Manufacturing an environmentally friendly PCB using existing industrial processes and equipment

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Abstract

This paper investigates the possibility of utilising an additive screen printing process with conductive ink and adhesive together with a degradable substrate to identify whether this process offers a viable alternative to current subtractive methods of PCB manufacture. Existing manufacturing equipment and production process were adopted in order to establish the compatibility of a sustainable and environmental friendly PCB with these processes. Experimental trials have shown that by using a stainless steel stencil 150 mm thick in conjunction with an MPM Ultraprint machine with a printing speed of 89 mm/s, a squeegee pressure of 0.97 bar and a downstop of 1.9 mm successful printing of the electrically conductive adhesive was achieved. It was also shown that the substrate was compatible with electronic placement technology and convection oven. Comparisons of the electronic assemblies to an industrial IPC standard illustrated that it is possible to develop a circuit, which is deemed acceptable under this standard. It can be concluded therefore that a screen printed conductive ink pattern, when printed on a degradable substrate can offer a viable alternative to current printed circuit boards and can be manufactured using existing technology and manufacturing processes.

Keywords: PCBs; Screen printing; Conductive inks

1. Introduction

This paper is concerned solely with examining the compatibility of a silver conductive ink tracks and a degradable paperboard substrate with the PCB manufacturing process, the robustness of the substrate itself will be analysed in future work. The initial section of this paper illustrates the extent of the environmental problem associated with the electronics industry and identifies the need to change the status quo.

Due to advances and progress in technology, electrical and electronic equipment rapidly becomes dated and obsolete this is reflected in the volume of waste electrical and electronic equipment (WEEE) being deposited in landfill sites across the European Union (EU). It has been estimated that, prior to EU enlargement, each citizen of the 15 member states generated 23 kg of electrical/electronic waste per annum [1]. While Hansen and Leipprand identified that the quantity of WEEE generated annually increases by a rate of 16%–28% per annum [2]. As printed circuit boards are constituents of most electrical equipment it is natural to assume that large volumes of boards are being disposed of in landfill sites. Indeed a UK government body, envirowise, found that during 2002 over 6500 tonnes of manufactured PCBs from products such as telecoms and computers are discarded each year [3]. This is a substantial quantity of waste entering landfills and the European Commission intends to address this mounting problem through the introduction of the WEEE [4] and restriction on hazardous substances (RoHS) [5] directives. These directives have forced manufacture’s to focus on the environmental impacts of their products and through imposing penalties and by making the use of certain materials, such as lead, illegal the EC hopes to ultimately preserve the environment. The WEEE directive (2002/96/EC), hopes to limit the quantity of electrical and electronic waste entering landfill through the promotion of the three R’s of waste minimisation: reduce, reuse and recycle.
The aim of this research is to use these three R’s to develop a sustainable and environmentally acceptable printed circuit board by screen printing a silver conductive ink onto a degradable substrate. Earlier work, by the authors [6], has shown that it is possible to reproduce PCB tracks of known length and width accurately and interruption free. It has also been established that when certain printing and post-printing techniques are adopted that it is possible to achieve a conductive performance comparable to that of existing copper boards.

However in order to ensure that the developed novel board has actual industry merit it was necessary to ensure that it was compatible with existing manufacturing equipment and processes. To this end and in conjunction with Kostal Ireland it was decided to reproduce an existing copper board using the new technique, to screen print an electrically conductive adhesive to facilitate the surface mounting of components, to use an automatic pick and place machine to mount the components and to cure the board through a reflow oven. The manufactured boards were then analysed under Section 12.2.2 of IPC-A-610 C, acceptability of electronic assemblies [7]. This would establish if the process was practical and indeed viable, the results of this investigation are detailed in this paper.

2. Manufacturing process and equipment

2.1. Manufacturing process overview

The manufacturing process for the development of an environmental printed circuit board is designed as a “drop in” replacement for existing PCB manufacturing methods, and is detailed in Fig. 1.

From this figure it is apparent that the initial step is to reproduce the desired interconnecting pattern by screen printing the pattern onto the specified substrate.

Once the pattern has been created it is then possible to print the electrically conductive adhesive (ECA) with provides both an electrical connection and an adhesive bond between the surface mount component and the interconnecting pattern.

Having printed the ECA the next step is to automatically place the surface mount components; in this case a component placement machine was employed.

