The importance of Test and Inspection when implementing lead-free manufacturing

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Abstract
There have been many papers, articles, and studies about process issues, reliability issues, repair issues, and of merits of different alloys. However there has been very little attention on impacts on test and inspection when going lead-free. This paper addresses that missing piece.

The paper will address issues that will impact defect levels and defect spectrum during the transition to lead-free manufacturing. Since there are exemptions of which product types are mandated to go lead-free, and not all components will be available in lead-free versions there is not a clean path to lead-free manufacturing. Both manufacturers that are forced to go lead-free as well as companies that are exempted will be impacted. This and other issues will have a big impact on the optimal test strategy. Unfortunately there are at this point in time very limited production data on lead-free defect types and defect levels however what has been learned about defect levels and defect spectrum from early experiments will be shared.

The paper will also address different test and inspection systems readiness to test lead-free printed circuit board assemblies (PCBA).

Introduction
The most important factors almost everybody in the industry is discussing regarding lead-free today are the laws put into effect in Europe and China. The implementation date for those new laws is July 1, 2006. There are other countries talking about lead-free, including the USA. Because of the big market in Europe and China almost everybody that manufactures Printed Circuit Board Assemblies (PCBA) has to switch to lead-free manufacturing. The European laws are also referred to as WEEE (Waste Electrical and Electronic Equipment) directive and RoHS (Restriction of Hazardous Substances) directive.

The new laws in Europe and China are not only about eliminating lead. There are many other materials that are banned in the material in a PCBA. However lead is the dominant material and the rest of this paper will address the lead-free effort from a board test and inspection point of view.

Challenges
During the last several years the industry has experimented with many different type of alloys. The USA has mainly converged towards the NEMI and SMTA recommendation of 3.9% silver, 0.6% copper and the rest tin. NEMI recommends 0.7% copper and the rest tin for the wave soldering process.

Europe mainly is experimenting with tin, 3.4-3.9% silver, and 0.5 – 0.9% copper.

Major Japanese OEMs investigated numerous lead-free alternatives, including alloys containing bismuth and/or zinc, such as Sn/Ag/Bi/Cu, Sn/8Zn/3Bi and Sn/58Bi. The Japanese industry has now also moved toward Sn/Ag/Cu alloys and so has the rest of the Asia region.

As can be seen everybody is moving towards the tin, silver, copper alloy, with small variations of how much silver and copper.

A key difference with the lead-free alloy is a higher melting point of around 217 degrees Celsius, an increase of 34 degrees C (or close to 65 degrees F), compared with 183 degree Celsius for the tin-lead alloy we are using today. The higher melting point will have significant impact on the process and potentially on component reliability.

It is important to be aware that there are exceptions in the law. Products that are affected by the law are: Electronic toys, Electronic tools, Radios, TVs, VCRs, DVDs, Household items, IT equipment, Personal Computers, Notebook PCs, telecom etc. However some products are exempted, such as: Network Infrastructure, Medical, Instruments, Automotive, Defense, Aerospace, etc. The exempted products are high reliability and mission critical products. This indicates that the industry and end users are concerned about reliability and quality, underlining that extra attention is needed during the transition and until a good track record has been established for lead-free PCBAs.

A complicating factor when going lead-free is that lead is in many areas of the PCBA. Lead can be found in the solder paste and solder. Components also have lead on their connection pins and in many cases also internally. In many cases many bare-board finishes include lead.

Because lead is in many types of material used on the PCBA and some products are mandated to switch to lead-free, while others are exempted, it will not be a clean switch [1]. See figure 1. These two factors will create many issues that will be addressed.

Today we have tin-lead solder and tin-lead components. In most cases it will not be as easy as at once we have lead-free solder and all components are lead-free, see figure 1, Path A.

For the industry that is forced to go lead-free the most likely path is that they switch to lead-free solder paste, but not all components will be lead-free in the beginning, as illustrated in figure 1, Path B.

