

Inkjet printed interconnections on flexible substrates

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Abstract

Utilization of inkjet printing as a manufacturing method in electronics has been studied at Tampere University of Technology. In order to successfully utilize inkjet deposited circuit patterns with traditional electronics components, different aspects must be considered. One of the critical issues is the electrical contact between discrete components and inkjet printed conductive traces.

In this study, discrete passive components were joined to conductive traces that were inkjet printed with metallo-organic nano silver ink on flexible substrates such as polyimide foil and polyethylene naphthalate (PEN). Discrete passive components were attached using isotropic conductive adhesive. JEDEC 22-A104C Standard temperature cycling tests as well as shear strength tests were carried out on the manufactured samples.

There is a need for information on the reliability of inkjet printed interconnections and this is why accelerated reliability testing was selected as the test method. This also gives information on failure mechanisms of printed interconnections, which is very critical in terms of overall reliability. In addition, the reliability of the interconnections is directly related, in terms of yield and operating life, to the environmental load of the final product.

In this paper, results concerning the reliability of inkjet printed interconnections are presented as well as the contribution of these results to the material selection of the material used in the final product.

Key words: printable electronics, temperature cycling, shear strength, environmental performance

1. Introduction

Inkjet technology in electrical circuit board manufacturing offers novel solutions for electronics packaging solutions as well as possibilities to reduce waste compared with traditional circuit board manufacturing using subtractive processes [1,2]. Inkjet printing is additive which means that desired material is deposited directly onto the substrate thus eliminating the need for corrosive materials and processes.

At the department of Electronics at Tampere University of Technology we have been conducting research on additive electronics manufacturing, especially inkjet technology, with the help of our industrial partners. The capabilities of inkjet manufacturing and its integration with other manufacturing methods and assemblies are to be presented via a technology demonstrator.

The functionality of the technology demonstrator will be assembled on a flexible substrate with inkjet printed interconnections. The core of the device incorporates integrated circuits, discrete passives, a liquid crystal display, and a user interface.

In this study the interface between an inkjet printed pad and an attached passive component is investigated using a JEDEC 104C [3] standard temperature cycling test and a shear strength test of the attachment.

2. Environmental considerations

The yield of the manufacturing process of inkjet printed interconnections influences not only manufacturing costs but also the environmental load by decreasing the amount of energy, inks, process chemicals and substrate used [4]. In addition, the importance of high yield of a printed structure is greater when complex multilayer structures are used, since even a single defect in one layer can harm the whole structure [2,5].

The operating life of the product also has an effect on environmental efficiency. For example, in relation to short life-cycle products, shortened operating life increases waste and requires extra production to replace damaged products. Therefore, the printed structures should be reliable throughout the intended operating life of the product and in addition, the reliability aspects should be well known

in order to optimize the printed structures for a specific application without incorporating excess reliability [6].

From the environmental point of view, the environmental impacts of the manufacturing and end-of-life phases of the substrate options and the electrical properties of substrates should also be compared. The differences in the conductivity of printed lines in different substrates can be significant. However, the energy consumption during use may have only a minor effect on the environmental load of the product life cycle [2].

3. Material selection

Forming a conductive path on a substrate requires the following stages. First, the substrate material is carefully cleaned of dirt and possible residues from previous processing stages. Second, the metallo-organic conductive ink is deposited onto the substrate. Third, the jetted ink is sintered in order to form a conductive path.

It is very important that the substrate used can withstand the thermal load of the sintering process. The use of such substrate materials as PEN, for example, excludes some commercial silver nano inks because their minimum sintering temperature exceeds substrate capabilities.

The total thermal load required to sinter the ink is determined by the size of the metal particles in the ink, the weight percentage of the metal content and the solvent used [7]. By choosing an ink correctly, the total thermal load can be reduced. This leads to wider substrate selection.

For this test a commercial ink with physical properties suited for our substrate selection was chosen as the metallo-organic conductive ink. Some important parameters are given in Table 1.