The final step of the process is to cure the electrically conductive adhesive, this is achieved by running the printed board through the solder reflow oven at a specific temperature for a designated period of time.

With a brief description of the overall manufacturing process provided, the next section will detail the manufacturing settings necessary to achieve accurate printing and placement both of the conductive ink and surface mount components. It will also outline the physical characteristics of the electrically conductive adhesive and ink.

2.2. Interconnecting pattern

In order to establish if the technique outlined in Section 2.1 offers a real and viable alternative to the subtractive method of PCB manufacture a datum board, consisting of typical track widths and lengths, was used in these experiments, the interconnecting pattern is shown in Fig. 2. This is a standard printed circuit board which is currently in production, by using such a board it will be possible to determine both the performance of the environmentally friendly boards (Fig. 3) but more importantly if the new production technique is compatible with existing equipment and manufacturing methods.

2.3. Screen printing

Screen printing uses a printing screen or stencil which consists of a frame onto which is stretched a fabric mesh with open apertures in the screen forming the design or circuit to be printed. As the ink or coating is forced through the open design (by a squeegee), the interconnecting pattern of the screen is replicated on the substrate [8]. This printing process is illustrated in Fig. 4.
The screen printing process is essentially a simple efficient method of reproducing patterns on a variety of substrates, which include plastics, fabrics, metals and papers. However the key to screen printing reliable electronic circuits depends on monitoring the printing parameters and maintaining specified limits. These limits determine if the print will be successful and indeed which process parameter settings offer the best opportunity to print error free. When screen printing, there are a number of key operating parameters of which screen type (mesh and emulsion thickness) conductive ink properties (viscosity, particle size and solids content) are among the most important.

For screen printing the interconnecting pattern detailed in this paper a conductive ink of 1.62 Pa s viscosity and a solids content of 68±2% was employed together with a steel screen of mesh thickness 200 μm and an emulsion thickness of 18 mm. Previous work by the authors [9] has shown that a snap-off of 1 mm, a squeegee hardness of 70 shore, a pressure 0.41 bar and 0 s standing time results in the best alternative when printing onto the degradable substrate. These operating settings were adopted when reproducing the interconnecting pattern detailed in Fig. 3.

As has been detailed previously in order to bond the components to the interconnecting pattern it is necessary to use an electrically conductive adhesive. This adhesive is also screen printed into position, a stainless steel stencil 150-mm thick with desired laser cut apertures was used in conjunction with an MPM Ultraprint machine (Fig. 5). It was found that a printing speed of 89 mm/s, a squeegee pressure of 0.97 bar and a downstop of 1.9 mm allowed for successful printing of the adhesive. As is typical with the printing of adhesives and solder paste contact printing was used, by this it is meant that the stencil is in direct contact with the substrate during printing and that the snap off height is therefore zero.

With the method of ink and adhesive deposition outlined and explained the following section details the method of automatic component placement.

2.4. Automated placement of surface mount components

Manual placement of surface mount components is operator dependant and as a result is unreliable, inaccurate and uneconomical. For prototyping purposes it is possible to manually mount components however for large-scale production of even the simplest circuits it is impractical, to this end it was necessary to ensure that the environmentally friendly PCB was compatible with automated placement machines. Concerns regarding the flexibility and rigidity of the substrate arose prior to experimentation and as such a number of initial investigations were performed to provide the operating settings, which provided a successful relationship between accuracy of placement and speed of placement.

To ensure maximum accuracy in the placement of components a vision system is used to tell how far a component lead is from the corresponding land and to
instruct the machine for the discrepancy. The vision system is a good way to compensate for deviations in land patterns due to poor printing tolerance levels. When using the vision system feeducials or alignment targets should be provided on the boards, the location of the vision alignment targets (a cross) used when mounting the surface components on the developed are shown in Fig. 6.

As is typical two of these feeducials were used to teach the vision system the coordinates of the board and ultimately the position of the lands where the components were to be placed.

Having outlined the method of component placing and the printing techniques used to print both the interconnecting pattern and also the adhesive, the following section outlines the properties of the electrically conductive materials employed in these tests.

2.5. Electrically conductive materials

The electrically conductive ink and the electrically conductive adhesive have similar physical characteristics but perform distinctly different tasks on the printed circuit board.

