IMPACT OF FPC FABRICATION PROCESS ON SMD RELIABILITY

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ABSTRACT

The functionality of electronic devices continues to increase at an extraordinary rate. Simultaneously consumers are expecting even more and in ever smaller packages. One enabler for shrinking electronics has been the flexible circuit board that allows the circuit board to fit a wide variety of shapes. Flexible printed circuits (FPC) have the capability to be very thin and can have unpackaged components directly attached using surface mount technology (SMT) and flip chip on flex technologies. Bare die can also be thinned and attached very close to the circuit board. However one caveat of high density flexible circuit boards with thin die is that they can be very fragile. The use of back side films and underfill can protect the die making circuits more robust. For underfill to work well it requires good adhesion to the circuit board which can mean that flux residues under the die normally must be removed prior to underfilling.

The flux cleaning process can require harsh cleaning chemistries when high temperature solder is used and when die have a very low standoff from the circuit board surface. Some typical vapor degreasing solvents have been found to attack flexible circuit boards at layer interfaces and reduce circuit board reliability. These solvents remain trapped in the circuit layers and can result in blistering and delamination of the circuit boards during subsequent assembly steps. Eliminating or reducing the occurrence of delamination on flexible circuit boards leads to an overall more robust circuit.

Certain board suppliers manufacture more robust boards that do not delaminate, but fabrication processes and material selection can be proprietary and some suppliers are unwilling to alter their processes. Consequently, an alternative method to prevent delamination that does not require specific assembly or materials information needed to be established. This paper described a process developed to circumvent or eliminate delamination caused by chemical solvent absorption that uses a post-assembly laser excising fabrication process.

Key words: Delamination, flexible printed circuits, FPC, vapor degreasing, laser excising, underfill

INTRODUCTION

The functionality of electronics continues to increase at an extraordinary rate. Simultaneously consumers are expecting even more and in ever smaller packages [1, 2]. One enabler for shrinking electronics has been the flexible circuit board that allows the circuit board to fit in a wide variety of shapes [3]. Flexible circuit boards have the capability to be very thin and can have unpackaged components directly attached using surface mount assembly and flip chip on flex technologies. Unfortunately, with this flexibility come other reliability issues. One issue is the tendency of flexible circuit panels absorbing the chemical solvents that are used during the surface mount device (SMD) assembly cleaning process, specifically the process of vapor degreasing. These solvents can remain trapped in the circuit layers and cause blistering and delamination of the circuit boards during subsequent assembly steps, as shown in Figures 1 and 2.

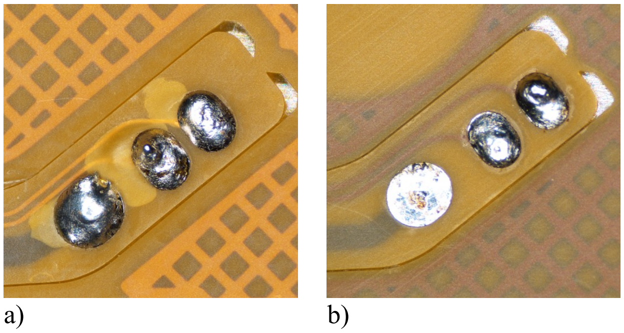
a) b)

Figure . a) Example of failed circuit with delamination; **b)** Example of acceptable circuit without delamination.

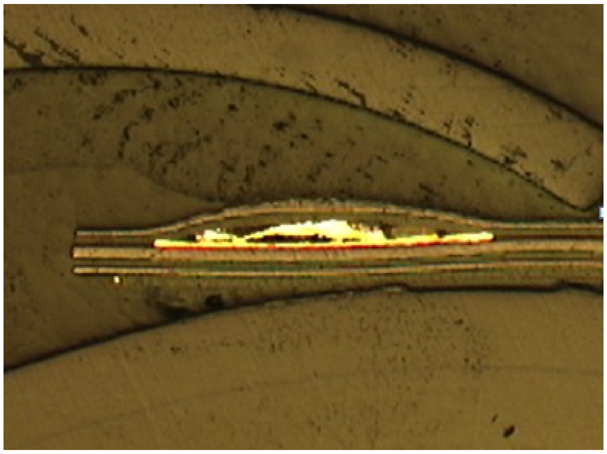

Figure . Cross section image of a flexible circuit solder pad with delamination.