Table 1. Metallo-organic ink properties. [8,9]

Metal content	19 - 21 wt%
Vehicle	Ethylene glycol
Sintering time	5 - 60 min
Sintering temperature	120 – 240 °C
Resistivity	4 - 90 $\mu\Omega\cdot\text{cm}$

The minimum sintering temperature permitting proper sintering of the samples with the intended ink is 120 °C. However, the resistivity of the printed trace increases as the sintering temperature is lowered. Some substrate materials, such as polyethylene

teraphthalate (PET), were excluded because of their too low maximum temperature tolerance.

For these tests Polyimide (PI), Polyethylene Naphthalate (PEN), and Liquid Crystal Polymer (LCP) were chosen. Properties of these substrates are presented in Table 2.

Table 2. Substrate properties. [10,11]

	PEN	PI	LCP
Dielectric constant [°C]	2.9	3.2	2.85
Tg [°C]	155	410	
CTE [ppm/°C]	13	20	17
Moisture absorption [%]	0.3	1.3	0.04
Substrate thickness [μm]	50	50	50

In order to solder components on inkjetted silver traces, pads need to be plated with e.g. electroless Ni/immersion Au. In this study, standard passive components were attached directly to inkjet printed pads with isotropically conductive adhesive (ICA). The adhesive selected for the tests was commercial single- component epoxy with conductive silver particles. Important physical parameters of the used adhesive are such as CTE 45 ppm/°C and Tg 40 °C.

Figure 1 shows the layout of the test structure that was used in the study. ICA was dispensed onto the inkjet printed pads using an aluminum stencil after which standard size 0603 zero-ohm discrete resistors were assembled in the correct locations. Finally, the ICA was cured according to the specifications given by the ICA data sheet. Figure 2 shows an image of the attached SMD components.

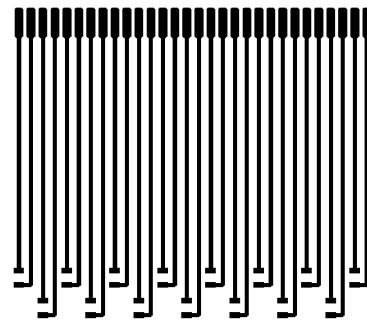


Figure 1. Layout of inkjetted circuit pattern

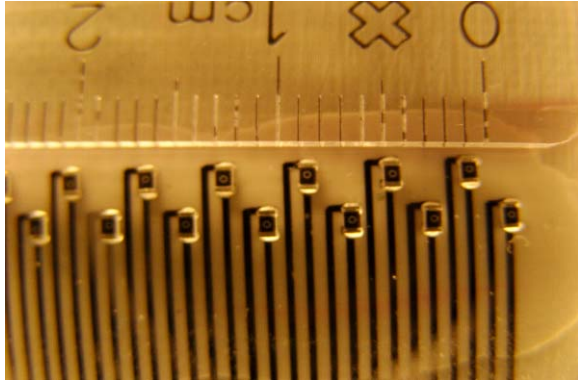


Figure 2. Passive components attached to inkjet printed interconnections on flexible PEN substrate.

4. Experimental

The test samples which were used in temperature cycling tests as well as in shear strength tests were manufactured using the same materials and process parameters.

Inkjet printed traces and pads were printed using metallo-organic silver ink. Eight layers were printed on top of each other, resulting in a layer thickness of approximately 1.2 μm . Samples were then sintered for 1 hour. The sintering temperature was 220 $^{\circ}\text{C}$ for LCP, and PI substrate and 150 $^{\circ}\text{C}$ for PEN. Maximum temperatures for each substrate were used in order to keep the resistivity as low as possible. After this, the components were attached as described earlier.