As has been mentioned previously the purpose of the adhesive in surface mounting is to form both an electrical and physical bond between the surface mount components and the interconnecting pattern. Electrically conductive adhesives are epoxy-based thermosetting resins that are hardened by applying heat. In the case of this adhesive it was found that 6 min at 150°C was sufficient to harden the adhesive.

There are essentially two distinct ingredients to the ECA, an nonconductive epoxy resin which serves as a matrix and then platelets or filler material which provide the conductivity [10]. To ensure that these materials are conductive it is necessary to ensure that the conductive platelets are in contact, if they are not then the electrical signal will be unable to flow through the material.

The role of the conductive ink is to provide the interconnecting pattern along which electrical signals are sent to the various components. The conductive ink is typically a thermoplastic material. Thermoplastics are solid materials that can be dissolved in solvent or heated until they melt and turn liquid. The sole purpose of the solvent in an ink system is to turn the thermoplastic binder into a liquid so that fillers can be added and a viscosity suitable for printing achieved. Once the solvent is evaporated or the thermoplastic is allowed to cool the thermoplastic will turn into a solid once more, however can then be melted or dissolved again, thus binders in solvent-based inks cannot withstand high temperatures or exposure to some solvents once they are applied and dried [11].

The majority of conductive inks and adhesives use silver as the conductive metal filler (Fig. 7). Less expensive but highly conductive metals such as copper work well initially, but the resistance will increase greatly over time. The reason for this is that all metals oxidise when exposed to oxygen in air and moisture, and other oxidising agents. The metal oxide starts to build up on the surface of the metal. In most metals, this surface metal oxide layer is not very conductive however silver and gold generate metal oxide layers that are very conductive.

With a description of the manufacturing process provided, the operating setting of the screen printing machines and also the physical characteristics of the conductive materials detailed, the next section will analyses the data obtained from the industrial tests performed on the environmentally friendly PCB.

3. Analysis of industrial trials

3.1. Importance of defined feeducials

The role of the feeducial of alignment target was outlined in Section 2.3, for successful alignment of board with the stencil when screen printing the electrically conductive adhesive it is essential that the feeducial is sharp, clearly defined and provides a good contrast with the colour of the board material. Figs. 8 and 9 show the differences between a successfully printed and a poorly printed feeducial.

From the industrial trials undertaken in this research it can be stated that using paperboard with a black background enabled the vision system to clearly identify the feeducial, as the contrast between silver and black was
greater than with other colours. Indeed of the 198 circuits printed successfully 72% were printed on the black paperboard, 4% on green and the remaining 24% were printed on blue coloured paperboard.

The definition of the feducial is critical also, when the feducial is printed incorrectly i.e. with smudged edges or bridging other tracks it is impossible for the vision alignment system to locate the feducial and therefore to position the board correctly. The result in this case is a board, which cannot be printed; of the 33 boards printed 5 were incompatible with the screen printing machine. The cause of these failures is in the initial laying of conductive ink onto the substrate and there are many potential failure modes. If the squeegee is not clean and in contact with the substrate at a 45° angle then the flow of ink across the screen can be interrupted leaving a greater deposition of ink in one area in relation to another causing spreading or bridging of the feducials. A second cause of ill-defined feducials can be the substrate itself, this process of laying the interconnecting pattern involved the overprinting of conductive ink to improve conductivity. However if the substrate is bowed or twisted then it is impossible to accurately ensure that the substrate returns to precisely the same position for the second overprint. This will result in an inaccurate position of the second layer of conductive ink, smudging the original layer and making the outline of the feducials hazy and difficult to identify.

The solution to the problem of hazy feducials is uncomplicated; the substrate should be clamped into position and should not be bowed or flexed in anyway. The screen should be cleaned after 15 prints, after this time it was found that the apertures of the screen become blocked and also the conductive ink had migrated across the bottom of the surface of the screen. The squeegee should also be cleaned at this stage and checked for signs of wear.

In general, it can be stated that when using a black paperboard substrate and by following the screen printing set-up details outlined above it is possible to accurately print a layer of electrically conductive adhesive in the position required using existing industrial equipment.

Having shown that it is possible to print a layer of ECA the next section will outline the acceptability or not of the circuits developed by analysing the assemblies using Section 12.2.2 of the IPC-A-610C industrial standard [7].

3.2. Examining the manufactured boards under IPC classifications

When analysing data or circuits based on the IPC-A-610 C standard it is important to note that there are three classifications of electrical product. Class 1 is concerned with general electrical products where cosmetic imperfections are not important and the major requirement is the function of the electronic circuit and it is into this classification that the assembly being examined falls.

