DOES PCB PAD FINISH AFFECT VOIDING LEVELS IN LEAD-FREE ASSEMBLIES?

David Bernard
Dage Precision Industries
Fremont, CA
d.bernard@dage-group.com

Keith Bryant
Dage Precision Industries
Aylesbury, Buckinghamshire, United Kingdom
k.bryant@dage-group.com

ABSTRACT
With European environmental legislation and market forces driving the change to lead-free solders for printed circuit board assembly, there will be significant changes in the soldering process. Voiding is one of the known major consequences of these process changes exaggerated by the use of new soldering materials. Excessive voiding can lead to poor quality joints, BGA "popcorning", open circuit failures during burn-in or thermal cycling, even field failures can be the result. Therefore voiding needs to be minimised to retain process quality and to reduce rejects and returns in the change to lead-free production
This paper will evaluate reasons for the increase in voiding, explore the different PCB pad finishes in use for lead-free and the amount of voiding produced by a controlled soldering process using these surface finishes. With the use of advanced technology including automated digital x-ray measurements, the total amount of voiding, void size and location will be measured and compared.
The summary will contrast the findings of these tests and measurements; conclusions could then be drawn on the preferred PCB pad finishes for lead-free assembly. Those seeking to improve printed circuit assembly process control and reduce failures can use the methodology in this paper to keep voiding within acceptable levels.

Key words: Lead-free, voiding, pad finish, x-ray inspection

INTRODUCTION
Much has been written about the level of voiding that is observed as we move from lead containing solder pastes and component finishes to a lead-free assembly environment. It is generally acknowledged that moving to lead-free assembly will result in an increased level of voids within the formed joints. Many papers have put forward theories for this and a huge amount of research has been published on this subject. From this body of evidence, certain facts appear irrefutable:

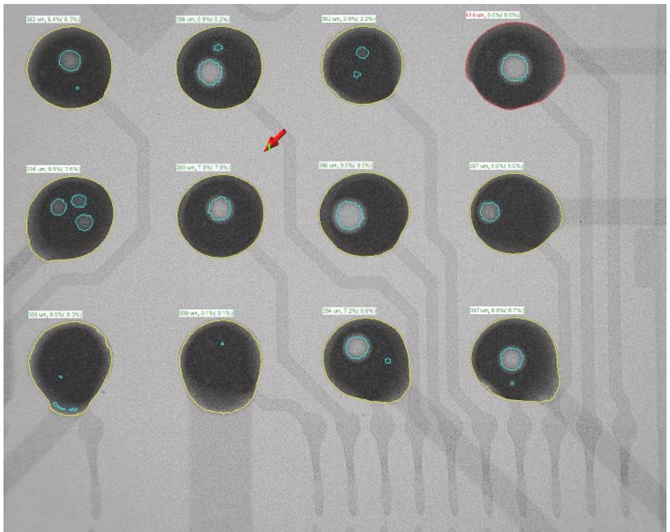
- Voiding increases when using the most commonly available Tin/Silver/Copper (SAC) alloys as solder pastes.
- These SAC alloys have a higher melting point compared to tin/lead (Sn/Pb) solder.
- The increased surface tension that the SAC alloys have adds to the propensity for voiding.
- Any moisture entrapment within PCB's and components becomes more of an issue with steeper temperature gradients and higher melting point materials.
- Many lead-free solder pastes contain more aggressive flux chemistries than lead containing materials. This often means a higher volume of gas has to vent through the joints.
- Reflow profiles used during the SMT process and cooling rates following reflow have a significant influence on the level voiding and the position of the voids within the joints.

Whilst the above reasons are well established as the causes for more voiding when using lead-free materials, there is, however, much conjecture on what is the safe level of total voiding, the largest safe single void, the safe position of voids within a joint and much else. This paper will not enter into this debate, simply report on findings and draw comparisons.

