20

Printing as an Alternative Manufacturing Process for Printed Circuit Boards

Huw J Lewis and Alan Ryan
University of Limerick
Ireland

1. Introduction

The use of printing techniques as a manufacturing process for physical products is well established in the form of 3D rapid prototyping printing systems. Additive methods of manufacturing of this form are being considered as environmentally friendly as less material is wasted and the number of processes needed for the finished product is reduced.

Printed manufacturing is also being established in the electronics industries as conductive inks and electrical conductive adhesives have been developed (Gomatam & Mittal 2008). This has allowed for the creation of printed circuit boards, on various substrates using screen printing methods and developments towards the use of desktop printing for circuit design (Ryan & Lewis 2007). Coupled with this, a range of printing methods can now be used to produce components such as transistors, diodes, sensors and RFID tags, and batteries (www.plasticelectronics.org 2009).

Mass printing processes fall into approximately 6 main types (Table 1), with the properties of each analysed in Table 2. All of the processes excluding inkjet printing require some form of stencil or impression plate on which the required pattern is formed. Ink is either forced through the stencil in the case of screen printing, or is held within the impression plate for other processes. The ink is deposited onto the substrate surface when the impression plate and substrate come into contact. The means of inking the plates vary depending on the process.

Printing systems offer high resolution and speeds, and are thus suited to Mass manufacture. The resolution of the patterns formed depend on the process and the substrate, with roller based systems being able to repeatedly print lines at 50μm, screen printing to approximately 75μm, and pad printing to 10μm. The speed of printing ranges from 50 m/min to 250m/min using the roller based lithography, rotogravure and flexography methods, with screen, pad and inkjet printing up to 75K units an hour on high speed machines.

Printing processes by their very nature apply thin layers of ink/resin onto a substrate (16 microns) (Raghu et al 2008), which can be built up to form the required shape or pattern. This inherently involves the over printing of existing patterns to develop the required thicknesses. Hence two problems occur, the alignment of the substrate for subsequent printing, and the amount of time required to continually over print to get a defined thickness. For rapid prototype systems, the alignment is held by keeping the component in one position, hence fixing the datum, and applying a single type of ink/resin which is usually cured by ultra violet light. This tends to be an accurate but slow process utilizing ink jet type technology, and is utilized for physical components.

Alignment of substrates isn't as critical if a single print pass is used. This is the norm for printed products such as newspapers, wall papers, cloth etc. The printing process is a high speed production system, thus a single print is desirable rather than a series of runs building up the ink thickness. To this end the range of product that can be developed using the printing process is limited. However, as has been mentioned this type of process is ideal for the electronics industry.

Screen printing has long been used to print solder paste onto circuit boards, thus it is an obvious step to develop a screen printing process that will also print the interconnecting track of the circuit thus removing an etching process. This Chapter will describe the methods of utilizing a screen printing processes to develop a printed circuit board using a degradable substrate and screen printing process.

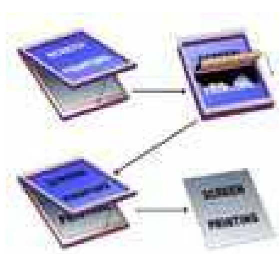
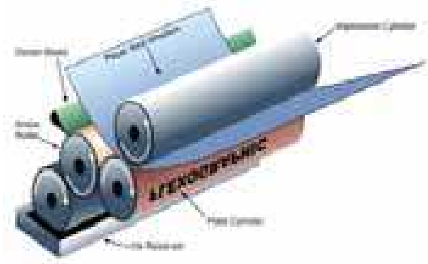
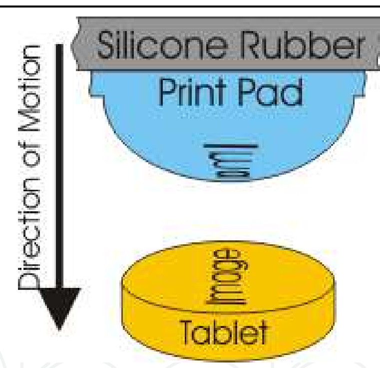
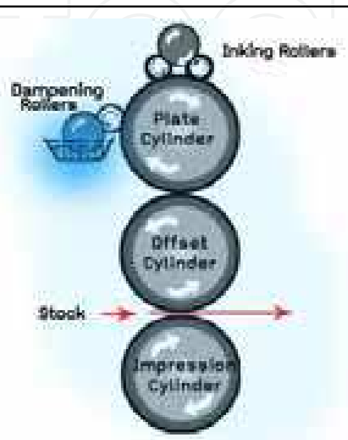
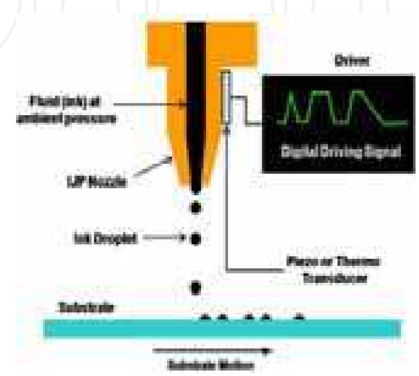
Type	Schematic	Type	Schematic
Screen Printing		**Flexography**	
Rotogravure		**Pad Printing**	
Offset Lithography		**Inkjet**	

Table 1. Common Printing Methods

2. Printed circuit boards

The first printed circuit was designed and developed by an Austrian engineer Paul Eisler, as part of a radio set in 1936. His invention consisted of rectangular sections of thin copper supported on a dielectric substrate. These were used as a direct replacement for the discrete wiring or point-to-point construction, which was the popular method of developing an electrical circuit at this time.
The printed circuit board consists of 3 basic elements

- The substrate containing the electrical interconnecting tracks
- The components
- The medium (traditionally solder) for attaching the components to the track.

2.1 Substrate

A modern PCB consists of a copper coated epoxy glass laminate substrate (Herbert 1965), which provides both the physical structure for mounting electrical components and the electrical interconnection between these components (DRI-WEFA 2001), (Figure 1). Thus the laminates must have considerable strength.

0= High 5=Low	Screen Printing	Offset Lithography	Flexo-graphy	Roto-gravure	Pad Printing	Inkjet
Speed	2	4	3	5	2	1
Resolution	1	4	3	5	2	2
Film Thickness	5	2	2	2	2	1
Viscosity	2-5	5	2	2	2	1
Substrate Flexibility	5	2	3	2	4	5
Pressure	4	1	3	2	3	4
Ink volume required	4	3	3	1	4	5
Initial Waste	5	1	3	2	4	5
Image Carrier Cost	3	4	2	1	4	5
Hardware Cost	4	3	3	1	4	5

Table 2. Summary of the Parameters of Printing Processes (Adapted from Jewell & Bould 2008))

2.1.1 Production of a rigid substrate for a PCB

Currently a printed circuit Board (Figure 1) consists of a substrate (epoxy resin) populated by various numbers of components which are attached to the interconnecting pattern on the board using solder. Within the PCB family there are typically 3 types (Figure 2): the first being single sided boards where components are attached to one side of the board only. The single sided is commonly used for commercial and military circuitry and offers the lowest cost and simplest processing, (Gilleo 1992). When circuit density demands exhaust the routing limits of a single sided circuit, a double-sided circuit is the next full level of density increase where conductor layers are placed on both sides of the substrate. Circuit patterns are then formed on each conductive layer, (Gilleo 1992). The third family member is a multilayered board, which consists of alternating layers of conducting foil and insulation. In all three structures, the insulation layers are constructed of multiple laminates of epoxy-glass sheets bonded together to form a strong and rigid structure. Multilayered boards are used for complex circuit assemblies in which a large number of components must be interconnected with many track routings, thus requiring more conducting paths than can be accommodated in one or two copper layers. (Groover 2006)

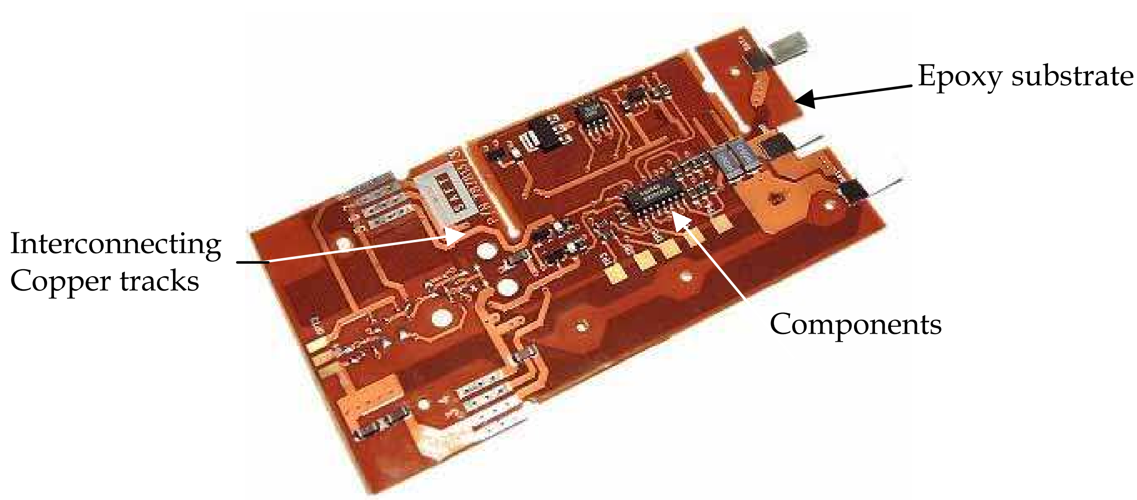


Fig. 1. Populated Printed Circuit Board

Circuit fabrication involves a number of various stages from initial preparation, to hole drilling, through to circuit imaging and etching and finally the mounting of components, this process in its entirety can be termed circuitisation. Three methods of circuitisation can be used to determine which regions of the board will be covered in copper and ultimately result in the completed interconnecting pattern, these are the subtractive method, the additive method and a semi-additive method. In the subtractive method proportions of the copper cladding of the starting board are etched away from the surface, so that the desired interconnecting pattern remains, it is called subtractive, as copper is removed from the board. The additive method uses electrolysis plating techniques to deposit the interconnecting pattern on the unclad starting board, while the semi-additive uses a combination of the two techniques where the starting board has an initial thin deposition of copper on the surface of the board (Groover 2006). The typical method of circuit fabrication is the subtractive method of manufacture where plated copper is etched from the substrate to leave the desired interconnecting pattern. In the subtractive method a photosensitive material is applied to both sides of the laminate. Once this is allowed to dry, the board is exposed to light through a transparent photographic plate, (known as artwork), which carries the desired interconnection pattern, this turns the photosensitive solution opaque where the copper is to remain and is transparent where the copper is to be etched away. The laminate is then exposed to a chemical resistant solution, which clings to the opaque areas of the laminate, thus protecting the copper from the etching solution.