Exempt industries are most likely forced through Path C. They will continue to use the normal lead-tin solder paste, but some components will only be available as lead-free components. Because of this several of the exempted industries have already start talking about also switching over to lead-free, however later than the mandated industry.

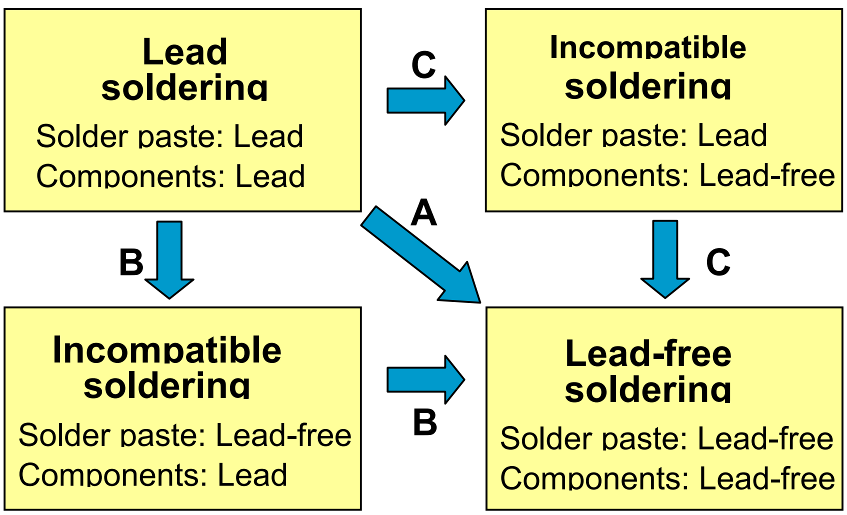

Figure 1. Lead-free transition issues.

After many years it is likely that almost everybody in the industry will be using a lead-free soldering process with lead-free components.

There will also be issues with keeping the lead-free components separate from the lead components, even if many companies are planning to use separate part numbers, because not all component vendors have committed to support separate part numbers yet.

Summary of issues important from a test / inspection point of view:
SMT: Higher reflow temperature will stress components and the PCB more. Logistics of lead-free and lead components was discussed. It is very likely that defect levels will increase. We should expect all defect types today but there might be a modification to their frequency. What has been learned so far is that voiding increases significantly. We also have seen more cracking of components (some externally, some only internally) due to moisture and the higher temperatures required during processing. Early reports also have noted more tombstones.

Wave: The wave soldering machines are likely to be retrofitted or replaced due to higher corrosion by the new alloys. Tin forms intermetallic compounds with the iron components of the wave system, resulting in contaminated solder. We expect an increase of insufficient barrel fill due to higher temperature needs for the new solder alloy. More solder-bridges have been reported compared to a standard tin-lead process. Another concern is additional failures to the reflow solder joints, such as joint separation, also due to the higher temperatures at the wave process.

Rework: A new concern with lead-free is that fewer repair attempts may be allowed due to the higher temperatures and that those higher temperatures could cause damage to the PCBA and neighboring components. NEMI currently has one project in place to investigate this, with the final report scheduled for February 2005.

Reliability: Early studies indicate that the lead-free solder joint generally has similar reliability than the lead version. However the higher temperatures may impact component reliability. Tin whiskers are significantly higher [2] for lead-free alloys than the lead-tin alloy. This is a long-term reliability issue and is unlikely to be detected before the product ships.

Logistics: A key issue is how to separate lead and lead-free components. This applies to many areas in production including many repair areas.

Other: Most lead-free production to date has mainly been done on lower complexity boards that are small in size and with few different component types. We expect that higher complexity boards with a large variety of component types will be initially more difficult to tune to an optimal lead-free process.

The industry is predicting higher defect levels during the transition from lead to lead-free. It is expected that defect levels for opens, shorts (bridging), voids, and misalignment will increase when going to lead-free. Tin-silver-copper alloys do not wet the surfaces being soldered as well as tin-lead-solders, so solder bridges will be less likely to clear themselves and parts will not self-align as well. For insufficient and excess solder the industry expects defect levels to be approximately the same they are today. Note that defect levels and defect spectrum will vary from manufacturing site to manufacturing site and from board to board. Therefore we are expecting to see large variations on defects and defect levels from site to site.