BACKGROUND
This paper brings together results from the SMART Group Hands-on Lead-Free Experience 2003 (1), where circuit boards with differing pad finishes were assembled over two days using exactly the same materials, components and conditions. The boards were then reflowed by either standard convection reflow or by vapour phase. For this report, the results using convection reflow only have been included. The results from the vapour phase can be found in reference 1. The omission of the vapour phase data in this paper is simply to allow accurate comparisons between the board finishes and should not be seen as any comment on vapour phase technology. The circuit boards were all made by the same company, stored in the same way, etc. In short, everything possible was done to allow a "level playing field" for all board finishes. Following reflow, the solder-balled devices on these boards were then subjected to x-ray

inspection using a Dage Precision Industries digital x-ray inspection system with automated BGA inspection routines and void calculating software. (Figure 1)

In addition to this data, several other companies, who have undertaken similar exercises, have allowed access to their data, on the understanding that certain details remain confidential.



382, 6.4, 6.3	386, 8.9, 8.2	382, 2.5, 2.2	414, 8.6, 8.6
394, 9.5, 3.6	388, 7.0, 7.0	386, 9.8, 9.8	387, 5.0, 5.0
389, 0.6, 0.3	398, 0.1, 0.1	394, 7.2, 6.8	397, 6.5, 6.3

Figure 1: This data from the x-ray system shows the automated BGA calculations. The first number is the ball diameter in microns, the second is the total percentage of voids within the solder ball and the third provides the percentage of the largest single void. For clarity in this paper, these values have been repeated in the table corresponding to the array of solder balls in the image.

PAD SURFACE FINISHES

There are many possible surface finishes available in the market place with most only differentiated by brand name. Therefore, this paper will define the results relating to the materials used within the surface finish and their methods of application. The most popular types surface finish were chosen for evaluation. These are described below. Some are more suited for lead-free applications than others and a few notes to this effect have been added. The five surface finishes chosen below represent a good cross section of those currently available and provide a solid basis on which to evaluate the results.

OSP (Organic Surface Preservative)

This is simply an organic treatment applied over clean copper pads to prevent oxidation. It burns off during reflow to allow soldering to the copper. Due to the poor wetting of lead-free pastes, bare copper can be left exposed after assembly. OSP is not suitable for repeated assembly cycles. However, it is the cheapest surface finish and if it is damaged it is easy to remove, clean the pads and replace.

Immersion Tin

By removing the oxide from the copper pads and processing the boards using this chemistry a layer of tin is deposited over the pad areas. As tin is the major part of the lead-free solders, the metallurgy of this finish is very suited to lead-free applications. However, there is the fear of the production of "Tin Whiskers" when using this finish. "Tin Whiskers" are thought to be formed when the tin is under stress producing dendritic metallic growth that could cause shorts on the board. There is currently much debate on this subject.

Immersion Silver

This is an electro-less deposit of silver, similar to the tin finish above but heavily promoted at the moment due to the issue of "Tin Whiskers". Its cost is similar to that of immersion tin, which lies between that of Nickel/Gold and HASL.

Electro-less Nickel/Immersion Gold (ENIG)

The mechanism here for protecting the pads is slightly different from the previous finishes. The gold provides a shield to stop the nickel from oxidising in air. When it is soldered, the joint is formed with the nickel, not the copper pad. This is the highest cost process, but provides a very flat, easy to solder surface. However the chemistry has to be well controlled or defects can appear.

Lead-Free Hot Air Solder Level (HASL)

This is the type of board finish that was preferred for many years but then fell out of favour as Quad Flat Packs (QFPs) and other high I/O devices became common. At that time, the board manufacturers could not give the assemblers a sufficiently flat platform to mount the QFPs with this finish. The process is much improved today, however, giving a much better surface. The concern today is that the move from leaded HASL to lead-free HASL could put more stress into the bare board, due to the higher temperatures required. This could cause board warping or, in severe cases, delamination of multi-layer boards. Having said all this, it is a low cost option without any metallurgy miss-match issues.

