Addressing the Challenge of Head-in-Pillow Defects in Electronics Assembly

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Abstract

The head-in-pillow defect has become a relatively common failure mode in the industry since the implementation of Pb-free technologies, generating much concern. A head-in-pillow defect is the incomplete wetting of the entire solder joint of a ball-grid array (BGA), chip-scale package (CSP), or even a package-on-package (PoP), and is characterized as a process anomaly, where the solder paste and BGA ball both reflow but do not coalesce. When looking at a cross-section, it actually looks like a head has pressed into a soft pillow. There are two main sources of head-in-pillow defects: poor wetting and printed writing board (PWB) or package warpage. Poor wetting can result from a variety of sources, such as solder ball oxidation, an inappropriate thermal reflow profile or poor fluxing action. This paper addresses the three sources or contributing issues (supply, process and material) of the head-in-pillow defects. It will thoroughly review these three issues and how they relate to result in head-in-pillow defects. In addition, a head-in-pillow elimination plan will be presented with real life examples to illustrate these solutions.

Introduction

While the electronics manufacturing industry has been occupied with the challenge of RoHS compliance and with it Pb-free soldering, trends towards increasing functionality and miniaturization have continued. The growing use of ultra-fine pitch and area-array devices presents challenges in both printing and flux technology. The decreasing size and pitch of components create new problems, such as head-in-pillow.

What Does Head-In-Pillow Look Like?

A head-in-pillow defect is the incomplete coalescence of the solder joint between a BGA, CSP, or PoP and the printed solder paste. For some reason, the PWB's printed solder and the package's solder spheres do not come together to form a single mass. At first glance, it looks as if a film has formed on the surface of the molten solder, preventing the merging of the printed and package solders. In fact, this may be true, as in some instances there seems to be an oxide film on the surface of the molten solders. In other instances, it appears that upon cooling, the exterior has already cooled enough to prevent the coalescence of the printed paste and the sphere at re-connect when the warpage subsides. From the cross-sections, it actually looks like a head has pressed into a soft pillow (see Figure 1).

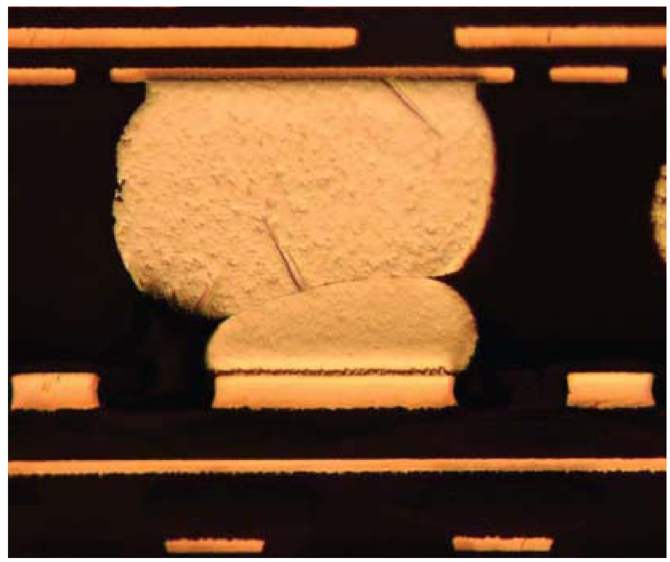

Figure 1. Example of a head-in-pillow (HIP) defect.

It is these issues that are the cause of head-in-pillow defects: poor wetting and warping of the component. Upon examination, the two causes are indistinguishable, but can be identified because random head-in-pillow defects are caused by poor wetting, while warping causes edge or center defects. Sources of poor wetting or warping can be sorted into three possible causes: supply issues, process issues, and material issues.

Supply Issues

Supply issues that form head-in-pillow defects can be identified as issues that arise before the BGA, CSP or PoP packages are placed on the assembly line for production. This includes sphere oxidation during manufacturing, packaging of the semiconductor, or shipping and storage. The manufacturer or product assembler cannot easily control these issues, but they must be understood and preventative steps must be taken, to minimize the problems.