From the previous discussion you can see that going to lead-free has a lot of issues and will very likely create process challenges, especially during the transition phase. Sometimes it is good to look back to see if similar manufacturing transitions have created changes in defect levels. And yes they have. Figure 2 shows defect levels from HP Loveland site when they went to a no-clean process. This shop built a high-mix of medium to low volume boards for multiple product lines, so there was a large variety of components, processes, and materials. Defect levels increased with more than an order of magnitude and it took close to three years to get defect levels down to the level they were prior to going no-clean.

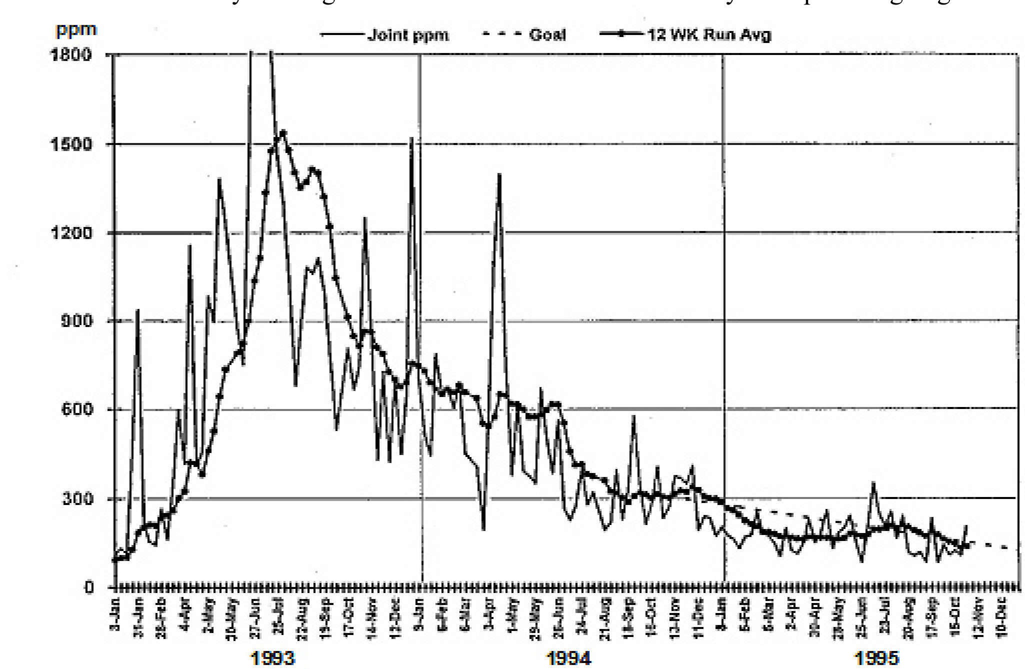

Figure 2. Defect levels at one manufacturing site when switching to a no-clean process.

Because of all the issues we have discussed it is not unlikely that we will see similar results when going lead-free.

Note again that defect levels and defect spectrum will vary from manufacturing site to manufacturing site and from board to board. Therefore we are expecting to see large variations on defect and defect levels from site to site.

A summary of transition issues that will be especially important to test and inspection are:

- Many are likely to see higher defect levels.

- New and traditional defect types make it important to look for defects all the way from solder paste, placement, before and after reflow, after wave and then electrically to test the product through ICT and Functional test.

- Increase of process issues and increased need for inspection focused on process control (SPI and AOI-pre reflow). Since we also expect higher defect levels at the end of the manufacturing process, test and inspection for defect containment will also be more important.

- Because of the reduced number of allowable repair attempts, test methods with very high diagnostic resolution will be important.

