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Test and Inspection as part of the lead-free manufacturing process

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Abstract

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. Data of defect levels and defect spectrum from lead-free production will be presented below. 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 remainder tin. NEMI recommends 0.7% copper and the remainder 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, or popularly called the SAC-alloy (for Sn, Ag, and Cu), 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.

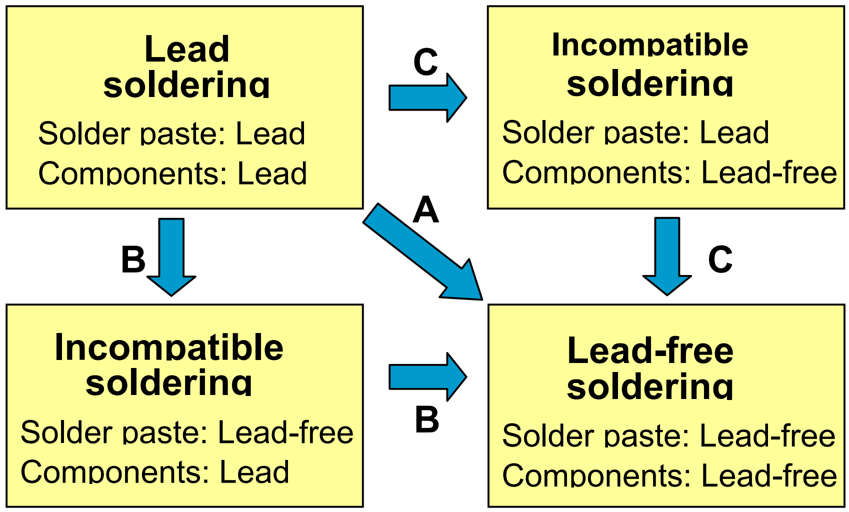

Figure 1. Lead-free transition issues

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 PCBA 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 that occur today but there might be a modification to their frequency. What has been learned so far is that tombstoning, misalignment, opens, and shorts have increased. Voiding has also increased significantly.

Wave: The wave soldering machines are likely to be retrofitted or replaced due to higher corrosiveness of 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, which grow over time, are significantly higher [2] for lead-free alloys than the tin-lead 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-bearing 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 with few different component types, and are built in high volumes allowing process optimization. We expect that higher complexity boards with a large variety of component types and built in higher mix environment 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 were a large variety of components, processes, and materials. Defect levels increased by more than an order of magnitude and it took around two years to get defect levels down to the level they were prior to going no-clean.

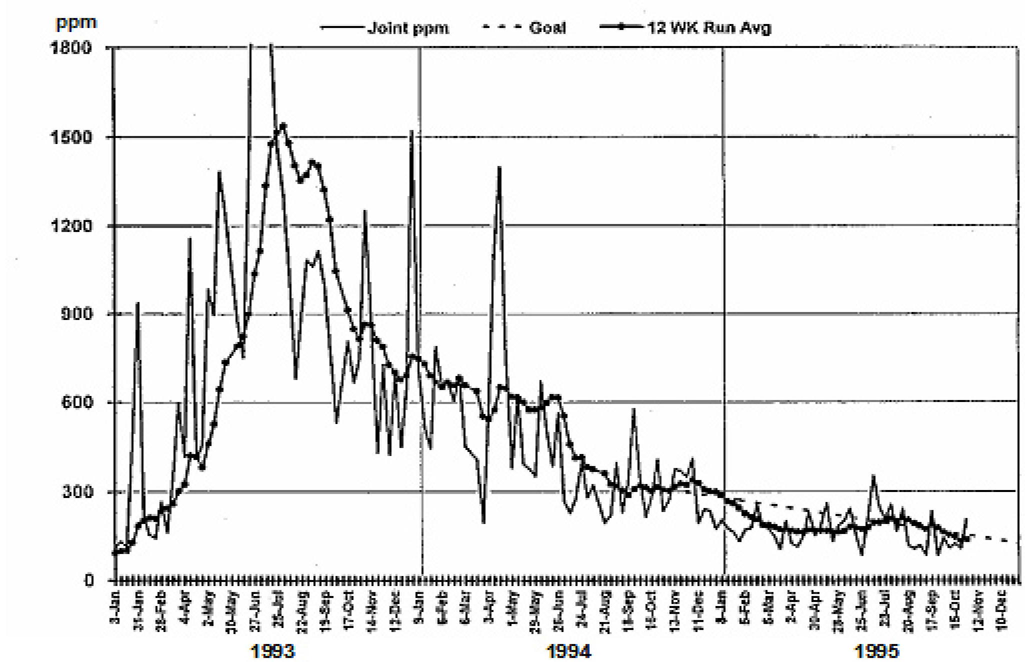

Figure 2. Defect levels at one manufacturing site when switching to a no-clean process

Because of all the issues we have discussed it is likely that we will see similar results when going lead-free, and some data will be presented in this paper.