The delamination can cause shorting of pads and lead to overall circuit failure. Completely eliminating or reducing the occurrence of delamination on flexible circuit boards leads to an overall more robust circuit. Within is proposed a method for the elimination of delamination caused by chemical solvent absorption; the use of post-assembly laser excise has been demonstrated to mitigate the issue of solvent absorption.

BACKGROUND

During the assembly of a SMD, it is common for the circuit boards to be washed following reflow to remove flux residue and other contaminants. There are many possible approaches to dealing with flux residue including leaving it on the board, washing it off with water, and washing it off with chemicals [4]. Which one of these approaches is selected is application dependent. Some applications require no residue, whereas in others some residue is a non-issue. The selection of the flux and underfill materials also has an impact on the degree of cleaning necessary. Some fluxes leave very little residue while others result in a large residual deposit. There are a number of "no-clean" and "low residue" fluxes on the market, but these typically have a low activity and do not create a sufficiently strong bond in all situations [5]. While there are some underfills available that claim to not require any flux residue removal, the repeatability of flow and void control may be compromised with their application, as they may experience problems sticking to certain flux residues. Furthermore, with the switch to lead-free and the necessity for higher temperature soldering, it has become even harder to remove these baked on flux residues.

In this case the underfill material was used to rigidly attach die to the flexible circuit using flip chip on flex technology with die on both sides of the flex. The application required excellent under-the-die flux removal to accomplish good die-to-flex adhesion and to create a void-free underfill. Water washing had previously been shown to reduce assembly yield owing to unintended component removal due to the high water pressure necessary for successful cleaning. The use of ultrasonic cleaners was also shown to cause accidental removal of components. A variety of different solvent chemistries were consecutively evaluated to try to clean the flux residues under die. The flux residues that result from a 260 °C reflow profile have been found to be very resistant to chemical removal by most commonly used chemistries. The most effective solvents at removing this flux residue were found to be those chemistries composed primarily of the compound *n*-propyl bromide (*n*PB). *n*PB-based cleaners have a solvency capability comparable to the popular chlorofluorocarbons and hydrochlorofluorocarbons, such as 1,1,1-trichloroethane, which have been phased out and restricted [6].

Various cleaning techniques were examined using the assorted chemistries, such as soaking batches of circuit boards in the heated chemistries and subsequently drying the boards in an oven. The method that proved the most successful for this application is vapor degreasing. Vapor degreasing is a common method for cleaning circuits and consists of exposing the circuit boards to a vapor cloud of hot solvent, which dissolves and washes away the residues [7]. Circuit boards are very clean and dry after vapor degreasing with *n*PB. Vapor degreasing is one of the cleaning techniques that introduce the least mechanical shock to the fragile bare flip chip components, which is very important for the application in this paper. During this process, flexible circuit boards will inadvertently absorb some solvent. If the majority of this solvent is not then removed, it can swell during later soldering steps causing pads to blister.

A general industry solution to reduce delamination is to extend the baking time following vapor degreasing. While this technique results in less delamination, it does not eliminate the problem completely and there is still damage to the inner circuit layers. An extended bake is also time-consuming and in general the added thermal cycle harsh on the circuit board panels. Reducing the exposure time of the flexible circuits to the vapor of cleaning solvents can reduce the amount of circuit blistering, but cleaning is a necessary process step in this assembly process and will cause other reliability issues if not done satisfactorily. A process which minimized the necessary chemical exposure time while still accomplishing successful cleaning of the flexible circuits was established, however some blistering still occurred.

It has been found that some flexible circuit boards do not easily delaminate when exposed to *n*PB, while others have wide spread delamination. Some flexible circuit board constructions are more robust against delamination due to the exact materials and processing used during board fabrication. Circuit board processes and materials are proprietary within a company. There are few companies that build their boards with the same processes, chemicals and tool sets and many companies are unwilling to significantly alter their processes. This situation can lead to a highly restricted or very limited set of available suppliers. An alternative method to improve circuit robustness against vapor degreasing chemistries that required minimal vendor action or information was necessary. The work herein was initiated to provide more robust circuits after SMD assembly by reducing the chance of delamination without requiring supplier input or action. The work may also reduce the FPC performance differences among various vendors, possibly expanding internally qualified flexible circuit supplier base. It should be stated that the flexible circuit is expected to be standalone robust preceding any impact of *n*PB. This is noteworthy since circuits from many board shops have been found to delaminate as received without any degreasing process.