VOID AND MEASUREMENT CALCULATION

The use of a digital x-ray system (2) with 65,000 levels of greyscale allowed voiding to be located and measured accurately. The algorithms used give accurate, reproducible values for void percentage and the largest single void size. The ability to view the solder balls at high oblique angles for any location 360° around each solder ball permitted the position of the voiding to be confirmed (figures 2 & 3). At the start of this work the void position was not considered to be very significant but subsequent findings, indicated later, did change this assumption dramatically.

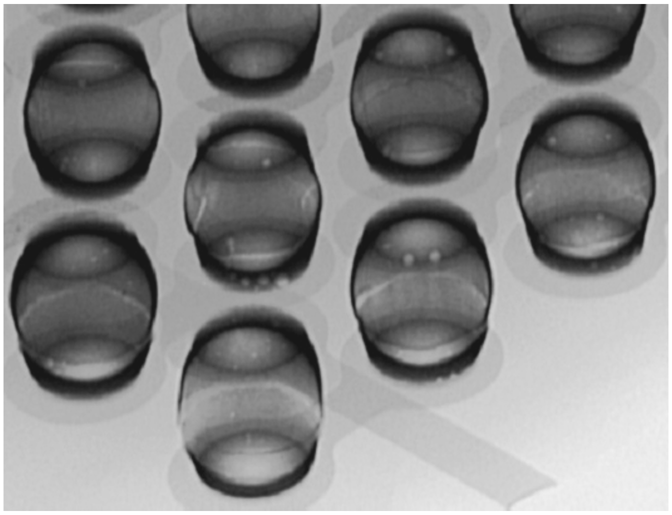


Figure 2: This is an oblique view x-ray image of a BGA assembled with Nickel Gold pad finish exhibiting voiding and cracks at the middle of the joint.

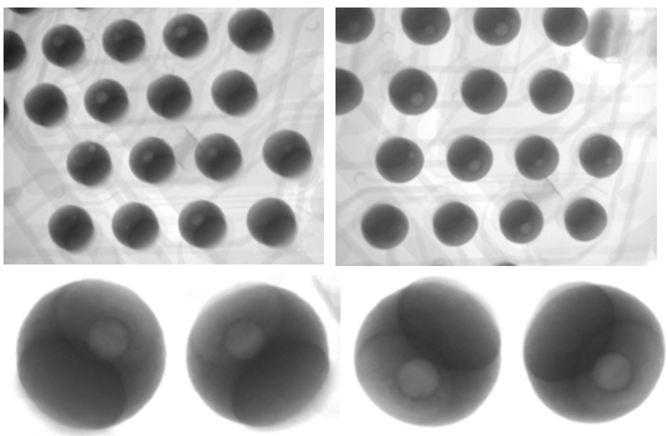


Figure 3: Oblique angle x-ray views taken at different orientations around a BGA (with a magnified view of a single solder ball). This show the position of the voiding with respect to the joint interfaces. The joint interfaces can be clearly seen as ellipses within the solder ball owing the x-ray system greyscale sensitivity.

RESULTS

The total percentage void results for the different pad finishes are displayed in graphical form as a mean value of all of the measurements taken for each pad finish. Any results, which varied more than two standard deviations from the norm, were not included, as these would tend to point towards an issue with the process, component or bare board finish and therefore outside the scope of this investigation. However, one of these issues will be discussed further at the end of this report.

The largest single void results display the average size of the five largest individual voids for each type of pad surface finish.

Average Total Voiding Percentage

The results from chart 1 indicate that those surface finishes that exhibit the lowest void percentage are immersion tin and lead-free HASL. This could be due to the affinity of the pad finish to that of the component termination and the solder paste.

It could be construed that the two pad finishes with the highest percentage of voids are the ones which are likely to produce the most gas from the action of removing oxide from the surface prior to soldering taking place.

It may be possible to draw more conclusions from these results, however there are many influences which can affect the levels of voiding and it may be misleading to look any deeper into these numbers.

Currently an IPC Class 1 joint allows 30% of the ball area to be devoid of solid material, so all of these results could be considered as good.