Faults, defects, process indicators and potential defects

These terms are important when planning test strategies for lead-free production and it is important to have a clear understanding of what they are. Therefore they will be defined and explained. Definitions will be in italic and underlined:

A Fault is a manifestation of a defect. An example is a digital device output pin that does not toggle correctly. For simplicity think about a two input OR-gate whose output is stuck high. This is a fault and is a manifestation of a defect. The causing defect can be any one of several: among others, a defective component, an incorrectly-placed component, an open input pin, an open output pin. The fault class is a subset of the defect class. Electrical test such as In-Circuit (ICT), Boundary-Scan, and Functional Test (FT) are mainly detecting faults.

A defect is, at the end of the manufacturing process, an unacceptable deviation from a norm. The fault described above is also a defect, but there may be defects that do not show up as faults. Examples are insufficient solder, a misaligned component, a missing bypass capacitor and an open power pin. Inspection systems such as Automatic Optical Inspection (AOI), and Automatic X-ray Inspection (AXI) detect many of the defects and also some of the same faults as electrical test. That the definition includes "at the end of the manufacturing line" is important when compared with "Potential defect".

All defects, which also include the faults, need to be corrected before the product is shipped, if high quality standards are to be followed.

A process indicator is, at the end of the manufacturing process, an acceptable deviation from a norm. Good examples are insufficient solder or misaligned components. The insufficient solder may not be so lacking that it renders a repair action. However if many of these conditions exist, a process improvement action may be required.

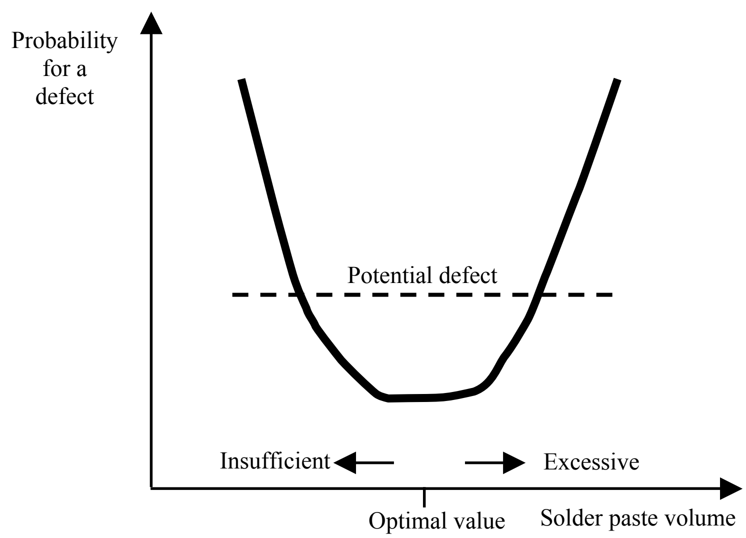

Figure 3. The concept that a potential defect(s) may or may not be defects at the end of the manufacturing process.

A potential defect is, in the manufacturing process, a deviation from a norm, that may or may not be a defect at the end of the manufacturing process. This is a new category and needs to be understood. An example is a pre-reflow misaligned chip component. This component may or may not self-align in the reflow oven. Another example is an insufficient paste volume that may not end up as a defective solder joint at the end of the manufacturing process [3]. Is it then important to keep track of these types of potential defects? The answer is yes and it is easiest explained by looking at figure 3. This example is also around solder paste volume. There is an optimal paste volume value that creates the fewest defects down the line. If the paste volume decreases, the probability for defects down the manufacturing line increases. Also as the paste volume increases from the optimal value, the probability for a defect down the line increases. For process control it is important to tune the process to the optimal value. However if only a few solder pads on a board have solder paste volume below a threshold it may not be optimal to clean the board and re-paste it. Remember that we are talking about potential defects.

Test and inspection engineers at the end of the line are mainly interested in finding faults and defects. Process engineers responsible for improving the manufacturing process are mainly interested in potential defects, process indicators, and systematic defects. Systematic defects are typically defects that occur on a larger number of boards and are due to some systematic problem, like a bent nozzle on a pick-and-place machine, soldering issues with one type of component, or a DFM (Design For Manufacturing) issue.