One manufacturing defect that has surfaced as a possible, but not well-known, contributor to head-in-pillow is silver segregation. Silver segregation is the migration of silver-laden intermetallics within the solder to the exterior surface of the sphere upon cooling. Some test cases have measured silver levels as high as 35% at the sphere surface. The high silver content at the surface changes the entire dynamic of the wetting and reflow phase of the component attach process. Silver segregation will cause an improper melting of the sphere such that it will not wet to the bulk solder of the paste. The source of the silver segregation is not well known, but it appears to develop from the supplier's lack of control within the cooling process.

Another major contributor to supply issues is the oxidation of the package's spheres. Sources of sphere oxidation are component storage, which includes moisture sensitivity level (MSL) and inert gas dry-box storage, baking processes and the component's on-line time. Inert atmosphere and humidity levels are the main controllable storage factors, which prevent oxidation and/or hydroxide effects. The baking process of the component can, and will, contribute to the increased oxidation layer of solder spheres.

Process Issues

Head-in-pillow defects caused by assembly line setup are categorized under process issues. These include printer setup, placement setup and reflow. If the solder printer is not set up properly then the paste printing process will not work effectively. Printing issues not related to solder paste properties are poor registration, imperfect or improper printer setup and poor stencil design. An improper board setup in the printing process can also contribute to poor and inconsistent transfer efficiency. Poor registration leads to printing off-pad or pump-out and is another part of the printer setup. Improper or poor setup may not be easily recognized for large or standard size component assembly, but when the solder paste deposits decrease below an area ratio of 0.66, the board setup is very critical. The last important area of focus for the printer setup is with board support and gasketing of the board to the stencil. To prevent this, it is important to make sure that there is no standoff between the stencil and the PWB. In some cases, dedicated vacuum board support may be required to obtain optimum gasketing and registration.

Stencil design is probably the most important of the process issues. Poor stencil design can lead to insufficient solder deposits, which can prevent the component from touching the paste or not having enough flux to overcome the oxide on the sphere or in the paste. Area ratio, as well as transfer efficiency, plays a huge role here. Although stencils may offer a small increase in the amount of paste applied, it is the paste itself that usually makes the difference. By feeding the stencil details into the paste measurement system at onset, the system can calculate the theoretical amount of paste that should be deposited, and then create a percentage (efficiency) by measuring the amount of paste that was actually deposited.

Ensuring High Transfer Efficiency

Inconsistent or reduced transfer efficiency will reduce the total solder paste volume deposited on the solder pad, and thus possibly contribute to the reduced wetting of the flux, causing a head-in-pillow defect. Transfer efficiency (see Figure 2) is just now becoming something that we are tracking scientifically (read statistically). Some variables that can affect transfer efficiency are stencil type, atmospheric conditions and the paste itself. Room temperature, and sometimes humidity, also affects transfer efficiency as the viscosity usually drops when solder paste is warmer, as well as causing the paste to become less tacky. Humidity affects water-washable pastes in the same ways, so much so that cold slump may be induced.

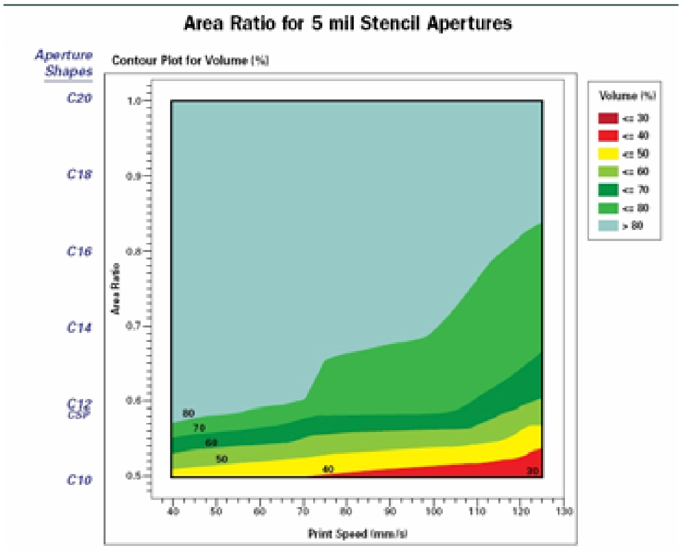

Figure 2. Example transfer efficiency contour plot of print speed versus volume.