4.1 Temperature cycling

Temperature cycling tests are used to approximate the life time in normal operating conditions. Temperature extremes as well as change in temperature rate are set following various standards. In this study, JEDEC 22-A104C [3] was selected as the standard because it is often used in consumer electronics. Maximum temperature in this standard is in condition G +125 $^{\circ}\text{C}$ (+0, -10) and the minimum temperature is -40 $^{\circ}\text{C}$ (+15, -0).

The total number of cycles was 1250. The real time measurement system makes it possible to determine the time of failure accurately as the system takes measurements every 15 seconds. Sample was classified as failed when the measured voltage of a sample exceeded 0.3 volts in 5 consecutive measurements or 4 times in two minutes. Using this classification, we can avoid individual errors caused by the measurement system. 0.3 volts was classified as a limit, which is approximately 6 times higher than the voltage at the beginning of the test run.

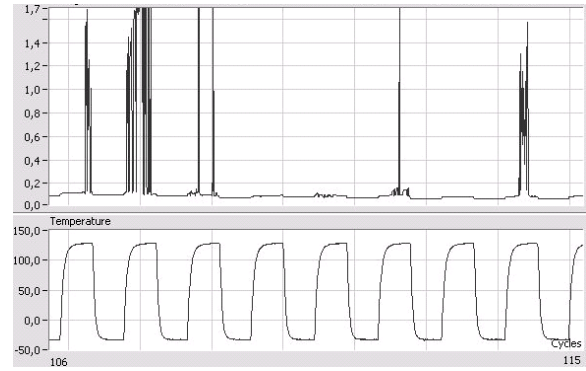


Figure 3. Example of a logged voltage with a failure in an individual sample.

After the temperature cycling tests, cross-sectional samples were made from the attachments. Observations were made with an optical microscope as well as with a scanning electron microscope (SEM).

4.2 Shear strength

The mechanical strength of the adhesive joints on PI, PEN, and LCP substrates was studied using a shear test. The purpose of the shear strength test was to define the force needed to dislocate an individual component as well as the failure mode.

In this test the flexible substrate was attached to a rigid bed. The bed was then attached to the machine base for measurements. The test arrangement is illustrated in Figure 4. In our experiments, a 5 kilogram cartridge was used to test the shear strength of the samples.

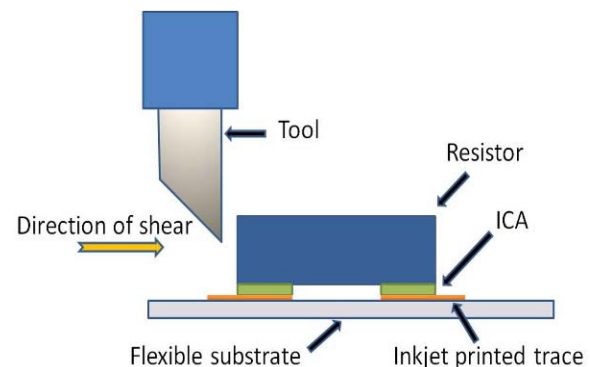


Figure 4. Shear strength test arrangement.

5. Results and discussion

Accelerated tests can be used to study reliability issues of electronic structures in a significantly shorter time than the failures would occur in the environment in which these structures are actually used. Qualitative tests aim at revealing the failure modes that occur in the system. A

quantitative test can be used to determine a probability density function for the system, which can further be used in a mathematical model to estimate the life time of the system in normal operating conditions.

The ICA- attached components as shown in Figure 2 were tested in a temperature cycling test. However, there are no standardized temperature cycling tests for an electronic system that consists of ICA- attached components on a flex substrate and therefore a JEDEC test method for soldered components was applied in this study. The aim was to determine probable failure modes of the assembly using highly accelerated tests and to see whether the chosen substrate has an effect on the location of failure.