Note again that defect levels and defect spectrum will vary from manufacturing site to manufacturing site and from board to board. Therefore we expect to see large variations on defects 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 In-Circuit test (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.

Different wetting characteristics

The biggest impact from lead-free solder on defect levels and the defect spectrum is caused by the different wetting characteristics of this alloy. The wetting characteristics of molten solder and the surfaces it is joining determine how well the solder covers pads and leads, and determines the shape of the solder joints. The wetting force of lead-free solder is not as strong as for the tin-lead solder. Early production and experiments have shown that this will impact defect levels and defect spectrum, and the following are the most obvious examples we have seen.

The first is solder pad coverage. Because of the lower wetting forces of lead-free sometimes the full pad is not covered with solder after reflow. This can be seen in figure 3. This illustrates two cases of empty pads where no components are placed. The pad to the left is tin-lead solder and you can see that it is fully covered with solder. The pad to the right is lead-free solder and solder is covering only the right side of the pad. In most cases this would not be considered a defect and would not negatively impact the manufacturing of the PCBA. However there may be an impact on in-circuit test (ICT) and/or functional test. If this is a test pad and the test probe is supposed to hit solder, because of the incomplete solder pad coverage it may hit raw copper instead. We know from experience that test probes do not make good contact with raw copper and this will result in a fixture contact problem, lowering the yield at ICT and/or functional test.

Figure 3. Solder Pad coverage. Photo to the left tin-lead solder, to the right lead-free

Another potential problem is with bent leads. If a pin is slightly bent the stronger wetting forces of the tin-lead solder compensate in many cases and an acceptable solder joint is formed. When lead-free solder is used there will be more cases where an acceptable solder joint is not formed. It will either be an open solder joint or it will be less reliable than needed.

The wetting forces also help readjust slightly misplaced components during the reflow process. Again because of the reduced wetting force the lead-free process will be less forgiving. This will increase the importance of placement accuracy and of pre-reflow inspection, or result in higher defect levels of misplaced components.

Also the wetting forces of solder help if there is solder paste between two pads potentially creating a solder bridge or electrical short between these two pads. For the tin-lead solder the wetting force in most cases draws the solder paste to the pads, thus eliminating the solder bridge. For the lead-free case this is less likely to occur, resulting in more shorts.

The last example is from the wave soldering process, where through-hole pins are soldered. Because of the lower wetting forces, the solder will decrease its ability to fill the hole properly resulting in insufficient barrel fill. This can be seen in figure 4, which is an x-ray image of one through-hole component. On one side of this component no solder has raised up in the hole.

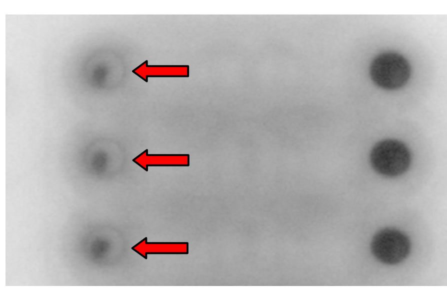

Figure 4: X-ray image of through-hole component with insufficient barrel solder fill

Lead-free examples

Many examples of lead-free soldering exist today. Most production experience of lead-free is from high volume consumer products. These boards tend to be lower in complexity if we consider component count, and solder joint count per board. The variety of component types is also typically lower than bigger boards manufactured in lower volumes. The following is production data from one major CM that manufactures two similar board types, one in tin-lead and one in lead-free. The boards are for consumer electronics and the lowest pitch for both board types is 20 mils (BGA, gullwing, and SMT connectors) and the smallest chip component on both boards is 0402. Number of components per panel is around 1,300, and number of solder joints per panel is around 3,000. These boards have been manufactured in high volumes – more than 85,000 boards for the tin-lead type and more than 60,000 for the lead-free type. Figure 5 shows the defect levels and defect spectrum for these two very similar boards. Note that the figure only shows defect types impacted by the lead-free process.