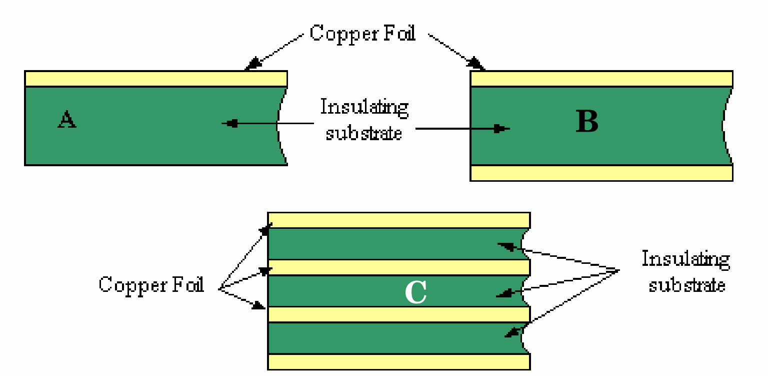


Fig. 2. Three types of PCB structure, (a) Single-sided, (b) Double sided and (c) Multilayer

The laminate is then placed into the etching solution and all exposed copper is removed leaving only the desired conductive tracks, the plating in the holes and the lands around the holes (Pardee & Pennino 1988). Once the interconnecting pattern has been created the next phase is to mount and connect the electrical components and thereby assemble the finished board.
Small light components may be attached to the board on the surface (surface mounted) (Figure 3) while larger components can be mounted using predrilled holes in the substrate, (through hole) (Figure 4).

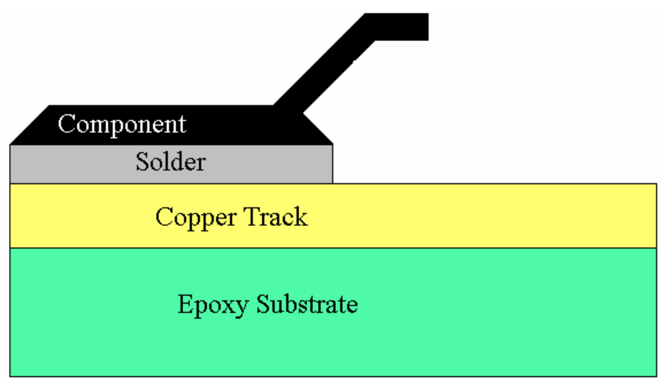


Fig. 3. Surface Mounted Component

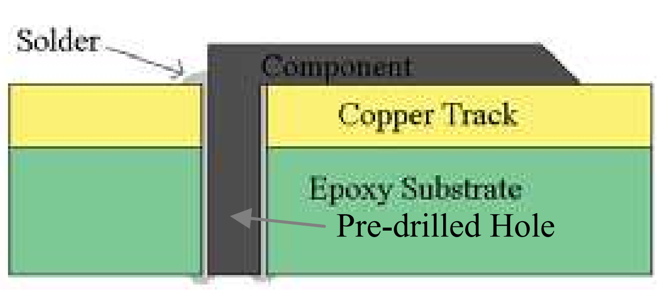


Fig. 4. Through Hole Component

Surface mount technology (SMT) (Figure 3) makes it possible to produce reliable assemblies at reduced weight, volume and cost. The surface mount components are placed on the circuit after a deposition of adhesive or solder paste on to the substrate. Accuracy requirements mandate the use of automated machines for placing surface mount components on the board as 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 (Prasad 1997). On attachment of the components the assembled boards are passed through a reflow oven for permanent connection.

From Figure 4 it can be seen that in through hole technology the leads of components are inserted into pre-drilled holes in the PCB. A single board may be populated with hundreds of separate through hole components all of which need to be inserted into the board. This is accomplished, for the most part, through the use of automatic insertion machines, while a small proportion are completed by hand for non-standard components that cannot be accommodated by the machines. The boards are then passed through a wave flow solder process, which connects the components to the tracks.

When examining a current circuit board and the manufacturing processes involved from an Ecodesign perspective a number of potential problems are discovered. During the manufacturing process, there are a number of effluent emissions (Table 3) generated by the subtractive process, these include the unwanted copper etched from the laminate, sulphates and acids included in the etching and protective solutions and polymer strains from the laminate. These potential effluents if exposed to the environment would result in contamination.

Organic solvents	Tin
Vinyl polymers	Lead
Stannic oxide	Palladium
Copper	Gold
Nickel	Cyanides
Iron	Sulphates
Chromium	Acids

Table 3. Effluents from PCB manufacture (World Bank 1998)

Sulphuric	Ammonia
Hydrochloric	Organic solvent vapours
Phosphoric	Isopropanol
Nitric	Acetone
Acetic	Petroleum distillates
Chlorine	Ozone-depleting substances

Table 4. Potential Air Emissions in PCB Manufacture (World Bank 1998)

A second item to be considered is the air emissions associated with the manufacturing process (Table 4). These potential air emissions have to be carefully considered by the designer, when selecting products and manufacturing processes.

As Holt explains (Holt 1994),

"Electronics designers can have a major impact on how natural resources are used and consumed through the selection of the correct materials and through the establishment of an eco-friendly design plan."

Thus in developing environmentally acceptable PCBs it is necessary to eliminate as many of these potentially damaging areas as possible while still maintaining the integrity of the final product.

2.1.2 Proposed PCB manufacturing process

The proposed alternative method of producing a PCB with environmental considerations involves using a sustainable degradable fibre based (paper) substrate to replace the existing thermoplastic epoxy substrate. This substrate will be used in conjunction with commercially available conductive materials (inks and adhesives) to generate a comparative PCB, which will be tested to current industrial specifications in order to determine if the developed board is a viable alternative.

Table 5 outlines the differences between the proposed environmentally conscious board and the existing subtractively manufactured board. From this table it can be seen that there are essentially 3 changes in the process, the substrate, the interconnecting method and the adhesion technique.

The benefits of the proposed system are that there are no effluents from the manufacturing process and the use of a sustainable degradable substrate, will offer the potential for improving the recycling and recovery of the conductive material, substrate and componenets.

Thus the three elements that can be investigated are the substrate/track, the adhesive medium and the components. It is not in the scope of this project to investigate the individual components, only the possibility of their recovery after the end of useful life of the PCB. Therefore this investigation will examine the use of and processes required to utilise conductive materials, in the forms of conductive inks and electrically conductive adhesives on a degradable substrate, as an alternative to current manufacturing methods, utilising a screen printing process in their manufacture.

The developed board will be compared against mass manufactured PCBs and current IPC (Association of connecting electronics industries 1998) and international standards in order to identify if the proposed alternative is a credible alternative.

3. Conductive inks and adhesives

The method proposed to replace existing PCB manufacturing processes is to print the desired track pattern, using a screen printing process, and conductive ink, and to attach components with electrically conductive adhesives (ECA). Whilst the function of the track and adhesive is different, the makeup of each is similar in that a conductive medium is added to a fluid (binder) to make it viscose and hence printable, the fluid or binder then "sets" to give a track or bond.

3.1 Conductive material formation

In this context "conductive materials" refer to composites of polymer binders and conductive fillers. This makes these materials different from other interconnecting or joining materials, be they copper tracks or metallurgical solder (Gilleor 1999). They consist of three