There is also a theory that voids inside a joint can act as stress relievers and reduce or diffuse cracks in the same way that rubber is used in castings and adhesives.

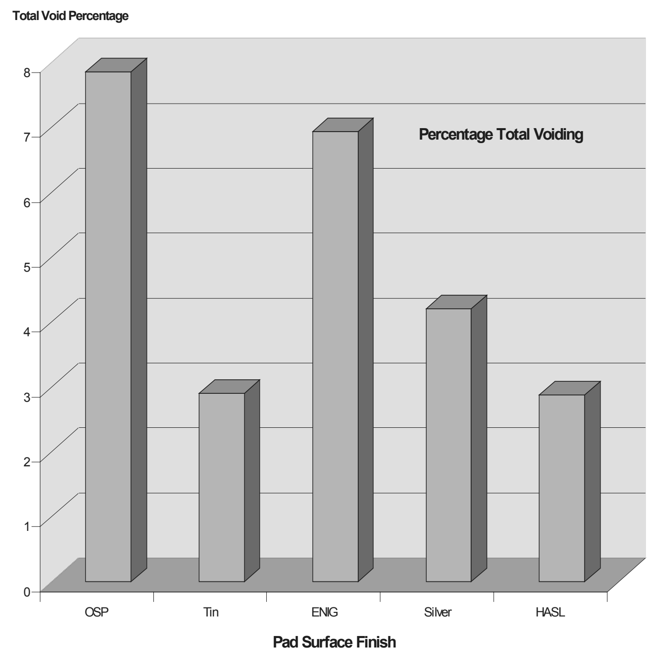


Chart 1: Average total void percentage of all BGA balls by board finish type.

Largest Single Void Percentage

These results, see chart 2, show that the voids in OSP board finish joints tend to be much larger compared to other finishes. When taken with the previous results, it suggests that the OSP finish produces, or traps, the most gas in lead-free joints.

It is generally accepted that small voids are potentially less of an issue than large voids, but there is a conflicting opinion that any voiding is detrimental to joint quality. Such void variation also points to the fact that the ENIG pad finish produced a quite high percentage of voids, which tend to be small in diameter. This could caused because the gas produced during reflow is of a different composition to the other finishes. As such, the gas takes longer to produce and is "frozen" in the solder before it joins together to form larger bubbles. It is noticeable from the results that the voids within the ENIG finish boards are more central, or close to, the joint face, whereas with OSP finish the voids are often close to the joint open edge.

The void profile of tin, silver and lead-free HASL finishes is much smaller and therefore it could be concluded that these pad finishes are more suitable for lead-free assembly.

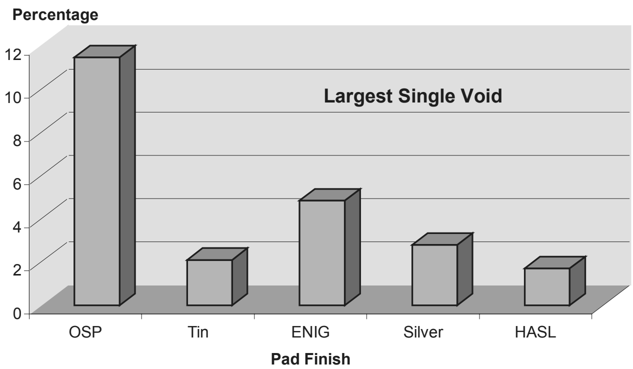


Chart 2: Single largest void average percentage by board finish type.

CONCLUSION AND ADDITIONAL FINDINGS

By automatically inspecting BGAs on differently finished boards within a digital x-ray inspection system, the total void percentage per ball and the single largest void were calculated. The results highlighted variances in the quantity of voiding depending on which board finish was used. Based on this data, it has been suggested that immersion, tin, immersion silver and lead-free HASL finishes might wish to be considered as preferential for use with lead-free assembly.