SEM image of the component attached to the silver pad is shown in figure 5. It was noticed that delamination at an ink jetted silver trace substrate interface caused some failures, but in many cases failures occurred during the transition of the temperature in the temperature cycling chamber, whereas at room temperature the electrical contact was restored as can be seen in Figure 3. This was somewhat expected since the upper temperature exceeds the recommended temperature of use of the ICA, which might cause breakage of the conductive path between the silver flakes of the ICA. It was seen that the main failure mode is not due to delamination of silver traces from the substrate, or detachment of ICA from a component or silver pads. Nevertheless, a few samples were found where the actual failure occurred when the silver trace broke due to delamination. This is shown in Figures 6 and 7.

Also, in many cases the measured resistance of the sample is lower than the resistance value at the beginning of the experiment. This could indicate possible uncuring of the adhesive.

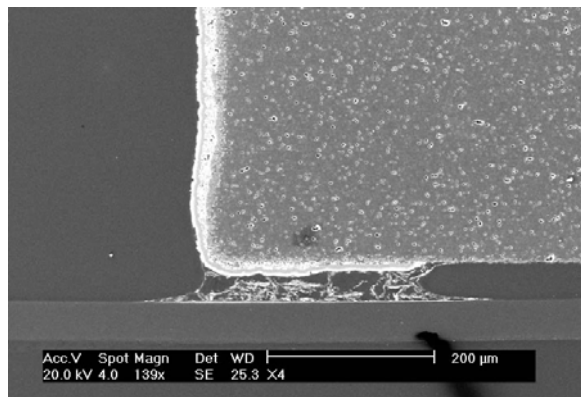


Figure 5. SEM image of the attached component after temperature cycling test.

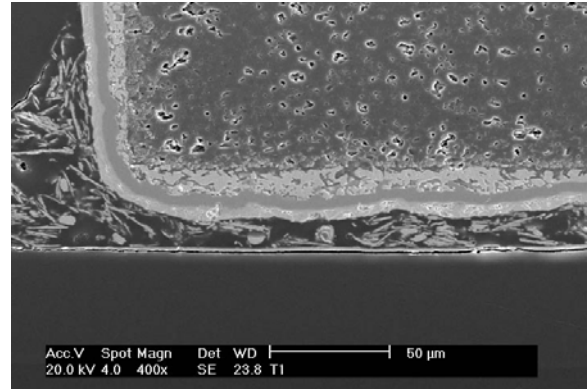


Figure 6. SEM image of a printed silver pad detached from the substrate.

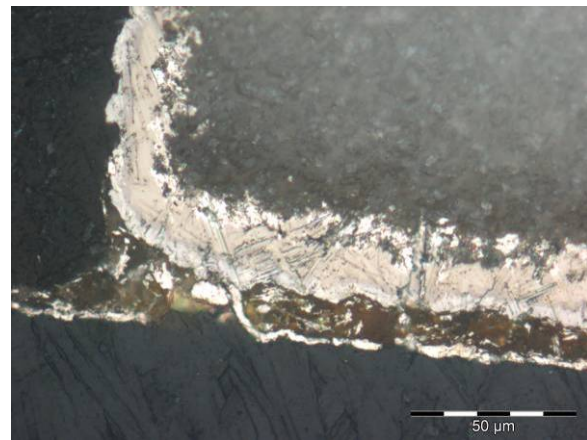


Figure 7. Microscope image of silver trace failure.

Mechanical strength of the adhesive joints on PI, PEN, and LCP substrates was studied in a shear strength test. Mechanical stresses are induced during operation e.g. by a drop impact, thermomechanical strain, vibration, and especially with flexible electronics, due to bending.

The average shear strength values are shown in Figure 8. It can be seen that with LCP substrate the shear strength force is highest and with PI lowest. However, the shear strength force is rather low, which indicates low mechanical strength. Further analysis of the failure mechanism revealed that the location of the failed joint was most commonly at the component-ICA interface. This suggests that a further study with different ICAs needs to be performed. In some cases with PEN substrate the silver electrode was also partially detached, as shown in Figure 9.