Test strategies for lead-free

As has been discussed, the transition to lead-free will likely create new process problems, higher defect levels, and potentially a shift in the defect spectrum. Faults, defects, process indicators, and potential defects are all likely to increase. There should therefore be steps implemented to minimize all of these and when, for a significant production volume, normal levels are achieved, more normal test strategies can be implemented again.

The first step before implementing lead-free manufacturing is to establish a good picture of the current lead-tin process. What are the current defect levels and defect spectrum? From a test / inspection point of view, where are the bottlenecks? Most manufacturing sites already have this in place, but if not, it should be established. Some understanding of levels of potential defects and process indicators are also an advantage to know.

For a site with many manufacturing lines it is recommended that only one line be switched over to lead-free first. Very tight test and inspection should be implemented for this line and engineering resources should be available to analyze any new systematic issues that may evolve. As been stated there are many new issues when switching to lead-free. The process window is narrower due to increased reflow and wave solder temperatures and component specifications on maximum allowed temperature. Implementing good process characterization steps is recommended and can be done with solder paste inspection and pre-reflow inspection. It is also important to have good test strategies after reflow to capture all defects. Data gathered from test and inspection should be used to improve the process and to eliminate systematic defects. If faults and defects are increasing significantly, adding test and inspection capability should be considered. When all issues have been resolved and defect levels and quality levels are acceptable, switching lead-free manufacturing to the next line should be considered.

Note that there are likely to be big variations from site to site and between board type and board type. Some sites may experience very few issues and defect levels will be overall the same, while other sites may have significant issues and significant increases in defect levels. Also variation in issues and defect levels can be seen from board type to board type. Some boards may switch over to lead-free without any problems, while others may create significant problems. The bottom line is that test and inspection will be significantly impacted if defect levels increase and the key is to be prepared for a potential increase in defect levels and hope for the best. Switching to lead-free is a significant process change.

Is test and inspection ready for lead-free?

Addressing test and inspection issues when going to lead-free, a key question is, are there any issues with the test and inspection methods and equipment itself? This will be addressed below:

Solder Paste Inspection (SPI)

The lead-free conversion for solder paste inspection is very straightforward. There is no special set-up or system needs in order to be lead-free ready. SPI systems are lead-free ready today!

Robust process characterization is needed for lead-free processes, as there are more unknowns with this new material. Using 3D SPI allows for quick optimization of print parameters and characterization. We know from studies from the past 10+ years for tin-lead solder paste, that solder paste volume is linked to long-term joint reliability. The same applies to lead-free solders and with lead-free processing causing increased reliability questions and concerns; the need for 3D SPI is even more obvious. Placing equal solder volumes is also known to prevent tombstones. The main advantages with solder paste inspection systems are that it finds potential defects and process indicators, which will lead to fewer defects and faults. Switching to lead-free it is even more important to control the process.

AOI pre-reflow and post-reflow

There are some differences in the visual appearance between lead-tin and lead-free solder joints that could impact AOI systems. Lead-free solder has a higher surface tension than tin-lead solder, resulting in a slightly different shape of solder joint. Also lead-free joints are grainier and appear slightly duller than traditional solder joints. To investigate if this would impact the performance of AOI systems, the National Physical Laboratory (NPL) in the UK did a study of six different vendors of AOI systems. The result was published 2002 [4]. The study found that today's AOI system can inspect lead-free boards and solder joints. False calls for lead-tin and lead-free boards and joints were also very similar. The results varied slightly for the six different vendors' AOI equipment; the conclusion was that most AOI systems can inspect lead-free boards today without any problems. Contact your AOI vendor to check if they participated in this study and the result for that particular system or refer to the study that can be obtained from NPL.