EXPERIMENTAL DATA

All experiments were completed in a 5 gallon capacity manual load vapor degreaser using a commercially available cleaning solution with the bulk ingredient *n*PB as the vapor degreasing chemistry. Flexible circuit panels were attached to a rigid pallet with high temperature tape and suspended vertically above the boiling liquid in the chemical vapor cloud for 15 minutes. The boards used had dimensions of 13.5 x 6.25 cm and were all of the same circuit design.

Solvent Absorption by FPC Boards

It was first necessary to determine to what degree flexible circuit boards with a known lower reliability absorbed the *n*PB-based cleaning solvent. Four boards were exposed to the solvent vapors as described above. The mass of the exposed boards was taken prior to exposure and immediately after removal from the boiling tank. The boards were then placed on an aluminum tray and baked in a forced air lab oven at 125 °C to remove absorbed chemical. The mass of each board was taken at hour increments during baking, see Table 1 below.

Table . Flexible circuit board solvent absorption data.

Board	**1**	**2**	**3**	**4**
Initial mass (g)	5.5163	5.2954	5.2040	5.2983
Post 15 min exposure (g)	5.5691	5.3442	5.2766	5.3463
Mass gained (g)	0.0528	0.0488	0.0726	0.0480
Post 60 min bake (g)	5.5215	5.2995	5.215	5.3068
% removed post 60 min	90.151	91.598	84.848	82.291
Post 120 min bake (g)	5.5192	5.297	5.2111	5.3038
Post 180 min bake (g)	5.5182	5.2966	5.2101	5.3014
Post 15 hour bake (g)	5.5167	5.2962	5.2048	5.2988
% removed post 15 hr	99.242	98.361	98.898	98.95
End mass gained (g)	0.0004	0.0008	0.0008	0.0005

The board mass data verified that the boards do in fact absorb a quantity of chemical during the cleaning process, approximately 48-70 mg. It can also be noted that the majority of the absorbed solvent mass was removed during the first hour of the baking process, an average of 87%. The remaining 14 hours of baking removed on average 11% of the total absorbed solvent mass. The final 0.76-1.64% of the absorbed solvent mass remained in the boards following the 15 hour bake time. It is evident that baking can remove most, but not necessarily all, of the absorbed chemicals, with nearly 1 mg remaining in some cases.

To evaluate how the absorbed chemistry affects the integrity of the circuits, two boards were exposed to the boiling solvent vapor and the user pads then soldered to using a 370 °C soldering iron, flux and solder. Two boards that were not exposed to the boiling solvent vapor were also soldered to in the same fashion. It was found that every pad of the exposed boards experienced delamination. Furthermore, none of the pads of the boards not exposed to solvent vapor experienced delamination. See Figure 3 for photos of each.

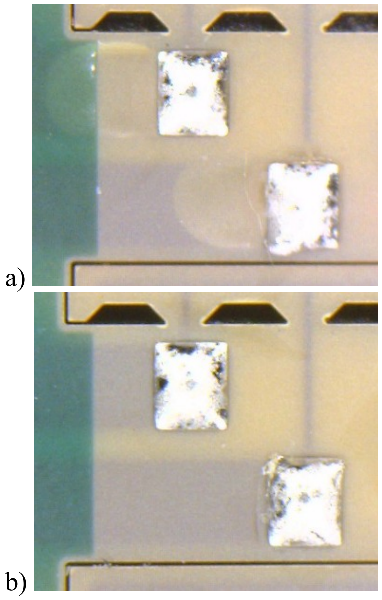

Figure . a) Board exposed to solvent vapors exhibits delamination; **b)** Board not exposed to solvent vapors does not delaminate.