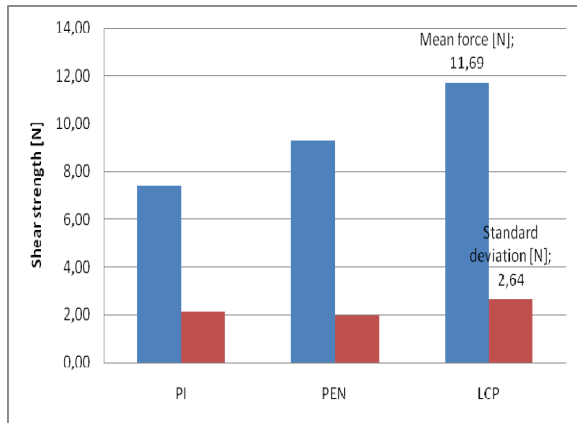


Figure 8. Average shear strength values for different substrates.

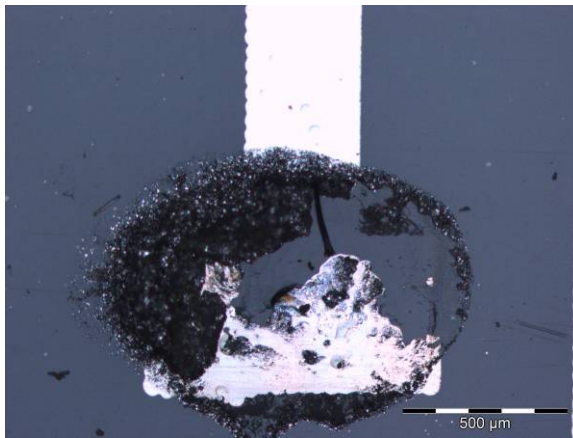


Figure 9. Partial detachment of silver electrode on PEN substrate.

A typical force vs. distance curve from the shear strength test carried out on our samples is illustrated in Figure 10. From the picture can be seen that the shear strain is relatively small. However, since the total shear strength is also small, there is little force which could inflict the strain.

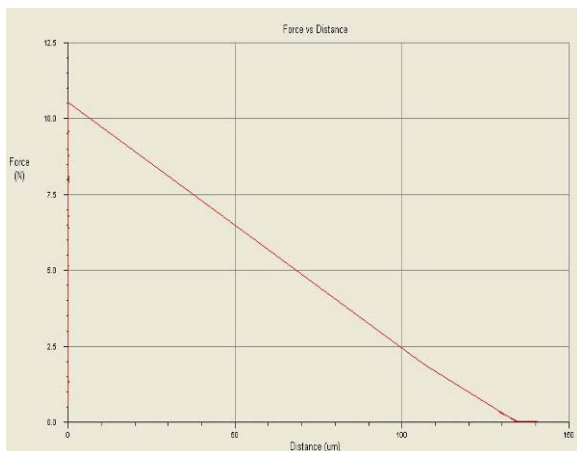


Figure 10. Force vs. distance curve

6. Conclusions

In this paper, the reliability of interfaces between inkjet printed conductive silver traces on flexible substrates and standard 0603 passives attached via ICA was examined using a qualitative approach. The test methods used were temperature cycling and shear strength tests. Results indicate that failures due to mechanical stress occur most commonly in the interface between the passive and the ICA. In temperature cycling most failures occurred at high temperatures. This indicates that failure mode is breakage of the conductive path between the silver flakes of the ICA. This conclusion is supported by SEM images taken from the cross-section samples, most of which showed no delamination or crack between interfaces. Changing the adhesive could have an impact on the failure mechanism and could improve overall quality. This is why further study is needed in order to define possible improvement in reliability by changing the adhesive. Also, by changing the silver ink used or by modification of the substrate surface energy we could improve the adhesion and furthermore shear strength, since it was found that in some cases the failure in shear strength of the system occurred between the flexible substrate and inkjet printed traces.

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