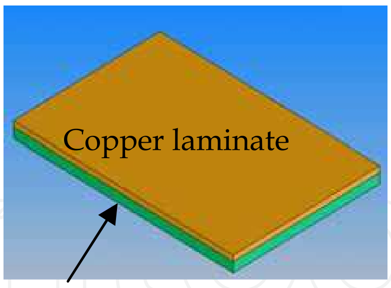
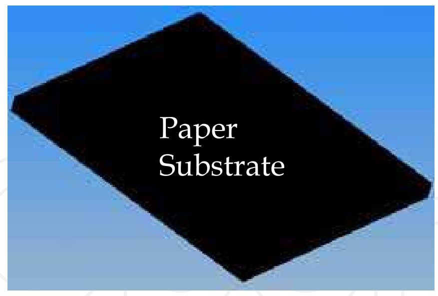
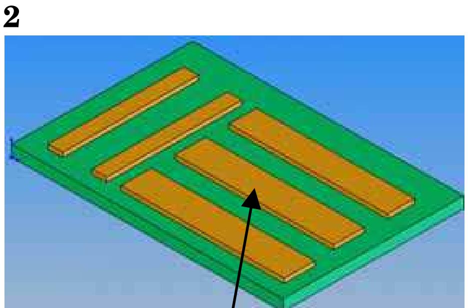
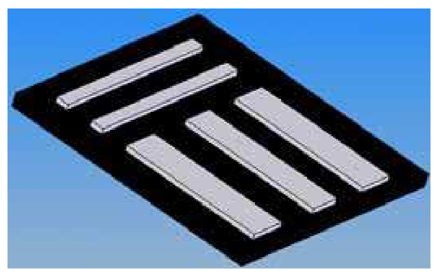
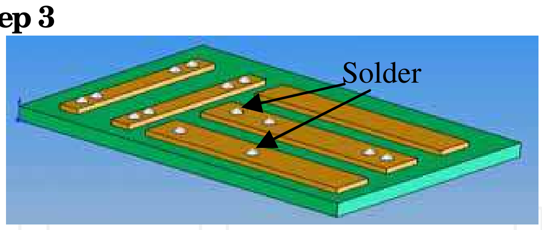
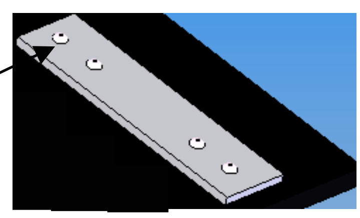
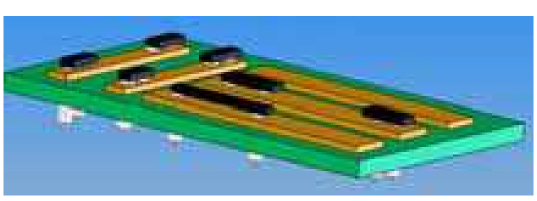
Existing Manufacturing Process	**Proposed Alternative Process**
Step 1  FR 4 Substrate FR 4 Epoxy, thermosetting polymer substrate laminated with copper.	**Step 1**  Fibre based paper substrate. Substrate is sustainable and degradable
Step 2  Interconnecting Pattern Unwanted copper etched away to leave interconnecting pattern, subtractive manufacture.	**Step 2**  Electrically conductive medium added to substrate where required to form the interconnecting pattern, additive manufacture.
Step 3  Solder used as the joint medium between components and interconnecting pattern	**Step 3** Electrically Conductive Adhesive  Electrically conductive adhesive used as the joint medium between components and interconnecting pattern
Step 4  Mass manufacturable populated board	**Step 4**  Mass manufacturable populated board

Table 5. Comparison of Manufacturing Methods

ingredients a binder material, a solvent and an inorganic material with the desired conductive, resistive or insulating properties (Kosloff 1980). The inorganic material is the metal or metal oxide that will make the material act as a conductor, resistor or dielectric (typically silver platelets). The binder material is a glass powder with thermal, mechanical and electrical properties tailored to provide adhesion to the substrate. The solvent contains plasticizers and binding solution, which control the rheological properties of the conductive material during the printing process (Lumpp 2000).

3.1.1 Binding material

In conductive ink, the binder is usually a thermoplastic material. Thermoplastics are solid materials that can be dissolved in solvent or heated until they melt and turn liquid. The solvent in an ink system turns 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 it will turn into a solid once more, however it 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 (Banfield 2001).
Epoxy is the most commonly used material as an ECA binder with silicone being the most unacceptable. The binder material however is only one constituent of the conductive material with the filler material providing the means of electrical conduction.

3.1.2 Filler material

The binder material is an insulator, thus adding a filler material with the desired electrical properties converts this insulating material into a conductor. All commercial conductive adhesives and inks are made with a non-conductive binder that is loaded with fillers that have the desired electrical characteristics. The most common filler materials are silver, aluminium, gold and copper. Each has different properties that determine how suitable the metal is for a particular application. These determining properties include electrical conductivity, aging mechanisms and cost (Wong 2000).
Silver is the most commonly used conductive filler for conductive materials with 80% silver loading being the limit in epoxy adhesives (Gleditch et al 2000). An alternative to silver is carbon, either graphite or carbon black, both of which are electrically conductive and are used in making electronic materials. However carbon-based materials are only used in special applications because of their poor conductivity; up to 3 orders of magnitude lower than for silver. According to Gilleo silver would seem at first a poor choice because of the cost, however, silver is unique among affordable metals due to the high conductivity of its oxide. This means that there is almost no change in conductivity as silver particles oxidise. Copper, which would appear to be the logical choice, produces oxides that become non-conductive after exposure to heat and humidity. Attempts to use copper in inks and adhesives have been under way for many decades. Some of the earliest printed circuit processes used copper powder with adhesive binder. The challenge for copper-based conductive materials is that of inhibiting oxidation under heat and humidity conditions. Copper oxidises so quickly that oxide will form unless chemical inhibitors are present (Gilleo 1999), but non-oxidising metals, such as gold, are cost prohibitive. Indeed, better conduction is achieved with silver than with gold because of the next important filler material attribute, particle formation.
Silver particles are easy to form and to fabricate therefore silver can be manipulated into a wide range of controllable sizes and shapes. The Danish EPA states that, the stability of the

electrical characteristics of conductive materials is dependent on the type and geometry of the metal filler (Danish EPA 2001). There are three different filler geometries, spheres, flakes and needles. The filler material should be of optimum geometry that provides minimum critical filler concentration for low resistance, the best contact between neighbouring metallic particles and the strongest adhesion to the polymer.
Conductive materials result in a higher resistance as compared to pure metals as even though an electron will flow easily through a metal particle, it encounters tremendous resistance when it has to jump from one metal particle to another. Even if the metal particles are pressed together tightly, the resistance to cross the gap between the particles is high compared to the resistance within the metal particles themselves. Given the fact that electrons must travel across thousands of the particle-to-particle gaps in a metal-filled ink or adhesive, it is easy to see why the resistance is greater than the resistance of a solid metal. (Banfield 2001)
Earlier versions of silver inks and adhesives used metal spheres as the conductive filler. When these spheres touch one another, there is only one small point of contact between the particles (Figure 5A). Filler flakes (Figure 5B), have more contact points and tend to be more conductive than spheres, however, Shimada & Wong claim that mixed filler shows the highest conductivity and offers the best alternative (Shimada & Wong 2000). When the flakes nest together, there is much greater surface contact between particles and more paths available for electrons to move from particle to particle.

Fig. 5A. Spherical formations

Fig. 5B. Flake formations

In general it is best to view conductive materials as a complex composite where filler, binder and additives can be selected to provide formulations having a wide range of useful properties. When examining conductive materials made from conductive particles suspended in a binding solution it is important to note that there are two distinct types, isotropic conductive materials and anisotropic conductive materials, where each distinct type has an alternative method of conducting the electrical signal through the material.

3.1 Conduction within electrical conductive materials

3.1.1 Isotropic conductive materials

These are conductive materials that conduct in all directions, isotropic conductive adhesives are currently in use in the electronic industry, primarily as die-attach adhesives (Wong 2000), whilst isotropic conductive inks are used to form the conductive layers in RFID tags, (Cuming 2006). They can be classified as non-filled or filled materials depending on how the polymer is made conductive.

3.2.1.1 Non filled conductive materials

Non-filled materials are polymers that are either inherently electrically conductive or doped and are known as intrinsically conductive polymers (ICP). Doping is the process of adding a small percentage of foreign atoms to a regular crystal lattice for the development of new properties. They are mainly polymerised compounds that derive their electrical properties from their molecular structure (Wong 2000). The most common polymers are based on polyacetylene, polyaniline and polypyrole. Gilleo (Gilleo 1999) claims that a few of these materials have been commercialised for end application such as battery electrodes and that doped polyacetylene has been found to achieve a conductivity of nearly 70% that of copper. However, he also explains that conductive polymers are extremely brittle and sensitive to oxidation and thus are not suitable to act as a replacement to solder as an adhesive technique, thus there will not be perused as part of this investigation.

3.2.1.2 Filled isotropic conductive materials

These conductive materials consist of approximately 60-80% metallic properties in a polymer/epoxy binding solution. When the material is cured the particles are distributed and a conductive polymer network is formed. By this network electrons flow across particle contact points by direct metallic contact making the mixture electrically conductive, (Figure 6). Due to the nature of the network formed, i.e. no fixed structure, the current is able to flow through the material in all directions (Wong 2000). Applications of the isotropic adhesives include the attachment of dies to lead-frames and the attachment of surface mount components to flexible circuits and ceramics (Chang 1993).

Conductive Flake Contact

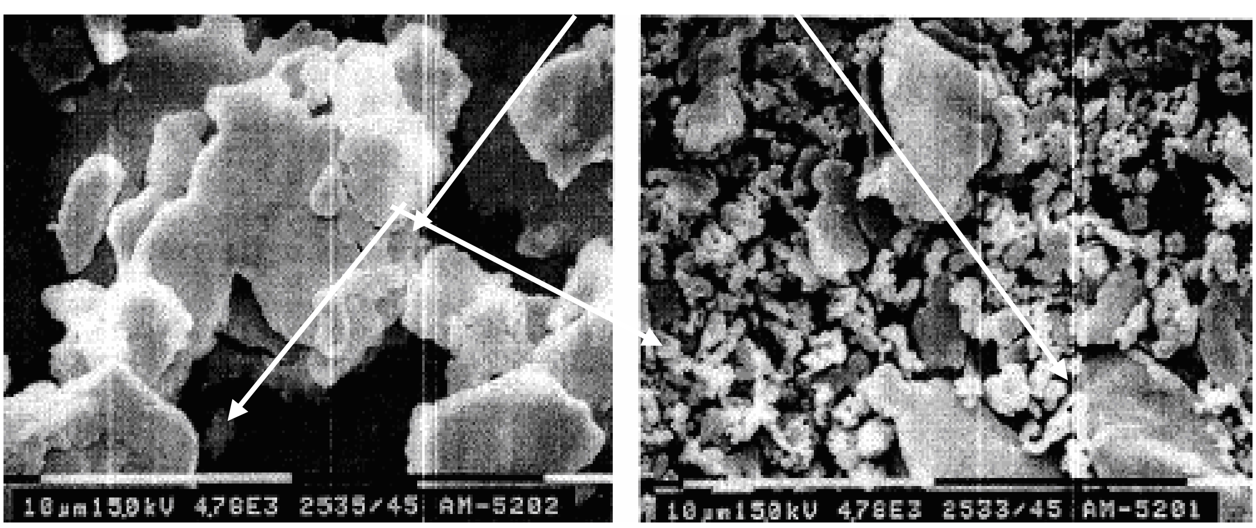


Fig. 6. SEM Micrographs illustrating contact between silver flakes

The second type of conductive material is the anisotropic conductive material.