At this point it was theorized that some quantity of solvent is absorbed into the circuit layers during the cleaning process, altering the chemical bonds between materials and weakening the layer-to-layer adherence. Although the baking process removes the majority of the solvent, a small amount remains and damage to the layer-to-layer connection already took place. When the soldering iron is applied, the heat causes the remaining solvent to expand, possibly vaporize, and further separates the already deteriorated bond between the adhesive and the copper layer, resulting in a visible blister on the circuit surface. A cross sectional analysis reveals that the delamination is indeed between copper and the adhesive layer. See Figure 4 for image below.

Figure . Cross-section of delaminated pad.

Solvent Absorption by FPC Polyimide and Adhesive Layer Materials

Table 2. Solvent absorption by flexible circuit material layer

Layer	PI 1	PI 2	PI 3
Initial Mass(g)	0.0433	0.0443	0.0432
Post 15 min exposure (g)	0.0434	0.0446	0.0434
Mass gained (g)	0.0001	0.0003	0.0002
Post 15 min bake (g)	0.0432	0.0444	0.0433
Post 60 min bake (g)	0.0432	0.0443	0.0431
Final mass loss/gain (g)	-0.0001	0.000	-0.0001

In order to determine exactly what part of the flexible circuit absorbs the chemical solvent, an experiment was conducted which exposed a variety of cured polyimide and adhesive flexible circuit board layer materials to the boiling cleaning solvent. Four by three cm pieces of four different polyimide materials and four different adhesive materials were exposed to the solvent vapors as described above. The mass of the materials was taken prior to exposure and immediately after removal from the boiling tank. The materials were then placed on an aluminum tray and baked in a forced air lab oven at 125 °C for 60 minutes to remove the absorbed chemical. The mass of each material was taken after baking for 15 min., and then 60 min, see Table 2.

The polyimide and adhesive materials mass data revealed that the most significant amount of the chemicals were absorbed by the adhesive layers. On average the adhesive layers absorbed 10% their mass in solvent, whereas the polyimide layers absorbed less than 1% their mass. A second significant observation is the notable overall loss of mass exhibited by the adhesive layers following *n*PB exposure and baking. At least 5.0 mg was lost by each piece of adhesive, compared to a 1.0 mg loss at most exhibited by the polyimide materials. The average mass deficit for the adhesive layer materials is 2.1% their starting mass, conceivably denoting that the *n*PB-based cleaning solvent dissolves part of the adhesives.

The adhesive materials changed visibly following exposure to the solvent vapors. Immediately upon exposure to the boiling *n*PB solution the adhesive materials deformed, curling and shrinking in size. Following baking the pieces remained curled and deformed, though to a lesser degree. The materials also acquired a glossy appearance in place of a usual matte finish. The adhesive materials that were exposed to the solvent and then baked also tore considerably more easily, signifying a weakening of composition. The ease of tearing further supports the theory that chemical solvent is not simply being absorbed into the adhesive materials and then harmlessly baked out, but also causing the materials to partially deteriorate. The polyimide layers showed no obvious reaction to vapor upon exposure or after baking. See Figure 5 for images of materials prior to and following exposure to the *n*PB-based solvent vapors.