Measuring transfer efficiency can be an effective way of ensuring the maximum return from a solder paste, but transfer efficiency can only be measured once the variation has been taken into account. It is the variation in solder paste deposits that can indicate the defect level. The consequence of excessive variation is susceptibility of the ultra-fine pitch defect levels. Because there is no single answer for all applications, we must look at the individual solder paste printing processes. Only then can you define the transfer efficiency's upper and lower specification limits. Each individual process has a different tolerable lower specification limit with regard to transfer efficiency, which must be established through testing. To recognize the amount of variation in, for example, solder paste height, eliminating the variation due to all other causes outside the actual printing process must occur. Some of the more common causes for variation are related to board support and squeegees. As control of these basic features of the solder paste deposition process is improved, the variation in solder paste height will be minimized and defect levels will decrease (see Figure 3).

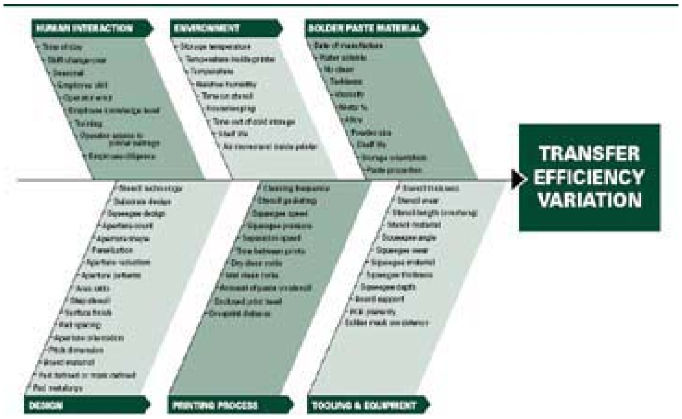

Figure 3. Transfer efficiency fishbone diagram.

Reflow

The majority of head-in-pillow defects come from the reflow process, which is a balancing act. A good profile is a split between too little and too much. During reflow, warping of the component lifts one edge, opposite edges ("Pringle® effect" or "potato chip") or even the corners or center spheres. This is why it is important to read the component manufacturer's recommendations and ensure the reflow temperature doesn't exceed the maximum processing limitations. This was brought to light when an OEM called to say they had seen a reduction in head-in-pillow when they switched solder pastes. After recommending a lower peak and reviewing the components' ratings, it was found they had been running too hot for many years!

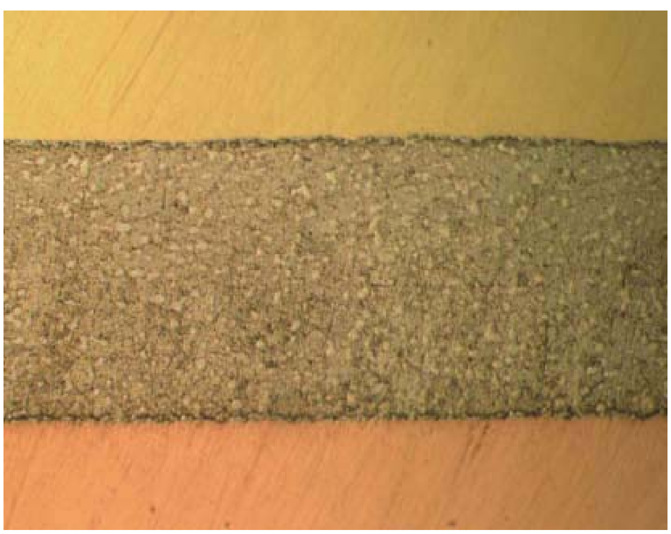

Figure 4. Large crystalline grain structure cross-section.

Typically, a reflow profile is configured to work with the available solder and components to give the highest tensile strength possible. However, this may need to be modified to control head-in-pillow defects. Besides tensile strength, some secondary goals are good wetting, solid intermetallic formation, homogeneous solder joint, and a small, tight crystalline structure (see Figure 4). All of these are achieved through reflow process management.

There are four parts of the reflow process that can be adjusted to reduce head-in-pillow defects. They are ramp rate, time above liquidus (TAL), peak temperature, and cool-down rate. Each one of these has a different effect on the final solder joint and each one is important.