3.2.2 Anisotropic conductive materials

Anisotropic materials provide unidirectional electrical conductivity in the vertical direction, This directional conductivity is achieved by using relatively low volume loading of the conductive filler well below the percolation threshold (Basteki 1999).

Anisotropic material, in particular adhesives, have been used for a number of years in attaching chips to package lead frames. The advantage offered by this method of connection are high density interconnects, a low temperature process and low cost. More recently, ACAs have been used to connect flip chips to other substrate materials, with varying degrees of success (Li et al 1993). The main driver towards the use of ACA materials in the area of SMT is the prospect of achieving extremely fine pitch connections at a low cost. However a disadvantage is that pressure and heat must be supplied simultaneously while the polymer matrix is hardened, otherwise the conductive pathway is lost.
With the two families of conductive material outlined it is necessary to explain how these families are formed.
Plastic polymer binders have a high resistance, if a small amount of highly conductive metal filler (silver) is added to the binder, the resistance will not change, since the metal particles will have large gaps between them. As filler is added to the binder, the resistance will remain high until a point is reached where the metal particles start to contact one another (Banfield 2001). Thus what is termed "the percolation threshold" or "point" has been reached. This is when a sufficient amount of filler has been loaded into the polymer to transform the composite from an insulator to a conductor (Morris 1999). Thus percolation theory predicts a critical filler concentration at which a three dimensional network is established and conductivity increases suddenly by several orders. Thereafter, conductivity changes slowly with increase in filer concentration.
This is illustrated in Figure 7 .

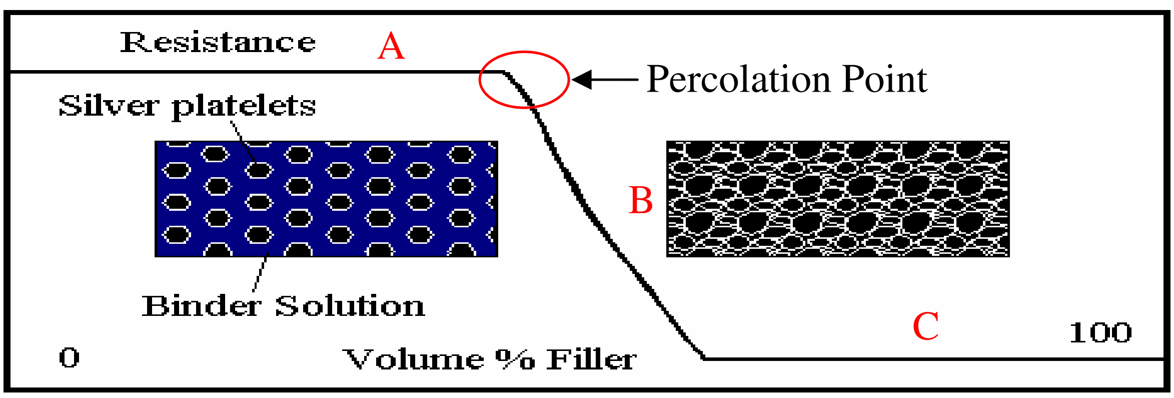


Fig. 7. Illustration of percolation theory (Gleditch etal 2000)

After the percolation point, adding a small amount of metal filler will produce a rapid drop in the resistivity of the conductive material. From Figure 7, Point A represents an area with large volume of binding polymer in relation to the quantity of conductive metal flakes. The resistance at Point A is quite high as there is a low percentage of filler material thus preventing inter-particle contact and resulting in an anisotropic conductive material being created. However as the loading of conductive material increases the resistance falls thus creating greater inter-particle contact and forming an isotropic conductive material, Point B (Banfield 2001).If metal filler continues to be added, a point is reached (Point C) where the resistivity levels off, and increased loading of metal filler will not improve the conductivity of the material. In fact, higher loadings of filler beyond this point will start to degrade the adhesion and scuff resistance properties of the material and can actually start to increase the resistance of the material as the conductive particles are not able to nest together efficiently (Banfield 2001). It is thus feasible that the conductive inks/adhesives could be used to develop the conductive track and component bonding method for a PCB, once printed on a suitable substrate.

3.3 Substrate

The substrate chosen is an important aspect of the total circuit board assembly, since it must hold the components, withstand vibration and shock and other processing in assembling (Kosloff 1980). There are a number of sub-factors of the substrate, which can adversely affect the final print quality these include:

- Substrate cleanliness
- Geometry size
- Surface roughness

Substrate Cleanliness: The cleanliness of the substrate is essential to an accurate print. Dust and dirt on the substrate can cause defects such as bridging ultimately leading to a short circuit in the PCB (Bentzen 2000). It is important therefore that the substrate is kept free from contamination and to ensure that the manufacturing environment is clean.

Geometry Size: It is important that the substrate is large enough to receive the interconnecting design but not so big as would make uneconomic sense. This factor is relatively insignificant as the printing parameters for a large substrate will be the same as for a small substrate (providing the same substrate materials are used in both cases).

Substrate Roughness: The surface roughness of the substrate is an important variable within the printing process. It is possible to establish the roughness of the substrate by moving a fine-tipped stylus across the surface in question. The deviations in the substrate surface create interference patterns that are used to calculate the roughness (Sergent 2001).

Once the roughness has been calculated it is possible to generate a profile of the surface roughness, (Figure 8). Here for a given length (L) along the surface of the substrate the variations in roughness are clearly visible. Points a and b represent peaks of surface roughness while points c and d represent valleys.

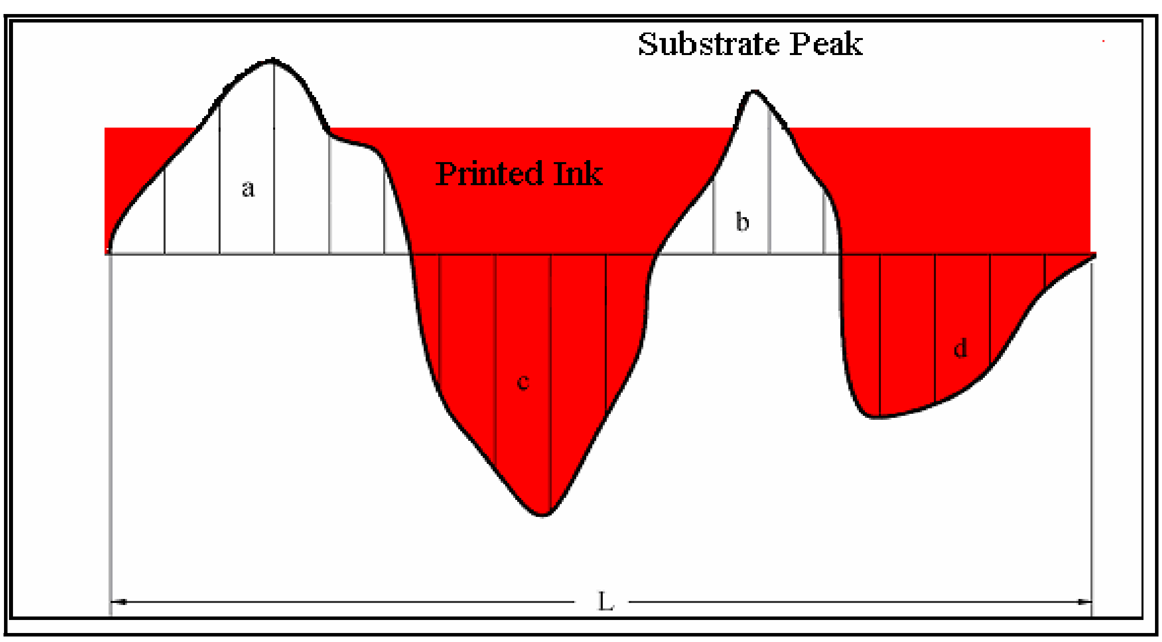


Fig. 8. Example of potential problem of substrate roughness

According to Sergent surface roughness

> "Has a significant impact on the adhesion and performance of thick film and thin film depositions. For adhesion purposes it is desirable to have a reasonably high surface roughness to increase the effective interface area between the film and the substrate. However for repeatability in the print integrity the thickness of the deposited film should be much greater than the variations in the surface" (Sergent 2001).

From the illustration of surface roughness it is apparent that if the substrate used is too rough, peaks in the substrate will interrupt the printed track. Thus selection of a substrate, which is of sufficient roughness, is critical to the final print integrity.

However as Waldvogel stated (Waldvogel 1977),

> "The substrate cannot be too smooth; a certain roughness is required for good adhesion of the conductive screened layers."

Therefore a medium is required where the substrate is sufficiently rough to achieve good ink adhesion to the substrate and not so rough as will result in large discrepancies in the ink thickness printed. In this case a standard paper card was utilised. Having chosen the substrate the method of applying the ink/adhesive needs to be developed. In this case screen printing was used, as it is a current standard in the electronic PCB manufacturing process.