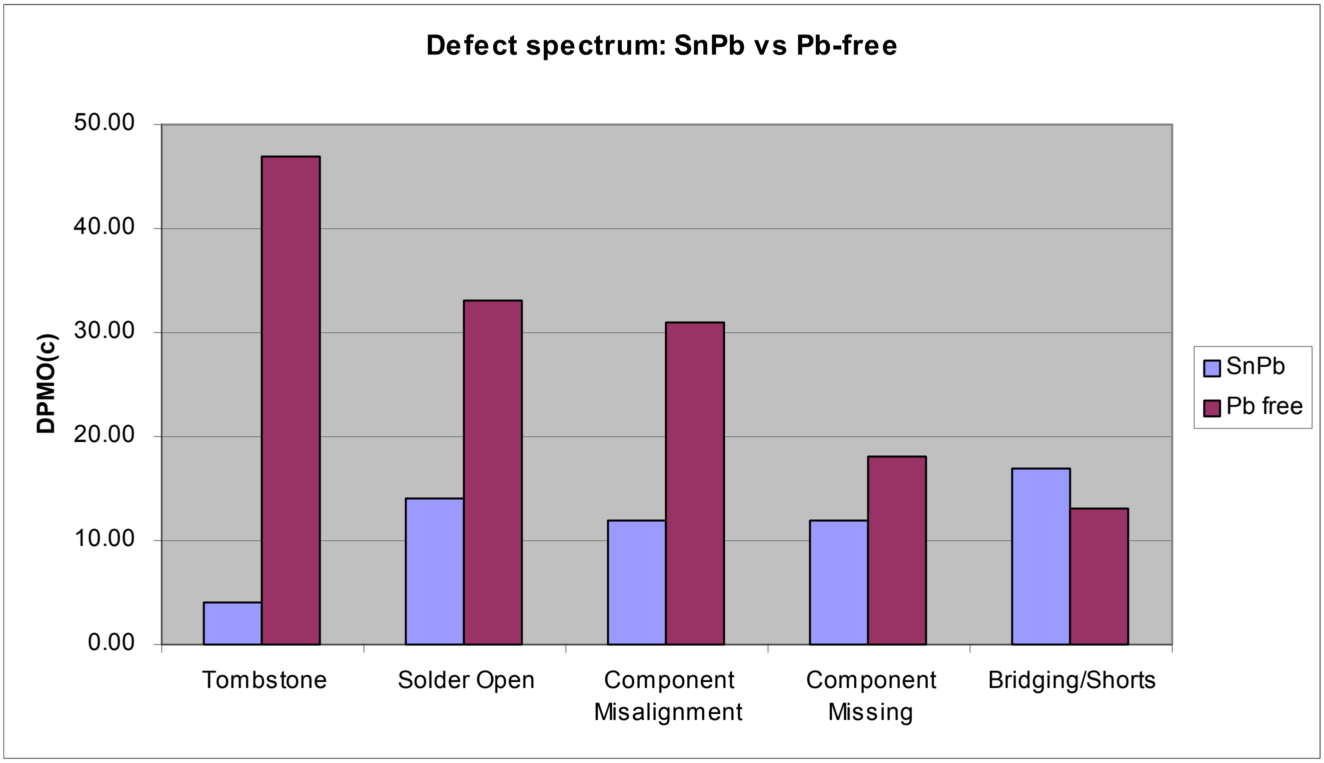

Figure 5: Defect spectrum and defect levels of lead-free high volume PCBA

As can be seen in figure 5 the greatest increase was found in tombstones. Note that the majority of chip components are 0402s. A significant increase of solder opens and component misalignments can also be seen for the lead-free board. Note also that bridging/shorts decreased for the lead-free board. This is opposite to what is to be expected and may just be a coincidence or because the lead-free board was under close control, supervised by the process engineers with most experience and manufactured with the most up-to-date manufacturing equipment.

The DPMO (defects per million opportunities) level for the tin-lead board was well below 100 DPMO, a very good number. Note that the DPMO level more than doubled for the lead-free board, however it is still very impressive. These DPMO values are calculated on a component basis.

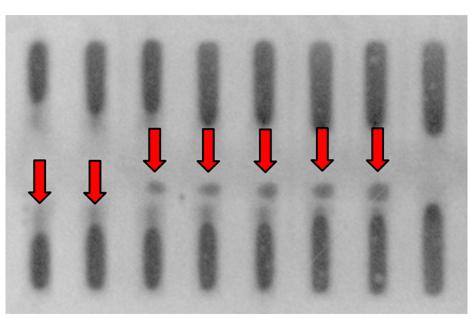

Figure 6: X-ray image lead-free solder of poor wetting

Figure 6 is an x-ray image of another example of a lead-free board. It illustrates the wetting problem discussed above. The two pins in the lower left corner are open. The solder joints to the right show significant wetting problems, and numerous voids can also be detected in the image.