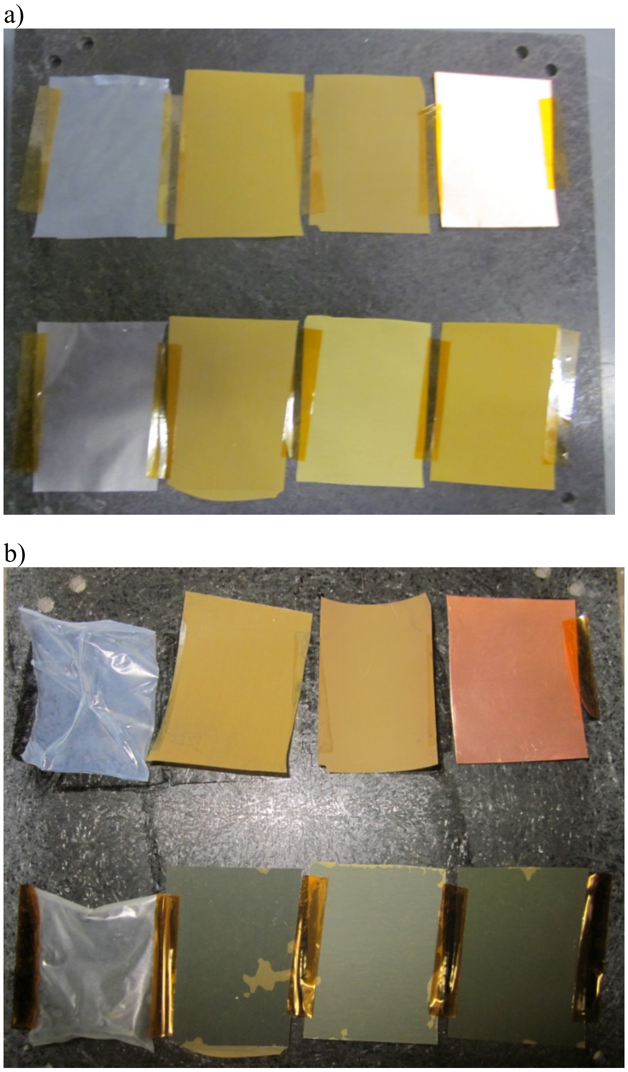

Figure 5. **a)** Adhesive (far left) and polyimide materials prior to vapor exposure; **b)** Adhesive (far left) and polyimide materials after vapor exposure.

Cross sectional analyses of sites of delamination, like that shown in Figure 4, and the solvent absorption study of the flexible circuit material layers together support the hypothesis that degradation of the adhesive layer is the primary source of delamination. The occurrence of delamination can be reduced by decreasing the interaction of the adhesive layers with the cleaning solvent. The primary channel of the chemicals reaching the adhesive layer is through the sides of the flexible circuit since the top and bottom of the circuits are composed of solder mask, polyimide, and copper layers, which have been found to be predominantly unaffected by the chemicals. The only means of access then are the individual flexible circuit edge areas. By minimizing the edge area of the circuits, the extent of exposed adhesive layer can be greatly reduced. It can then be theorized that limiting the amount of exposed edge area should result in less solvent absorption into the board and accordingly less blistering and delamination.

Solvent Absorption of Excised versus Non-excised FPC Boards

To test the theory that flexible circuit boards with reduced circuit edge area will absorb less solvent and consequently exhibit less delamination, flexible circuit boards with and without the individual circuits laser-excised were exposed to the solvent vapors. See Figure 6 for examples of laser routed and non-routed circuits. The boards were exposed to the solvent vapors as described above. The mass of the exposed boards was again taken prior to exposure and immediately after removal from the boiling tank. The boards were then placed on an aluminum tray and baked in a forced air lab oven at 125 °C to remove absorbed chemical. The mass of each board was taken after 45 min. of baking, then 120 min., 180 min., and finally after 15 hours, see Table 3 below.

Table 3. Mass gained and loss comparison of excised and non-excised boards, with and without solder mask.

Board	Excised	Non-excised
Initial mass(g)	4.9076	4.9909
Post 15 min exposure (g)	4.9962	5.0359
Mass gained (g)	0.0886	0.0450
Post 45 min bake (g)	4.9155	4.9888
Post 120 min bake (g)	4.9103	4.9873
Post 180 min bake (g)	4.9087	4.9866
Post 15 hour bake (g)	4.9036	4.9848
End mass gained (g)	-0.004	-0.0061

It was found that the non-routed boards absorbed significantly less solvent than the routed boards. A non-routed board gained only 45 mg following solvent exposure, nearly 50% less than an identical routed board which gained 88 mg. The non-routed boards still absorbed some amount of chemistry, but it was found that the majority of that chemistry was absorbed into the solder mask and not the inner board layer materials. A non-routed board with the solder mask removed absorbed only 9 mg compared to 53 mg for the identical routed board also with the solder mask removed. As a result, the amount of solvent absorbed by non-routed boards varies slightly vender to vendor due to different solder mask compositions.