4. Screen printing

Traditional screen-printing can be traced as far back as the 900's, where in China and Japan, artistic patterns were printed using screens made from human hair. Since this era the process has naturally progressed culminating in the system currently used in industry which was designed by Samuel Simon in 1907 (Bellis 2005).

Traditionally the screen printing process was used to print coloured inks onto large posters for advertising, however, in the mid 1960's with the development of conductive inks the electronics industry was quick to adopt and adapt this technology. Initially screen-printing technology was used to form resistors and dielectrics. However, since its introduction, screen-printing has been the dominant method of film deposition within the electronics industry because of the low cost associated with the process (Pan et al 1999).

The use of screen-printing is commonly associated with use in thick-film circuit production. A thick-film circuit is produced by

> "applying inks, pastes or coatings on substrates or bases and firing the printed electronic patterns to change their properties" (Kosloff 1980).

Screen-printing as a printing process is a basic, simple and efficient method of reproducing patterns on a variety of substrates. The process consists of the printing medium i.e. conductive ink being forced through open areas of a mesh-reinforced screen.(Figure 9)

These include:

- The screen chosen
- The squeegee chosen
- The substrate to be used
- The printing process parameters
- The conductive medium

Screen printing plates or printing screens are an essential part of the printing process as these carry the pattern to be printed. A printing screen consists of a frame or support on which a screen, of uniform mesh apertures, is stretched taut while the design or image to be printed is left open in the fabric with the rest of the screen filled in or blocked out (Kosloff 1980). (Figure 10).

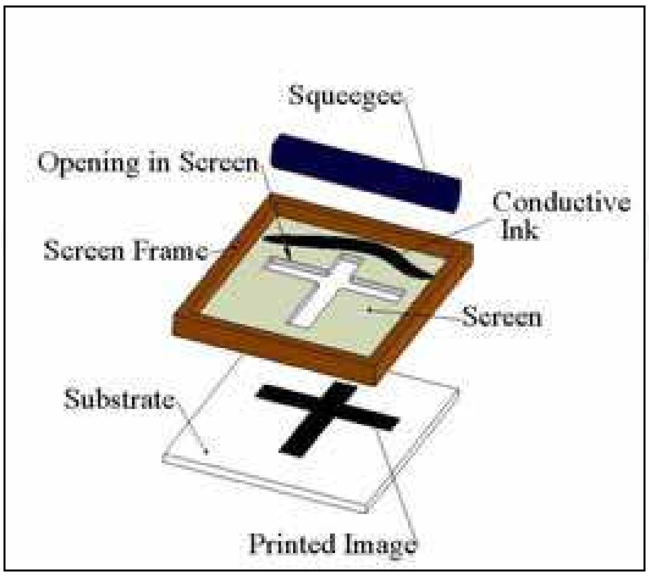


Fig. 9. Screen Printing Diagram Screen

A number of sub factors within the screen, which can influence the final print quality. These sub factors include:

- Screen Mesh Count
- Mesh and emulsion thickness
- Mesh Material.

Mesh Count: The mesh count is the number of openings or apertures in the screen per linear inch. The calculation of the mesh count allows the screen printer to determine the open area percentage of the screen, the greater the open area percentage, the greater the volume of ink printed. However care needs to be taken with this factor as too great an open area can result in print flooding and therefore destroying the final print resolution (Pan et al 1999).

Fig. 10. Screen Printing Screens

Mesh and Emulsion thickness: The mesh thickness is derived from the thickness of the wire strands within the screen. The greater the diameter of the wire, the thicker and more rigid the screen becomes. The thickness of a metal screen is typically 150 microns, but 100, 125 and 200 microns are widely available. For very fine pitch such as 0.3 mm a 100 or 125-micron screen could be used and for a pitch down to 0.5 mm 150 micron screens can be used. The screen thickness together with the aperture sizes also determines the amount of ink, which will be needed to perform the task (Pan et al 1999).

As the average width or pitch of track to be printed for a PCB is 0.3mm a 125-micron screen is suitable. However Robertson et al (Robertson etal 1999) has shown that modern screen printing techniques can achieve dimensions down to 50 μm track widths and spaces.

4.0.1 Screen vs. Stencil

Either a screen or a stencil can be used to apply the conductive material to the substrate. In general the frames of the screen and stencils are similar; the differences lie in the construction of the individual openings used for depositing the printing medium.

A screen will contain open wire mesh around which the conductive material must flow to reach the substrate surface, a stencil aperture is fully etched and therefore does not obstruct the flow of the conductive material (Prasad 1997).

In this case a steel wire mesh screen was used to apply the initial interconnecting layer of conductive ink while a steel stencil was used to apply the conductive adhesive, which is used to secure the surface, mount components onto the substrate.

When printing conductive adhesives the choice of stencil and squeegee is pertinent to a good adhesive joint, researchers recommend metal stencils with apertures 80% of the pad size (Ryszard &Andrzej 2000). The thickness of the stencil should be smaller for adhesives than for solder as a thinner joint is favourable, however it is recommended that conductive adhesives should have a thicker printed deposition than solder as they are less electrically conductive (Terstagge 2003). The viscosity of the adhesives is typically lower than that of the solder paste, (between 55,000 cps and 70,000 cps for the adhesive compared to 500,000 cps for the solder paste) thus less is required as the adhesive will slump easily and cause bridging (Lui & Lundstorm1999). A typical stencil thickness is 0.10mm to 0.15mm however it is application dependent.

Having examined the role of the screen and stencil in the screen-printing process and outlined the various screen parameters which should be considered before selecting a screen, the following section involved investigating the parameters influencing the choice of squeegee in the printing process.

4.1 Squeegee

Screen-printing squeegees come in varying different designs and are made from different materials.

4.1.1 Squeegee hardness and material

Squeegees are made from either polyurethane or metal, the selection of the squeegee is typically dependant on the material of the screen, which is employed in the printing process.

When using an emulsion screen the squeegee needs to push the conductive medium in front of it and to pump it trough the mesh in the open print areas. This is achieved by using a soft polyurethane squeegee (70-75 shore), which allows it to deform (breakaway) slightly where it contacts the screen. (McPhail,1996).
With a metal screen the squeegee rolls the conductive medium in front of it allowing the conductive medium to flow freely through the apertures of the screen without being pumped. It is neither necessary nor desirable for the squeegee to breakaway so a harder squeegee (80-90) shore or a metal squeegee is used (McPhail,1996).
In general metal squeegees should be used for metal screens as soft polyurethane squeegees used on stainless steel screens will wear out quickly and can result in scooping of material from large apertures. Metal squeegees must have a very smooth and non-sticking surface and at all times a sharp printing edge. This ensures that the ink will roll easily on top of the screen and help prevent clogging of the apertures.
A compromise of squeegee hardness and pressure must be achieved. If there is too little pressure, the conductive medium will escape under the squeegee and smear across the screen. If there is too much pressure or the squeegee is too soft then the squeegee will dip into larger apertures' in the screen and scoop the conductive medium out of them.

4.1.2 Size and shape of squeegee

When examining the squeegee used in screen-printing it important to first note that there are two distinct types of squeegees, a diamond type and a trailing edge type,.
Diamond Pattern: This pattern consists of a square section of polyurethane approximately 10mm by 10mm, which is clamped in a holder at an angle of 45° on both directions. This type of squeegee, allows the printer to print in two directions. However, as the squeegee is rigid and clamped into position it does not facilitate uneven substrates. If the substrate is warped in any way the use of this squeegee will result in incomplete prints (McPhail,1996).
Trailing edge pattern: This type of squeegee consists of a rectangular section of polyurethane supported in a holder. Two are needed, one for each direction of stroke, there is no need to hop over the printing medium as the second squeegee will drag it across once the initial cycle is reversed (McPhail,1996). The size of the squeegee is determined both by the size of the pattern to be printed and the clamp, which fastens the squeegee to the printing machine. Thus the size and shape of the squeegee are pre-set due to the equipment being employed.
Squeegee Angle: The squeegee angle must be between 45 and 60 degrees and the rolling ink should have a diameter of 15 to 20 millimetres for optimum conditions (Kosloff 1980).

4.2 Printing process

The objective when printing the conductive ink onto the PCB substrate is to establish a conductive track along which electrical signals will travel. To reach this objective the ink print must be aligned correctly, the correct amount of ink for each track must be present and the print should form an even layer of ink along the substrate.
The parameters of the equipment to print the circuit have been defined , it is now necessary to investigate the printing process The printing medium, or ink, is applied to the upper surface of the screen and a squeegee is dragged across the pattern area. The movement of the squeegee presses the screen into contact with the substrate surface and forces the ink

through the open meshes of the screen. Behind the squeegee, the screen because of its tension peels away from the substrate leaving a printed pattern of ink on the substrate, Figure 11.

To ensure the integrity of the final print is not compromised the printing process and its parameters need to be monitored and controlled. Control of the print coating is obtained by controlling the variables detailed below:

- Squeegee down stop.
- Squeegee pressure.
- Squeegee attack angle.
- Print speed.
- Print direction.
- Snap-off distance.
- Quantity of Ink before the squeegee.