Head-In-Pillow and Graping - Hand-in-Hand Defects

Ramp rate is literally the first step in the four-part reflow process and plays an important role in the formation of the intermetallics. Ramp rate, from room temperature to peak, should be watched for a few reasons. Ramp rates determine the spread and volatization of the flux, as well as having a sinister hand in head-in-pillow, graping, and oxidation build-up. A slow ramp tends to allow more solvent volatization, or "out gassing." This keeps the flux close to where it was applied, reducing spread and slump. It also gives enough time for the full volatization of the solvents in the flux, usually reducing voiding, as well as keeping the ΔT of the board well under 10°C. All this extra time may have a detrimental effect on some other points of interest, though, especially with the oxide build-up of component and substrate metallizations, as well as the solder alloy itself.

Flux exhaustion caused by extended reflow is another factor behind head-in-pillow and graping. Incomplete coalescence or "graping" (see Figure 5) is another side effect of flux exhaustion during reflow and is increasing in number. Graping occurs when the outer layer of alloy powder spheres have lost their protective coating of flux and do not fully coalesce into the main bulk of the solder during reflow. This produces an irregular surface finish, similar to a cluster of grapes. When BGAs and CSPs are affected by this same flux exhaustion, it is usually seen as a head-in-pillow defect.

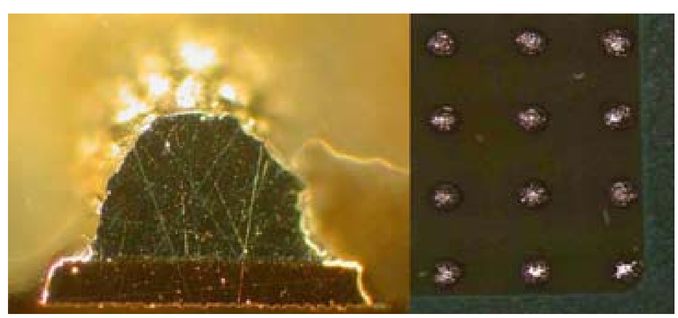

Figure 5. Cross-section of an acceptable solder joint with surface graping.

In cross-sections of these joints where graping has appeared, it seems that the wetting, inter-metallic layer, and tensile strength have not been affected and electrical continuity is maintained. This suggests that the graping is merely superficial. However, manufacturers should still try to prevent graping because quality assurance inspectors usually correlate an abnormal solder joint appearance with a “cold” or defective solder joint, and visual inspection equipment is trained to look for such characteristics in solder joints, reporting them as defective. [1]

Warpage

One of the major contributors to the supplier issues is the integrity of the BGA component. The main component integrity issue that contributes to head-in-pillow defects is component warpage during the product manufacturing reflow process. If the component begins to warp during the soldering process, the component spheres will separate from the solder paste and not wet to the bulk solder. Component package design, materials, and integrity all contribute to the potential warpage of the part. Internal verification testing should be completed to understand the potential component warpage prior to the implementation of a new package into the manufacturing process.

Time-above-liquidus (TAL) and peak temperatures have the same type of affect on head-in-pillow. Consider TAL and peak temperature as “total heat input” as you can have a longer TAL and lower peak, or a higher peak and shorter TAL. As it is, together they can play the most vital role in the reflow process. The name of the game is heat. Heat is responsible for solid intermetallic formation and a homogeneous solder joint, as well as proper flux deactivation. It is this heat input that warps the BGA and CSP packages, leading to head-in-pillow defects.

Cool down is the last line of defense against a poor solder joint. This is because the cool down ramp rate controls the formation of the crystalline structure of the metal lattice. The smaller, tighter, and denser we can make the crystal lattice, the higher the joint strength. Because it is along these facets of the crystal that the joint fractures, the longer, larger, and sparser the crystal facets are, the easier they are to cleave.

One way of visually investigating whether the solder joint is tight enough is to look at the post-reflow surface finish of the solder joint.

Material Issues

Head-in-pillow defects related to solder paste or flux performance are classified as material issues. These include poor transfer efficiency on standard apertures, insufficient wetting (fluxing) capacity, low oxidation barrier, and low activity. The key to overcoming head-in-pillow defects is to get each component sphere to contact, and stay in contact, with the soldering material, mainly the solder paste. If the solder paste itself has poor or inconsistent transfer efficiency, then how do you know that there is even going to be contact between the sphere and the paste? Low area ratios can account for a lot of the transfer issues, especially if the stencils are not electro-polished or electro-formed (e-fab); you must match the material set to the process and stencil design.