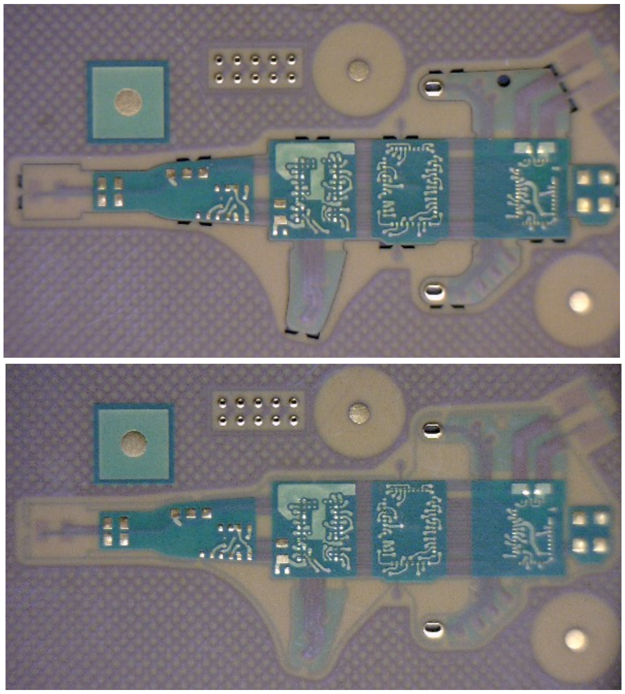
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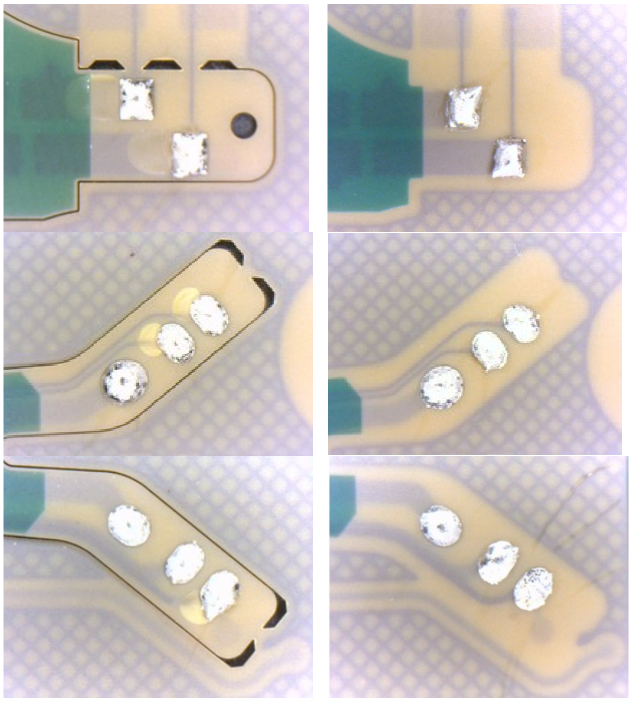
Figure 6. a) Example of laser excised board; **b)** Example of non-laser excised board.

In order to evaluate the integrity of the non-laser excised boards in comparison to identical laser excised boards, two non-routed boards and two routed boards were exposed to the solvent vapors and the user pads then soldered to using a 370 °C soldering iron, flux and solder. It was found that none of the non-laser excised circuits experienced delamination. Additionally all of the excised boards exhibited delamination. See Figure 7 for photos of each.



a) b)

Figure 7. a) Circuits are routed and experienced delamination; **b)** Circuits are non-routed and show no delamination.

To verify that the absorption through the cut edges was not a factor of the laser type or the laser processing itself, flexible circuit boards without laser excising were cut in a variety of locations using a razor blade. The boards were then exposed to the solvent vapors and the user pads soldered to using a 370 °C soldering iron, flux and solder. Delamination occurred at all knife-cut edges. See Figure 8.

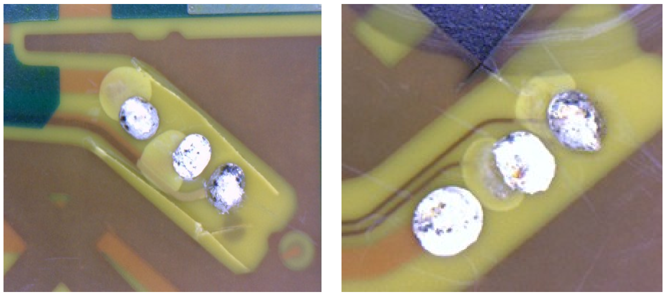


Figure 8. Boards with razor cut edges show delamination.