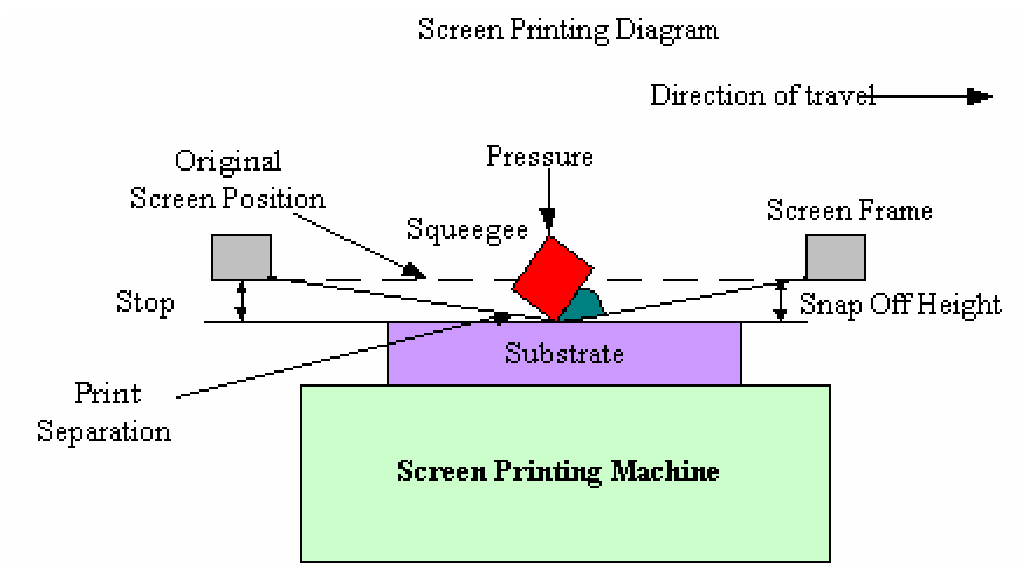


Fig. 11. Screen Printing Process

Squeegee Down Stop: This must be adjusted so as the squeegee only to just touches the screen surface. However, if the squeegee axis and the screen are not parallel it can be necessary to over-adjust the down stop to compensate. If the down stop is adjusted too far down, both screens and squeegees will wear out rapidly (Bentzen 2000).

Squeegee Pressure: The squeegee pressure should be as little as necessary to scrape the screen clean of ink when printing. If adjusted correctly, a thin layer of ink will remain on top of the screen. The printing speed and the screen type determine the amount of pressure required or indeed desired (Bentzen 2000). However if a thicker print is required an increase in the squeegee pressure will facilitate this (Parikh et al 1991).

Printing speed: The supplier of the conductive ink normally provides guidelines on printing speed. The possible printing speed depends on the ink's thixotrophic behaviour. The ink must be fluid when printed but jelly-like and stable once printed onto the PCB substrate. The more fluid the ink is when moved and rolled the higher the print speed can be used. The printing speed must be set so that the ink rolls perfectly on top of the screen. It is a major factor in the printing cycle time, the highest possible speed without compromising the print quality should be chosen (Bentzen 2000). By increasing the printing speed the likelihood of the final ink layer being thinner and patchy increases, therefore it is essential that a printing speed compatible with the chosen ink is employed (Parikh et al 1991).

Snap Off: This is the distance between the screen underside and the top of the substrate. From Figure the snap-off distance, i.e. the distance between the top of the substrate and the bottom of the screen at the start of the run, and the screen deformation can be clearly seen. The snap off distance is constrained by the tension of the screen. If the snap-off distance is too small, ink remains in the screen mesh due to insufficient tension and this results in a thinner print height. Conversely if the distance is too great, excessive squeegee pressure is required to deflect the screen resulting in a thicker pattern but a damaged screen and a worn squeegee (Parikh et al 1991).

Separation Printing: This is the term given to the separation of the screen from the substrate after printing. Figure 11 gives a graphical illustration of this term. It can be seen that during printing the force of the squeegee causes the screen to come into contact with the substrate. After printing, the screen returns to it original position giving rise to the term print separation. The speed of separation between screen and PCB after printing is important. Too rapid a separation speed when printing fine pitch will result in clogging of the screen apertures. Too fast a separation will also result in tailing and form high edges around the ink deposits. The ideal separation speed depends on the ink and the screen aperture wall smoothness. On the other hand a slow separation speed will slow down the printing process When printing electrically conductive adhesives contact printing is preferred to non-contact printing as less adhesive is printed. Contact printing involves the stencil being lowered onto the substrate before printing so that there is no snap-off or separation during printing. The above section has examined the screen-printing process and has illustrated the various process parameters and the numerous of distinct options available within each of the parameters. The following section outlines the process parameters chosen for screen-printing electrically conductive ink on to a degradable substrate. In developing a PCB using a card substrate and conductive inks/adhesives, the parameters indicated above were optimised through a number of empirical tests. This resulted in a number of PCB being developed and tested to an industrial standard.

5. Investigating industrial compatibility

The board is a single sided board and is sufficient to examine the structural, electrical and mechanical properties of the conductive ink, the conductive adhesive, and the interaction between these two and the substrate itself, when exposed to extreme environmental conditions. The test vehicle components are detailed in Table 6 and the component positions are illustrated in Figure13/14. To investigate the industrial compatibility of the proposed additive method of manufacture the initial step is to replicate the etched copper-interconnecting pattern by screen-printing the conductive ink onto the degradable substrate. In developing an additive system for PCB manufacture it must be compatible with existing processes i.e. screen-printing machines, surface placement technology, conveyor convection ovens.

This was investigated using a dedicated production line in a printed circuit board-manufacturing environment. The proposed process, Figure 12, adds an extra step to existing processes, where solder paste is printed to secure components. The test vehicle chosen was a circuit board currently in production.

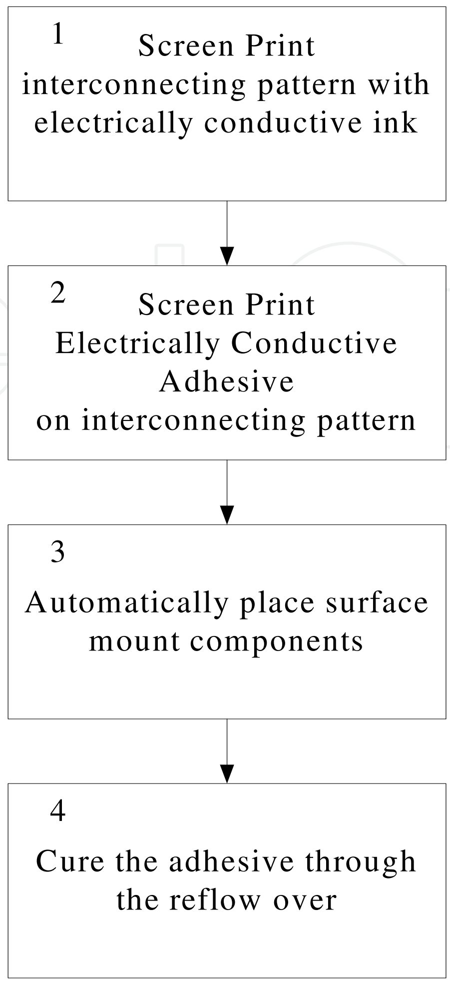


Fig. 12. The Manufacturing Process

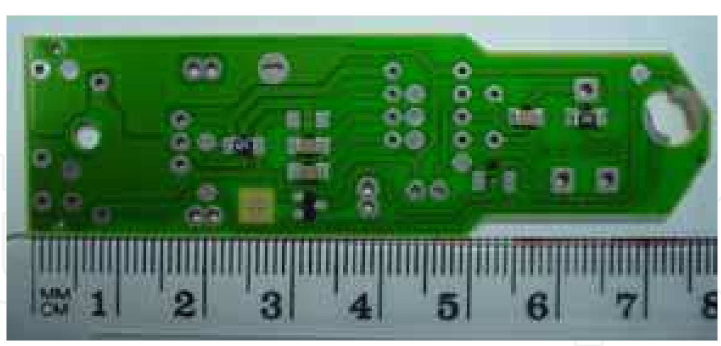


Fig. 13. Test Vehicle, single sided PCB

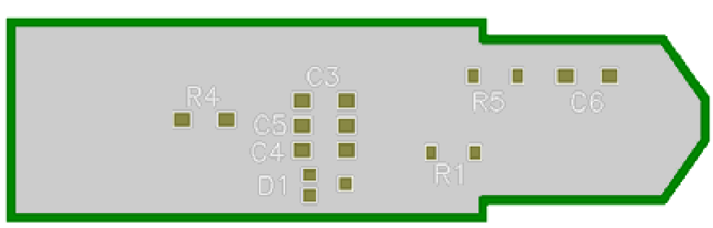


Fig. 14. Component Positioning

Part Identifier	Description
R4	820K ± 5%
C3	47 nF 50V/63V
C5	10 nF 50V/63V
C4	100 nF 50V/63V
D1	BAS 21
R1	150 Ω ± 5%
C6	10 nF 50V/63V
R5	13 kΩ ± 1%

Table 6. Test Vehicle Components

The substrate selected was a rigid paperboard material, with a surface roughness of 1.61 µm, the conductive ink was used Coates conductive ink 26-8204, (Coates data sheet 2000) and ECA: Ablebond 8175.both being off the shelf products. This resulted in 100% accuracy and completion of the printed circuit pattern, Figure 15.