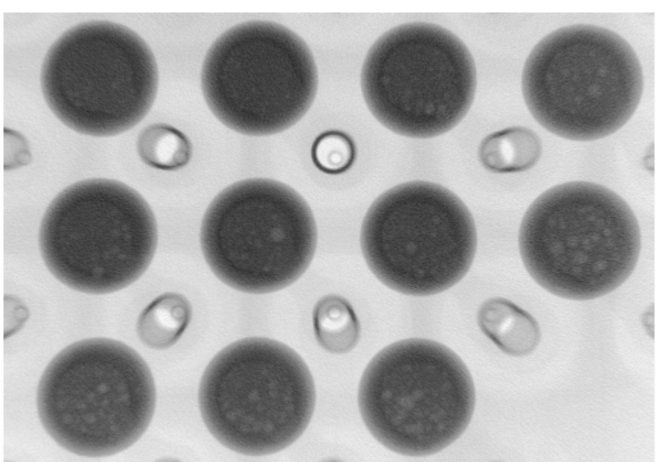


Figure 4: This shows a large number of small voids all within a smaller area of the balls. This suggests that all the voids are in the pad to void interface. Oblique x-ray views confirm this to be correct.

Whilst conducting this research, another voiding phenomenon was observed for the first time, which has the potential to become a severe failure mechanism. It is not easy to locate and cannot be seen on many x-ray systems. As can be seen in figure 4, this type of voiding consists of a large number of very small voids formed at the pad to ball interface. As all these voids lie in the same plane within the joint itself, the appearance of this phenomenon could easily lead to an open circuit or high resistance joint after thermal cycling, board burn in or, worse still, failure in the field. See figure 5.

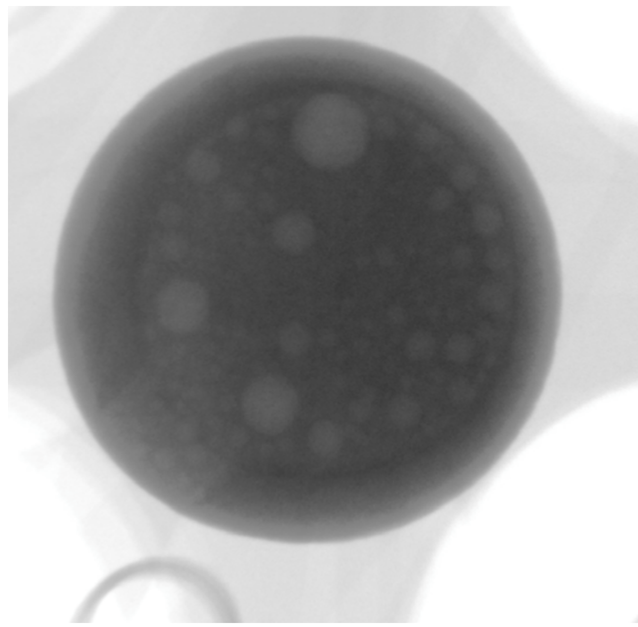


Figure 5: The above picture is an excellent example of this multiple-void defect. Not only does it show the voiding in the pad area, it is also visible on the track which can be clearly seen in the lower left-hand side of the image

The potential causes of this multi-small-void situation, which some have called 'Champagne Voiding' because of the profusion of small bubbles are:

- Oxidation of the pad finish
- Issues with the PCB manufacture, or
- Some form of inter-metallic reaction

Such 'Champagne Voiding' has been observed, so far, on boards with OSP, Nickel/Gold and immersion silver pad finishes. However, it is seen infrequently and without a defined pattern. This would tend to point to a random failure mode, not simply a material mismatch. Needless to say, more evaluation is going on and it is hoped to report more findings soon.

REFERENCES

[1] Results from Hands-on Lead-free Experience held at Nepcon UK, Brighton, England in 2003 and 2004. See www.smartgroup.org for more details.

[2] Bernard, D. and Ainsworth, S., “Comparing Digital and Analogue X-ray Inspection for BGA, Flip Chip and CSP Analysis”, APEX, Anaheim, CA, 2004.