Successive studies have been performed using flexible circuits from four suppliers which placed flexible circuit boards in solvent vapors and then followed this with exposure to heat via a reflow oven, as is done in product assembly. The exposed boards were then checked for delamination; it was consistently found that with a routed board that experienced delamination an identical non-routed board would not.

Additional Benefits of Method

There are a number of supplementary benefits of this approach to the SMD assembly process. Firstly, laser excise after assembly allows for reduced underfilling keep out zones as the possibility of underfill seeping between board and pallet, causing the two to cure together during reflow, is no longer an issue. Underfill can be applied wherever need be and the excess removed during the laser excising process, leading to an overall smaller flexible circuit.

Secondly, surface mount assembly is made simpler with a non-excised board due to the flexible circuit board lacking gaps from the laser excising. The lack of gabs means a vacuum can be applied during specific assembly steps, reducing board warpage and leading to better board control and improved accuracy during flux and solder paste printing and component placement.

Finally there is an increase in mechanical stability of non-routed boards. With all edges of the circuit still attached to the supporting surrounding material, there is less chance of circuit movement and bending during assembly, which can lead to breaking of component solder connections. The chances of trace fracturing are also greatly reduced.

Issues Produced by Method

Laser outlining after SMD is not without issue however. If performed in-house, there is the considerable cost of purchasing laser cutting equipment and the associated time and money for its upkeep. If the process is outsourced, there is the added cost of shipping the boards as well as the machine cutting time. The build time per panel is also increased due to the extra time necessary for the boards to be shipped to and from the outsourcing location.

An additional concern is the issue of laser debris. When laser excising prior to assembly, the boards can be cleaned post-laser excise, by plasma or other means. This process removes any carbon residue that may cover pads and potentially interfere with soldering. Laser excising post SMD assembly means the carbon residue will remain on the boards, as plasma cleaning cannot be done once components have been attached. Great care must then be taken to optimize the laser excising process, ensuring a minimum amount of carbon residue is created and that it does not interfere with any soldering pads. See Figure 9 for example of carbon residue on a circuit following laser excising. The amount of carbon residue that settles on the board can be minimized by designing and using a custom pallet that has holes and groves to allow the vacuum of the laser cutting machine to pull the debris through.

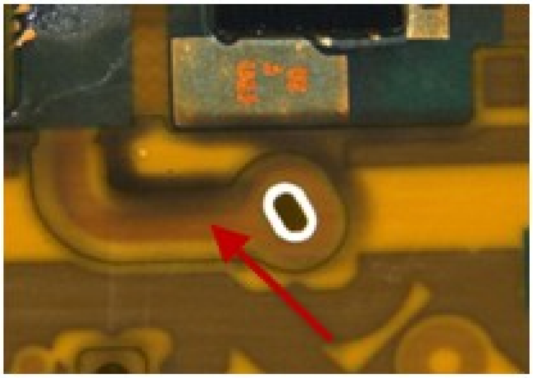


Figure 9. Carbon residue on circuit post laser-excising.

Further problems arise due to FPC shrinkage; flexible circuits are known to shrink and warp during high temperature reflow processes. The panel warpage can make laser excising more difficult and lead to lower accuracy and possible component damage.

ESD concerns are also elevated with this method. With the presence of active components on the board it is more important to monitor the shipping and the handling of the panels before and after cutting.

CONCLUSION

As electronics continue to shrink and their functionality continues to increases, the popularity of flexible circuits will rise. Although the use of flexible circuits can leads to a smaller board it presents other reliability issues. One such reliability issue is that of flexible circuit panels absorbing the chemical solvents that are used during the SMD assembly cleaning process, specifically vapor degreasing. Absorption of these solvents into the circuit layers can result in blistering and delamination of the circuit boards during subsequent assembly steps. Previous mitigation methods involve lengthy bake times or modifications in the cleaning processes, but these processes do not eliminate the problem, only reduce it. The occurrence and extent of delamination in flexible circuit boards varies from supplier to supplier, depending on the method of assembly and materials used. Unfortunately, this information is private to the company and an alternative method to prevent delamination that requires little information or involvement from suppliers was necessary. We have presented and discussed a process to circumvent or eliminate delamination caused by chemical solvent absorption that uses post-assembly laser excising.

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