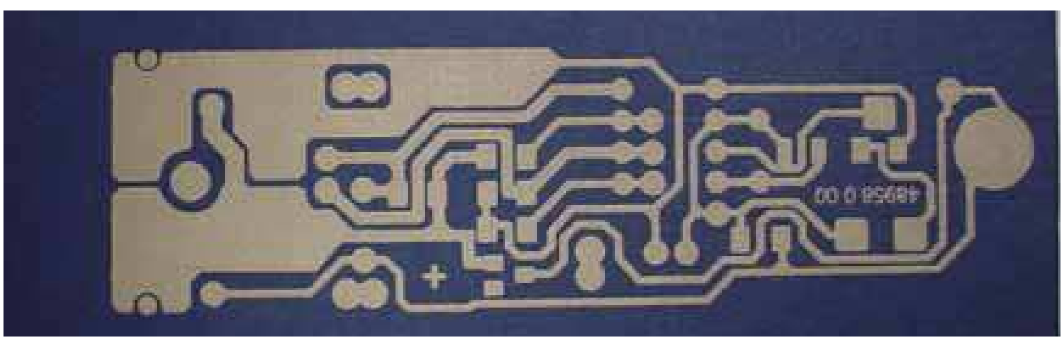


Fig. 15. Successful printing of Conductive ink

To secure the surface mount components a layer of electrically conductive adhesive, Ablebond 8175, was printed onto the interconnecting pattern using the same industrial screen printer, as used for the tracks (Figure 16).The adhesive was printed using a stainless steel stencil 150 µm thick with desired laser cut apertures as suggested by the manufacturers. It was found, through experimentation that a printing speed of 89mm per second, a squeegee pressure of 0.97 bar and a downstop of 1.9mm allowed for successful printing of the adhesive. To ensure that the conductive adhesive and components are deposited correctly, vision systems were employed. These systems use feducials (known reference points) on the board to position the board and stencil when printing the ECA and to ensure the board is correctly positioned during automatic component placement Figure 17. The shape of the feducial is not critical, two differently shaped feducials were used when printing the adhesive and mounting the Component, Figure 18. Once the feducials are located, the board is correctly aligned and printing or placement can begin. It has been shown that the degradable substrate is compatible with the screen-printing equipment, surface placement and conveyor systems encountered in manufacturing environments.
However as is common with the development of new technologies and/or manufacturing processes there are potential problem areas, which can influence the quality of the assembled boards.

Fig. 16. MPM Screen

Fig. 17. Automatic Component Machine

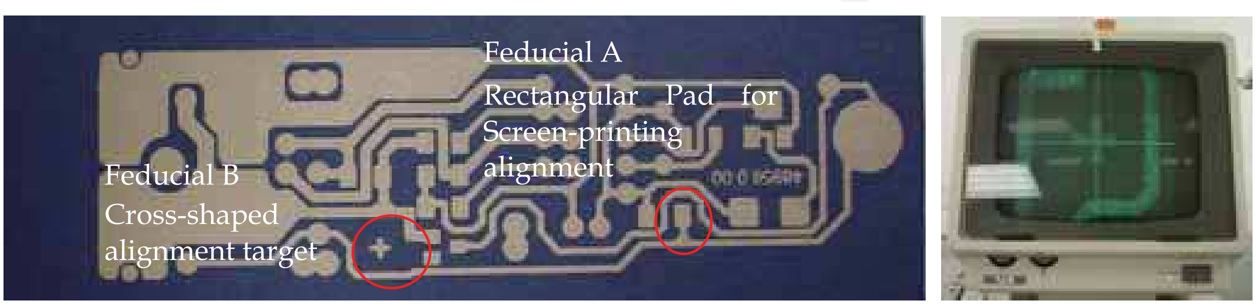


Fig. 18. Feducial used for Vision Alignment

5. Analysis of industrial trials

5.0.1 Importance of defined feducials

For large scale production of even the simplest circuits, automated processes are needed. To accommodate this it is essential that the feducial is sharp, clearly defined and provides a good contrast with the colour of the board material. Figure 20 and Figure 21 show the differences between a successfully printed and a poorly printed feducial. A number of different colour substrates were employed to determine if there was a difference between the number of accurate prints. Experimental investigations established that a black paperboard background enabled the vision system to clearly identify the feducial, as the contrast between silver and black was greater than with other colours. While the contrast of the feducial is important the definition of the feducial is also critical. 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 fed and therefore to position the board correctly, (Figure 22). 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 5 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.

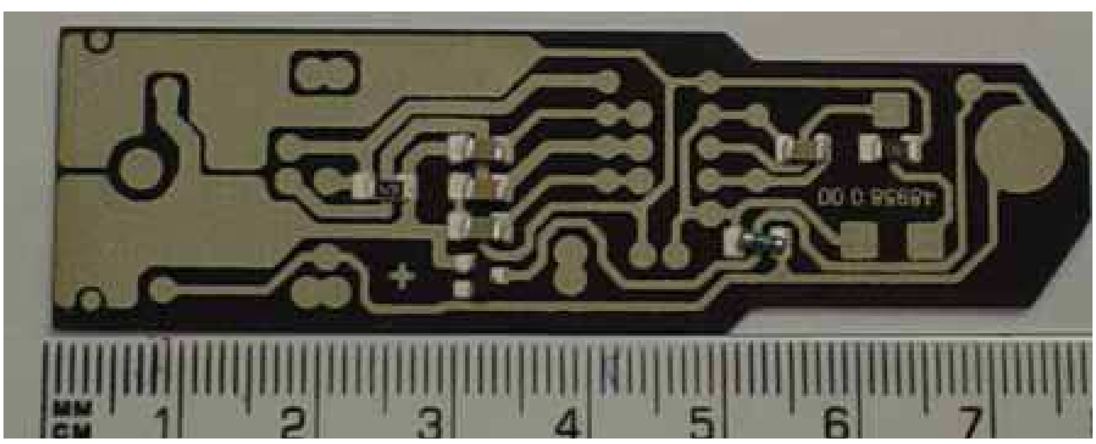


Fig. 19. Successful positioning of Components

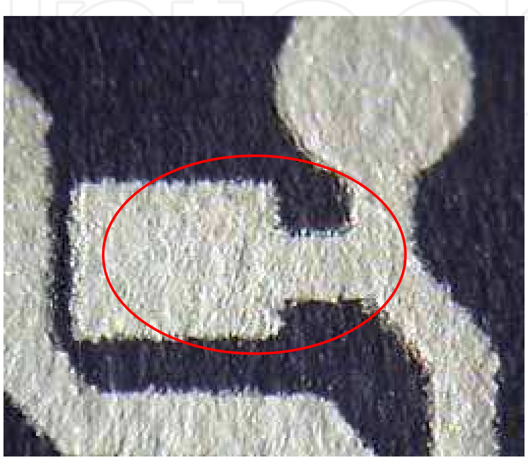


Fig. 20. Image of Defined Feducial

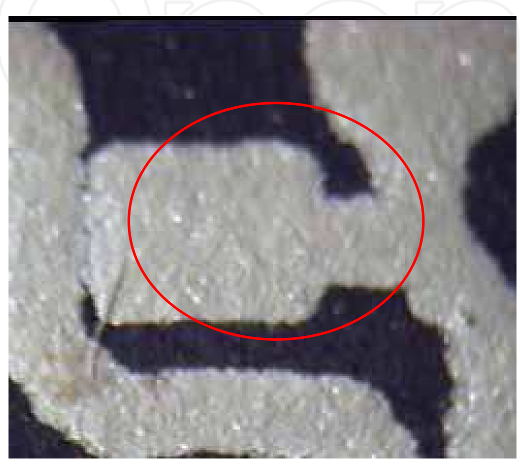


Fig. 21. Image of Poor Quality Feducial

5.0.2 The effect of poor ECA distribution

If the ECA is deposited in the incorrect position when the component is be placed there is no ECA in position to secure that component. If excess ECA is deposited it can spread out across the substrate resulting in bridging of tracks thus damaging the circuit (Figure 22). Excess adhesive can be deposited if the adhesive is at an incorrect viscosity or temperature as it will not flow smoothly across the stencil and will result in the adhesive being dragged through the apertures of the stencil and along the substrate. From Figure 22 it can be seen that the component does not form a satisfactory bond with the adhesive however when the ECA is deposited correctly, (Figure 23) the component sits correctly on the substrate forming an electrical and mechanical bond with the board.

Fig. 22. ECA Spreadage after Printing

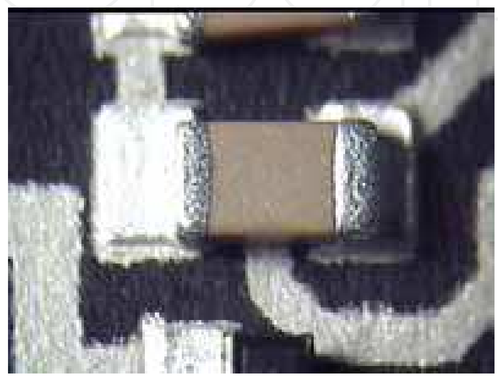


Fig. 23. ECA Printed Correctly

Fig 24. Surface Mount Laboratory

It has been shown that it is possible to mass manufacture a degradable printed circuit board using conductive inks/adhesives and a card substrate on current manufacturing processes and industrial equipment, (Figure 24).
It is now necessary to test these alternative boards against industrial standards and boards, to establish the alternative board's viability as a replacement for existing PCBs.

5.1 Testing boards to existing standards

The previous selection has shown that the alternative manufacturing process offers the ability to mass manufacture printed circuit boards using existing industrial equipment and processes. In order to determine the acceptability of the proposed alternative manufacturing process it is now necessary to examine these alternative circuit assemblies under existing international and industrial standards, temperature cycling (MIL-STD-833F 2004), temperature storage (MIL-STD-833F 2004) and humidity ageing (Wong et al 1999) The standard tests and requirements are outlined in Table 7, together with the test results on the developed boards

6. Discussion & conclusion

It has been shown that it is possible to utilise a degradable substrate and conductive inks/ adhesives to produce a PCB that is comparable to existing PCB. In doing so the system reduces the environmental impact of the manufacturing process. This is achieved by changing the manufacturing method from being subtractive, i.e. producing waste material, to an additive method, i.e. utilising only the material that is required. Further to this the pollution threat is removed as there isn't the requirement to produce the waste by etching, hence saving cost. The printing screen printing process is well established in the electronics industry, and by using a degradable substrate, recovery of components and even tracks is enhanced (Ryan 2006), leading to further environmental benefits.