Section 12.2.2 of the standard deals with surface mount assemblies and for the purposes of this analysis as the surface mounted components are rectangular components it was decided to restrict the examination of the circuits to this section of the standard.

Section 12.2.2.1 examines the components for side overhang where the target is no side overhang of the component (Fig. 10). While it is desirable that an automatic placement machine would facilitate no side overhang, there is provision in the standard for an industrial environment margin of error. For a class 1 electronic device a side overhang (A) less than or equal to 50% of the width of the component (W) or 50% of the land (P) whichever is less is defined as acceptable. See Fig. 11.

When the developed circuits were examined it was found that 4.81% (10 of 208) of the circuits failed this inspection (Fig. 12). From this figure it can be seen that >50% of the component is overhanging the land. If the assemblies are inspected under end overhang criteria of the standard (Section 12.2.2.2) it was found that 0.96% (2 of 208) circuits were deemed defective. It can be stated that 95.19% of circuits printed and placed resulted in acceptable class 1 electrical circuits, thus the manufacturing process offers real potential (Fig. 14).
The inaccurate placement of components is primarily due to inaccurate and poorly defined fucedials. When the placement machine is unable to distinguish the position of the fudicial it is therefore unable to verify the correct position of the board and thus the placement of the components can be skewed, Figs. 13 and 14.

With the examination of the assemblies for side and end overhang complete the next analysis is concerned with Section 12.2.2.3 of the IPC standard [7]. Here the rectangular components are inspected for end of joint width, where the target is a joint width equal to the width of the component (Fig. 15) while an acceptable tolerance for class 1 electronic assemblies is a end joint width (C) which is a minimum 50% of the width of the component (Fig. 16). When the assemblies are inspected for the end of joint width it was found that 3.37% (7/208) circuits printed were deemed defective.

Section 12.2.2.4 of the IPC standard is concerned with the side joint length where the target is a side joint that equals the length of the component termination. Inspection of the assemblies found that all, 100% of the assemblies were compliant with this inspection. Section 12.2.2.5 of the IPC standard is concerned with the maximum fillet height where it is acceptable that the adhesive may overhang the top of the end cap metalisation of the component but not extend onto the body and again it was found that 100% of the assemblies were compliant.

Section 12.2.2.6 is concerned with the minimum fillet height of the where for a class 1 product when a properly wetted fillet is evident it is deemed acceptable, it was found that on visual inspection all the circuits had a properly formed fillet between the component and the interconnecting pattern. This ensures that the assemblies also are deemed acceptable under section 12.2.2.7 of the standard, which is concerned with adhesive thickness.

The above section has examined electronic assemblies developed using a conductive ink interconnecting pattern printed on a degradable substrate with components mounted onto the board using electrically conductive adhesives. It has been shown that it is possible to develop
a board using these techniques to an industry standard using existing industrial processes (Fig. 17).

4. Conclusions

This paper has shown that it is possible to develop a printed circuit board using electrically conductive silver ink, a degradable substrate and surface mount components. More importantly it has proved that by using a steel squeegee, a stainless steel stencil 150 mm thick, a squeegee pressure of 0.97 bar and a printing speed of 89 mm/s that it is possible to use existing industrial screen printers to lay a film of electrically conductive adhesive.

It has proven that by adopting the specified operating settings that it is possible to produce a printed circuit board on paper to industrial IPC standards and as such this process offers potential as a viable alternative to existing manufacturing processes.

It has been shown that by using specified target alignment and vision systems that it is possible to use automated component placing equipment to accurately place components onto the environmentally acceptable PCB.

The key role of the fiducial has been demonstrated, it must be clearly defined, accurate and complete to ensure that the screen printer accepts the interconnecting pattern. This is dependant on the initial screen printing parameters, which effect the deposition of the interconnecting pattern.

5. Subsequent work

Having shown that it is possible to successfully integrate the environmentally friendly printed circuit board into an existing production environment subsequent work involved subjecting the manufactured boards to rigorous testing (temperature cycling, humidity, shock and flammability testing) to determine its suitability in everyday application.

A method of recovery of the constituent components within the environmentally friendly PCB was developed and finding from this work have illustrated that it is possible to recover between 47% and 86% of the conductive materials, depending on the recovery method chosen.

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