environment.

It was desired to use a pressure sensitive adhesive to hold the components rather than the thermoset SMT adhesive in order to avoid having adhesive placement and curing steps as part of the process. Consequently a search for better performing high temperature tapes than the Kapton tape was conducted. Three commercially available tapes were shortlisted for trial due to their high reported adhesion strengths and were tensile tested at room temperature and at elevated temperature. 3M 8902 tape was found to be the best performer.

An aluminium mould tool was manufactured to produce a 4mm thick plaque. An end fan gate was used to encourage a uniform flow front across the width of the cavity. Overmouldings of the flasher circuit components were produced in LDPE because of its low viscosity, using the 3M 8902 tape as release film, the tape's adhesive to secure the components and a heavier duty spray adhesive (Plastikote) to secure the tape to the cavity surface.

The components were found to be present at the surface of the moulding but to have moved from their original positions by around 5 mm in the direction of injection flow. The movement appeared to be largely because of the tape moving bodily within the mould. A different adhesive or method of holding the tape in the mould is therefore required.

Electrical Interconnection

A trial of interconnecting the components embedded in the low pressure injection mouldings was conducted. An electroless copper process was selected as this is widely used within the PCB industry and the infrastructure is therefore well established. The major task in metallising plastics is to choose the correct surface pre-treatment and activation to ensure good adhesion of the electrolessly deposited layer. In general these are specific to the material and even to the injection moulding conditions, so the results presented here using generic treatments are likely to be able to be improved upon by skilled practitioners.

ABS, LCP and the biodegradable polymer were all tested as substrates and found to differ significantly in performance. Around 0.5 µm of electroless copper was plated on all three, however the adhesion was limited. ABS and LCP were found to be the best, enabling uniform coatings to be applied (Figure 5), but often failed the standard adhesion test (application and peel off of an adhesive tape). On the biodegradable material the coating tended to blister and peel off (Figure 6).

Figure 5. Electroless copper plating on IC embedded in ABS moulding. The dark area is poorly plated SMT adhesive residue.

Figure 6. Electroless copper plating on leg of IC embedded in biodegradable polymer moulding.

Figure 7. Etched circuit pattern on ABS moulding, showing connection to the pads of a SMT LED.

Figure 8. Functional component-loaded ABS moulding, interconnected by hand application of a silver ink.

To achieve electrical contact to the circuit components the plating must cross from the polymer surface of the moulding to the metal surfaces of the component. Good wetting of the polymer in the melt phase to the metal surfaces is therefore important. Figures 5 and 6 also

illustrate different degrees of wetting of the polymer to the component legs of the IC. In Figure 5 there is a slight gap between polymer and leg, and evidence of knit lines. In Figure 6 there is a more intimate contact between the surfaces of the polymer and the leg. From this point of view the biodegradable polymer is more likely to allow good electrical contact to be made to the IC if good plating adhesion can be achieved.

An alternative to plating for electrical interconnection is deposition of a conductive ink, for example by screen printing. This method is expected to be less sensitive to small gaps between polymer and component and a printing trial is currently in preparation. A functional circuit shown in Figure 8, has already been produced by hand application of a silver ink to a loaded moulding.

The ABS mouldings were subsequently electroplated to a thickness of around 10 μm , and then patterned using a spray photoresist and etching in ferric chloride. The patterning quality was too poor to produce a working circuit, but electrical connection to the pads of some components was achieved. An example is shown in Figure 7.

Discussion

The preliminary work presented above has illustrated some of the process development issues to be addressed. One is to find or develop an adhesive which is tacky at room temperature, which has sufficient adhesive strength at high temperature to hold components against the shear forces imposed by the melt, and which releases the components and moulding on solidification, i.e.; can be peeled off. Preferably there would be no curing step. A method of securing the carrier tape in the mould tool is also needed. If this is by an adhesive it should have similar properties to the component adhesive, but the release properties are more critical to allow easy removal of the moulding from the mould. An alternative is a clamping mechanism such as a vacuum chuck, which would have the advantage of avoiding contaminating the mould by adhesive residue build-up over time.

If plating is to be used for the electrical interconnection the appropriate conditions to achieve a high quality, high adhesion coating for the moulding material in use must be identified. While considerable expertise in plating plastics already exists, the current application has the complication that both the surface of the moulding and of the components must be plated. An issue for process development of screen printing a conductive ink for interconnection, is sensitivity of print quality to small protrusions of the components from the surface of the moulding which may cause bleed.

As has already been stated intimate contact between moulding and components is required for good quality electrical contacts to the components. It may also be important for reliability of contact and resistance to thermo-mechanical stress. Wetting and adhesion of thermoplastics applied under injection moulding conditions specifically to the materials of electronic components is the subject of a current project at

Loughborough University, but in general wetting and adhesion of thermoplastics applied under injection moulding conditions is not well covered in the literature [12]. Most reported work is on thermosets, which are applied in low viscosity form and at relatively low temperature and pressure. While there is a lot of industrial experience with insert moulding/multi-material injection moulding, usually mechanical interlock is relied on to retain the insert rather than adhesive forces.

Conclusions

An alternative process for the manufacture of electronic circuit assemblies oriented to end-of-life processing has been proposed, in which the electronic components and metal content can be easily separated out from the organic content at end-of-life. No separate printed circuit board is used to interconnect the components, so the process may be termed as “substrateless”. The basis of the method is assembly of electronic components onto a carrier which is subsequently overmoulded with a thermoplastic which could be biodegradable or soluble. Production of the interconnection pattern is the final step in the process.

Proof-of-principle and initial process development trials have been described. Electronic components adhered to a carrier film have been successfully overmoulded with several different thermoplastics in a prototyping and in a manufacturing grade injection moulding machine. Several different release film/adhesive combinations were tried. An epoxy thermoset surface mount adhesive was found to hold the components securely to a polyimide (Kapton) film during injection. Component displacement observed when using a high adhesion polyimide tape is suspected to be due to the film not being secured adequately to the mould tool.

Interconnection patterns were created on some component loaded mouldings using electroless copper plating followed by electrolytic copper plating and patterning by photolithography. Although the quality of the patterns created was generally poor, electrical connection to some component contacts was achieved. A functional demonstration circuit was successfully produced by hand application of a silver ink to a loaded moulding.

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