Parameter	**Test**	**Pass/Fail**	
Electrical Requirements			
Volume Resistivity	<1X10^{-3}μΩcm	Conductive Ink	Pass
		Conductive Adhesive	Pass
Shift of joint resistance	<±20% change after humidity aging	Conductive Ink	Pass
		Conductive Adhesive	Fail
Mechanical requirements			
Impact Strength	Required to sustain 6 drops from 1.524m	Prior to humidity aging	Pass
		Post humidity aging	Pass
Shear Strength	>3KgF	Prior to humidity aging	Fail
		Post humidity aging	Fail
Structural Requirements			
Joint structure	Section 12 of IPC-A-610C	Result of examination of Joint	Pass
Functionality			
Functionality performance	Direct comparison to normal board as per company standard	5 test points	Point 1 84% pass Point 2 88% pass rate Points3-5 100% pass rate
Flammability			
Flammability Examination	BS 61189-2	Pass subject to coating with a flame retardant	

Table 7. Requirements of Proposed Circuit Assemblies

7. References

Banfield, D.(2001), Understanding and Measuring Electrical Resistivity in Conductive Inks and Adhesives. www.*SGIA.org*

Bastecki, C. (1999) A benchmark process for the Lead-free assembly of Mixed Technology PCBs. A report to Alphametals Corp., .

Bellis, M., (2005) *The History of Printing and Printing Processes*. .

Bentzen, B.,(2000) *Solder Paste Printing*., SMT in Focus. p. 1-5.

Chang, D.D.,(1993) An Overview and Evaluation of Anistropically Conductive Adhesive Films for Fine Pitch electronic Assembly. *IEEE Transactions on Components, Hybrids and Manufacturing Technology*, . 16(8): p. 828-835 Coates Ltd(2000) Product Data Sheet. Massachusetts US

Components, (2000) I.f.I.a.P.E., *IPC-A-610C*.: Association of connecting electronics Industries. (www.Ipc.org)

Cuming, E. (2006)., *RFID INTERCONNECT ADHESIVES*. 2006. p. 1-4

Defense, D.o.,(2004) *MIL-STD-883 F, Method 1010.8 Temperature Cycling*. p. 3

Defense, D.o.,(2004) *MIL-STD-883 F, Method 1008.2 Stabilisation Bake*.. p. 1

DRI-WEFA,(2001) *Printed Circuit Boards Industry Yearbook 2001-2002*. , DRI-WEFA

EPA, D., *Environmental and Technical Characteristics of Conductive Adhesives versus Soldering*. 2001: p. 13-15

Gilleo, K.,(1992) *Handbook of Flexible Circuits*., New York: Van Nostrand Reinhold

Gilleo, K.,(1999) Introduction to Conductive Adhesive Joining Technology, in *Conductive Adhesives for Electronic Packaging*, L. Johan, Editor. Chapter 1 Electrochemical Pubs Ltd.

T. Gleditch, H. Hvims, R. Rorgren, and J. Vahakangas, (2002)*The Nordic Electronics Packaging Guideline—Chapter C: Conductuve Polymers, Level 2: Introduction, [Online]*. Available: http://extra.ivf.se/ngl/CPolymerBonding/ChapterC.htm [May 25, 02].

Gomatam,R & Mittal,K,L (2008) *Electrically Conductive Adhesives, VSP,* Leiden,

Groover, M., (2006) Fundamentals of Modern Manufacturing. 3rd ed. 2006: *Wiley*

Herbert, R.J.,(1965) *Impact of Microminiaturisation on Printed Circuit Boards*. Available from http://ieeexplore.ieee.org

Holt, HR.,(1994), *A First Step in Electronic Ecodesign*. Proceedings of the IEEE International Symposium on Electronics and the Environment, San Fransisco CA: p.191-195

Jewell E and Bould D(2008), *Comparing the print process for micro manufacture*, Program notes, *An introduction to print for micro manufacture*, Swansea University 2008. www.ukdispay.net

Kosloff, A., (1980) *Screen Printing Electronic Circuits*. 2nd ed. 1980, Cincinnati: The Signs of the Times Publishing Company. *Cincinnatti*

Li, L., Lizzul, C.; Kim, H.; Sacolick, I.; Morris, J.E (1993)*Electrical, Structural and Processing Properties of Electrically Conductive Adhesives*. IEEE Transactions on Components, Hybrids and Manufacturing Technology,. 16(8): p. 843-850

Liu, J. and P. Lundstrom,(1999) Manufacturability, Reliability and Failure Mechanisms in conductive Adhesive Joining for Flip-Chip and Surface Mount Applications, in *Conductive Adhesives for Electronic Packaging*, L. Johan, Editor. Electronchemical Pubs Ltd. p. Chapter 9.

Lu, D., Q.K. Tong, C.P. Wong (1999), Mechanisms Underlying the Unstable Contact Resistance of Conductive Adhesives. *IEEE Transactions on Electronic Packaging Manufacturing*,. 22(3): p. 228-232

Lumpp, J.,(2000) Hybrid Assemblies, in *The Electronic Packaging Handbook*, G.R. Blackwell, Editor. CRC Press LLC.

McPhail,(1996) *Screen Printing is a Science not an Art*. Soldering and Surface Mount Technology, . 8(2): p. 25-28

Morris, J.E.,(1999) Conduction Mechanisms and Microstructure development in Isotropic, Electrically Conductive Adhesives, in *Conductive Adhesives for Electronic Packaging*, J. Johan, Editor., Electrochemical Pubs Ltd

Pan, J., G. Tonkay, and A. Quintero, (1999) Screen Printing process design of Experiments for fine line printing of Thick Film Ceramic Substrates. *Journal of Electronics Manufacturing*, 1999. 9(3): p. 203-213.

Pardee, S. and T.P. Pennino, (1988) Software tools speed circuit board design. *IEEE Spectrum*,. 25(9): p. 40-44

Parikh, M., W. Quilty, and K. Gardiner,(1991) *SPC and Setup Analysis for Screen Printed Thick Films. IEEE Transactions on Components, Hybrids and Manufacturing Technology*,. 14(3): p. 496-498.

Prasad, R.P., (1997) Surface Mount Technology Principles and Practice. *2nd ed. 1997*,: Chapman & Hall. New York

Raghu D, Harrop P, &. Holland G, (2008) *Encyclopaedia of Printed Electronics* IDTechtEx.com,

Robertson, C., Shipton R.D, &Gray. D.R,(1999) Miniature Sensors using high Density Screen Printing. *Sensor Review*. 19(1): p. 33-36.

Ryan A & Lewis H, (2007) *Manufacturing an environmentally friendly PCB using existing industrial processes and equipment*, J. Robotics & Computer Integrated Manufacture. Vol. 23, pp 720-726.

Ryan, A, (2006) An Alternative Manufacturing System for Printed Circuit Boards, *PHD dissertation University of Limerick*

Ryszard, K. & Andrzej (2000)M. Electrically Conductive Adhesives in SMT- the Influence of Adhesive Composition on Mechanical and Electrical Properties. in *IMAPS*. Poland

Sergent, J. (2001), Advanced Ceramics and Composites, in *Book of Ceramics and Composites*, H. Harper.Mcgraw hill Newyork

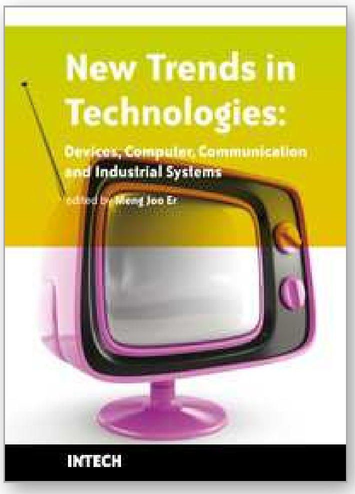
Shimada, Y., L. D., & C.P. Wong.(2000) Electrical Characterisations and Considerations of electrically conductive adhesives. in *International Symposium on Advanced Packaging Materials*.

SMTinfo,*Electronic Production Part 5: Conductive Adhesives, Terstagge, D, (Online)*. Available: http://www.smtinfo.net/docs/Electronic%20Production/f.htm.

Waldvogel, C. (1977)Computer designed multilayer hybrid substrate using thick film technology. in *Annual ACM IEEE Design Automation Conference Proceedings of the 14th conference on Design automation*. New Jersey: IEEE Press

Wickham, M., *Electrically Conductive Adhesives Workshop*. 2005, National Physics Laboratory C.P. Wong and D. Lu, (2000) Recent Advances on Electrically Conductive Adhesives for Electronic Applications (Piscataway, NJ: IEEE,), pp. 121–129.

World Bank Group (1998) Electronics Manufacturing, in *Pollution Prevention and Abatement Handbook. , World Bank Group*. p. 302-306 (available at www.ifc.org)
www.plastic-electronics.org (accessed January, 2009)



New Trends in Technologies: Devices, Computer, Communication and Industrial Systems
Edited by Meng Joo Er

ISBN 978-953-307-212-8
Hard cover, 444 pages
Publisher Sciyo
Published online 02, November, 2010
Published in print edition November, 2010

The grandest accomplishments of engineering took place in the twentieth century. The widespread development and distribution of electricity and clean water, automobiles and airplanes, radio and television, spacecraft and lasers, antibiotics and medical imaging, computers and the Internet are just some of the highlights from a century in which engineering revolutionized and improved virtually every aspect of human life. In this book, the authors provide a glimpse of new trends in technologies pertaining to devices, computers, communications and industrial systems.