The second half of the solder paste equation is the fluxing action. There are three parts to this: activation, oxidation barrier and stencil/tack life. High activation is an obvious choice because this is the working part of the flux, which removes the oxides from the solder and the spheres. Oxidation barriers, such as a higher rosin content of the paste’s flux, are useful because it will protect the alloy from forming new oxide, which means there’s more activation for the component’s oxide. Also, it usually adds tack, which is a huge benefit for overcoming head-in-pillow. If the paste stays tacky and the package does warp, the paste will stretch to provide a continuum, so the solder and component will become a single alloy mass upon reflow. There are artificial ways to add an oxidation barrier and additional activation, such as nitrogen reflow or a flux/ paste dipping process. Nitrogen reflow *prevents* the formation of additional oxides during the reflow process, but does not *remove* oxides and hydroxides that have already formed on the components. Flux or paste dipping are viable options because this adds activation directly on the component, rather than leaving it to chance on the board. In addition, this flux or paste can be used for rework on the back-end. Of course, material solutions such as matching the solder paste to the process can overcome both supply and process issues.

Materials Testing

New testing procedures are available for developing a solder paste resistant to head-in-pillow. [2] A novel method of introducing a solder sphere into molten solder paste seems to merit some further investigation. It seems that even molten solder paste can exhibit benefits from a flux that has a sufficient oxidation barrier (see Figures 6a and 6b). In recent testing, solder pastes that have exhibited good coalescence results in assimilating a solder sphere into the molten solder after some time, had also performed well in eliminating head-in-pillow defects.

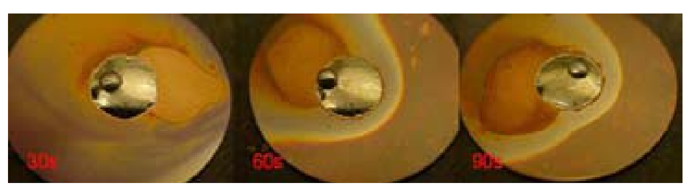

Figure 6a. Solder sphere coalescence test at 30, 60 and 90 seconds (poor oxidation barrier).

Other tests that have proven useful include a detailed "tackiness" test, in which not just the peak force is determined, but also "stringiness." Stringiness is determined by total distance the solder paste will stretch before the force goes to "zero," in other words, how long the paste will stretch before it actually breaks.

Figure 6b. Solder sphere coalescence test at 30, 60 and 90 seconds (superior oxidation barrier).

This is important because a long stringiness can allow for more warpage of the package, yet still maintains contact with the main mass of solder paste on the board. This ensures that when it does liquefy, the two will remain in electrical and physical contact. Contact is essential for maintaining the link between the PWB and sphere surfaces. If these two surfaces technically never separate, there is no way for a head-in-pillow defect to form.

Conclusion

Through failure analysis and empirical testing, it was determined that there were two major causes of HIP defects, which are poor wetting and warpage. After breaking down the entire assembly process, three areas were determined to contribute to the poor wetting and warpage: supply, process, and material.

The most difficult issue for the user to control is the supply. The BGA or CSP manufacturer may provide a component that will always have the tendency to warp or not have controls in place to reduce the oxidation level on the spheres. Therefore, the user must then make sure that our manufacturing processes and controls within the product assembly are optimized. Viewing and adjusting this process through the use of statistics yields two important objectives. First, an outside perspective on each part of the process arises by focusing on the details of each segment step, sharply increasing the understanding of the process. Secondly, using this data to eliminate problems from the process itself, while streamlining each step of the process and discarding surplus, increases process flow and cost savings, while defects minimized and yields increased. Polishing the printing process, where the majority of all solder issues can be traced, sets the foundation for success. Once consistent printing is assured, then other issues such as graping and head-in-pillow defects may be eliminated through optimization of the reflow parameters or evaluating a solder paste with an enhanced oxidation barrier, longer tack life, or better wetting performance. As shown, head-in-pillow defects can be eliminated through tight process controls and robust materials.

References

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