AXI (Automatic X-ray Inspection)

X-ray inspection uses different materials' impedance to x-rays to create an image that a computer can analyze. Now with lead-free will x-ray continue to work? The answer is yes! The materials used in lead-free alloys still will give enough contrast to give good x-ray images of solder joints. Figure 4 shows an x-ray image of a board using the normal tin-lead alloy. Figure 5 shows the same board type with a lead-free alloy. As can be seen there is not much of a difference. Note that the human eye can only differentiate between sixteen levels of gray. Accurate measurements will give a 5-10% thinner value for lead-free as for lead-tin alloys. This can be compensated if accurate thickness measurements are needed. However, the shape of the solder joint is how most defects are detected, and those shapes are basically the same for lead-tin and for lead-free solder joints. So x-ray equipment will work with lead-free boards.

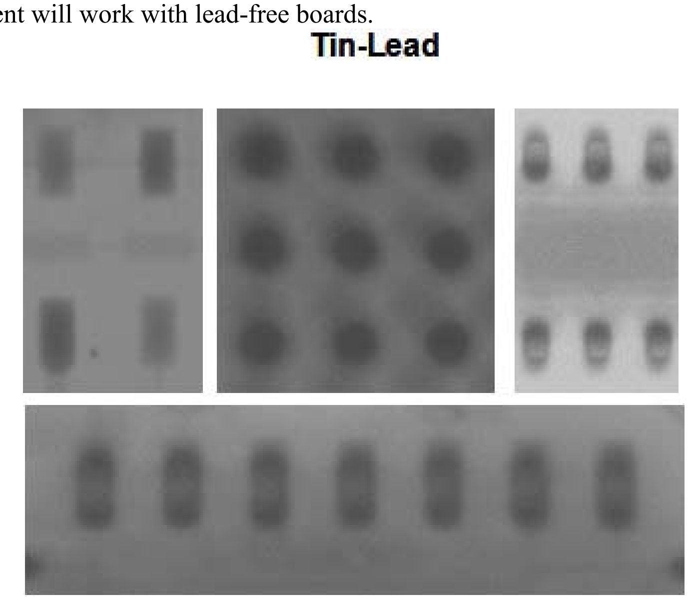

Figure 4. X-ray images of tin-lead solder.

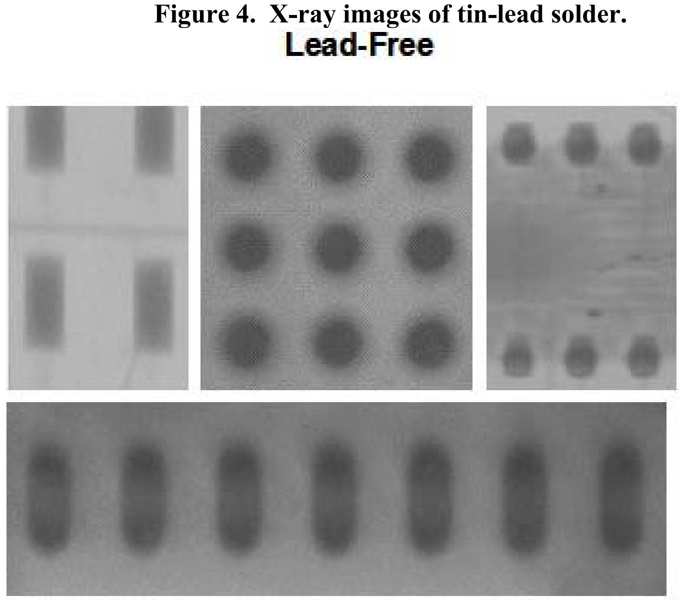

Figure 5. X-ray images of lead-free solder.

ICT

ICT relies on good contact between the test probe and test pad. This is achieved by using a hard, sharp probe hitting a soft, solder-coated testpad. The probe penetrates the soft solder on the pad, breaking through any contaminants like lead oxide and flux residue. The depth of penetration is a function of the yield strength of the material and the sharpness of the probe. The deeper the penetration, the better the contact. Tin-lead solder has a yield strength of about 5000 psi and, coupled with an 8-oz sharp steel or beryllium tipped probe, this makes good contact.