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 tin-lead 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 has been stated, there are many new issues when switching to lead-free. The process window is narrower due to the wetting issues, 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 tin-lead and lead-free solder joints that could impact AOI systems. Because lead-free solder has a lower wetting force than tin-lead solder, it results 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 [3]. The study found that today's AOI system can inspect lead-free boards and solder joints. False calls for tin-lead 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 7 shows an x-ray image of a board using the normal tin-lead alloy. Figure 8 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 15-20% thinner value for lead-free as for tin-lead 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 tin-lead and for lead-free solder joints. So x-ray equipment will work with lead-free boards.

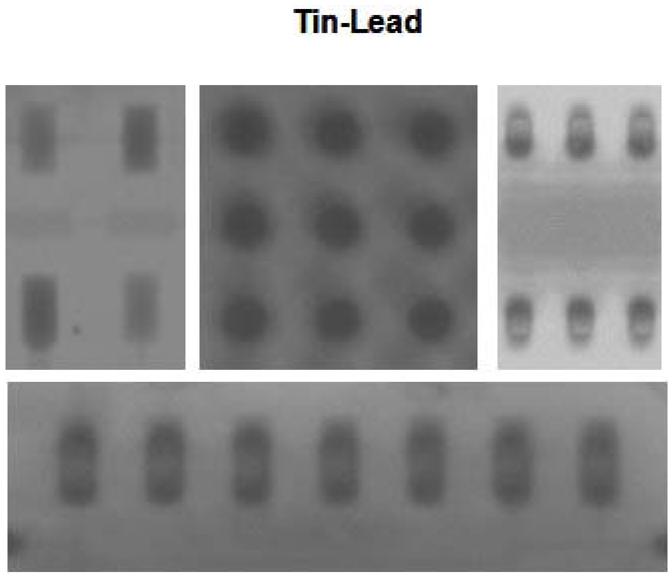

Figure 7. X-ray images of tin-lead solder.

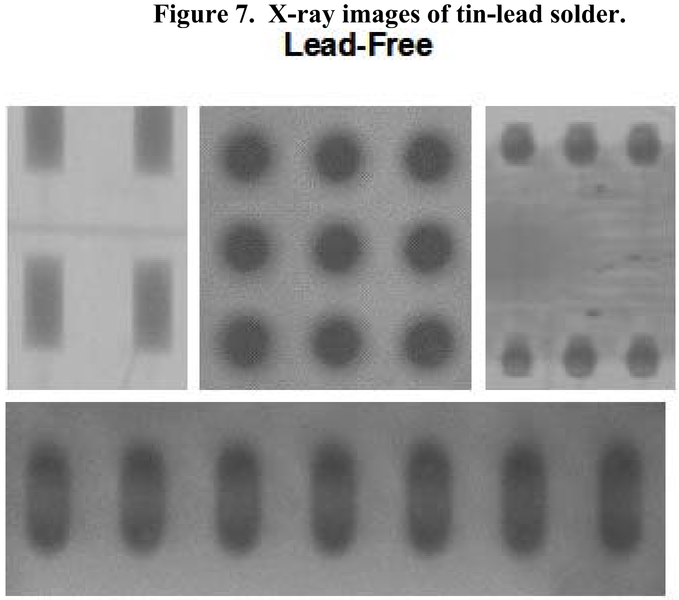

Figure 8. X-ray images of lead-free solder.

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 test pad. 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 test pads. If no action is taken, test pad 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 test pads</u>. All ICT testability guidelines indicate this.

The solution is to make sure that the solder paste stencil includes openings for test pads. 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 [4] 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. So far, we have a very limited set of data and more needs to be gathered for lead-free manufacturing. Most users we have been working with have only done experiments and prototype runs with lead-free and that cannot obtain accurate production data. In particular, data from higher complexity boards should be gathered from normal production.

Summary of lead-free defects known today

However, we can summarize what changes we have seen so far. These observations are mainly from production of low complexity boards, 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.
- 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 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 mean that more attention to test and inspection is needed. Studies and early experiments show that test and inspection systems and methods are ready for lead-free. Additional data gathering of defect levels and defect spectrum for production lead-free boards is needed.

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