HASL (Hot Air Solder Level) provides a solder-coated surface to all locations on the bare PCB. If switching to OSP (Organic Solder Preservative), this step is removed. Now, solder is only applied to locations defined by the stencil in the paste machine. Typically, these locations did not include testpads. If no action is taken, testpad targets will be raw copper. Raw copper has a yield strength an order of magnitude higher than lead-based solder, and it is so thin that the test probe may damage the pad. Plus, it will rapidly build up an oxide layer during and immediately after re-flow. As a result, contact will be poor between the fixture and the board under test. If at all possible <u>you should never probe raw testpads</u>. All ICT testability guidelines indicate this.

The solution is to make sure that the solder paste stencil includes openings for testpads. This will provide solder on the pads restoring contact. By the way, lead-free alloys have a yield strength that is less than most lead-based solder alloys used today, so the contact performance should be similar. In addition the tin oxide is electrically conductive so a layer of oxide on the solder joint will not be a problem for probing the lead-free solder. Compare that with the lead oxide that works like an insulator and must be penetrated by the test probe to make electrical contact.

Due to poorer and slower wetting of lead-free solder, stronger fluxes may be used to promote better wetting. There is some indication that the flux residue from lead-free solders may be harder and more difficult to penetrate than for tin-lead solders due to the elevated soldering temperatures. We recommend working with solder paste vendors on a solder paste mix to minimize the effect of these contaminants.

The ICT DFT guidelines can be found in the latest SMTA document [5] that has been developed by industry representation of both ATE vendors and ATE users. It also contains DFT guidelines for AOI, AXI and Boundary-Scan

Functional test

A new issue with lead-free is the higher reflow temperature of the alloy. This may restrict the number of repair attempts that are allowed due to potential damage to the board and adjacent components. The first thing to minimize repair attempts at functional test is to do a better job at process test so extremely few manufacturing defects escape to functional test. In addition fault isolation at functional test is often done by a shotgun approach, where you start replacing the most likely component to be defective. If that does not work, you replace the second most likely component. You continue this approach until either you repair the board or you give up because you have reached the number of acceptable repair attempts, you run out of possible components to suspect, the board is damaged, or you run out of time. Writing the functional test program with better diagnostic resolution would be an advantage from this point of view, but may not be technically possible or economically justifiable. Using software solutions that minimize the amount of shot gunning needed would be recommended.

Board test functional test is done through edge connectors, a bed-of-nails, or a combination of both. If a bed-of-nails is used the same issues and recommendations apply as for ICT fixturing described above.

Future work

Defect levels and defect spectrum are very important factors when selecting an optimal test strategy. We have so far not been successful in gathering extensive data from lead-free production. Most users we have been working with have only done experiments and prototype runs with lead-free and that cannot obtain accurate production data. We are working with users to obtain this data but have not received enough to be presented in this paper. We hope to gather that data and present it in future papers.

Summary of lead-free defects known today

However we can summarize what changes we have seen so far. These observations are mainly from prototype runs and lead-free experiments:

- Voiding: Significant increase in voiding, however it is still debatable which voids are defects or not.
- Tombstones: Significant increase in some cases.
- Cracked components: An increase in internal and external cracking due to moisture and higher temperatures.

- Insufficient barrel fill: This is for through-hole components that have been through a wave or selective wave process.
- Bridges: Mainly in the wave or selective wave process.
- Tin whiskers: This is a long-term reliability issue and is unlikely to show up during production testing

Conclusions

The switch to lead-free is a major process change and will impact PCBAs for both products that are mandated to switch to lead-free before July 2006 as well as PCBAs for exempted products. Since not all components will be available in a lead-free version, while others will be available only in a lead-free version, all PCBA manufacturing will be impacted. From a test and inspection point of view, defect levels in many cases will increase significantly and also the defect spectrum is likely to change somewhat. Higher defect levels and a changing defect spectrum means that more attention to test and inspection is needed. This is to reduce potential defects and process indicators as well as to detect all defects and faults. Studies and early experiments are showing that test and inspection systems and methods are ready for lead-free. Data gathering of defect levels and defect spectrum for production lead-free boards are needed.

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