A Proposed Mechanism and Remedy for Ball-in-Socket and Foot-in-Mud Soldering Defects on Ball Grid Array and Quad Flat Pack Components

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Abstract
A common source of defects on area array components is the "ball-in-socket" (or "pillowhead") defect. This defect is defined as one or more connections that show physical contact but no wetting or intermetallic connection after reflow. The defect is difficult to detect on x-ray, and can only really be verified on cross section or if the joint in question is in a location accessible to visual inspection. Worse, the assembly may pass electrical test, since there may physical contact between the bulk solder and the metallization on the component lead. The lack of an intermetallic bond results in almost immediate failure in the field, however.

The same sort of defect can also occur on large quad flat pack components, with the component lead resting on top of the solder deposit without a metallurgical connection. In this case, the defect is referred to as a "foot-in-mud" defect.

The source of these defects is not always obvious, and little has been written about their prevention. This paper presents an in-depth examination of the physical causes of this defect type, along with specific steps that may be taken to eliminate it. There are several potential root causes, but the end result of all is vertical movement of one portion of the component (tilting), resulting in lack of contact with the land during soldering. Formation of an intervening oxide layer prevents soldering, even when the two metal surfaces are brought together.

Prevention of these defects relies on good design practices that limit thermal gradients, well-designed reflow profiles and capable reflow equipment. The specific solder paste used can also have an impact on the appearance of this defect, for several reasons including the alloy melting behavior, flux activity and rheology, and printing characteristics.

Background
Ball-in-socket defects often occur randomly on ball grid array (BGA) components without an obvious root cause. Figure 1 demonstrates the appearance of a typical ball-in-socket defect. Note that the ball appears to be connected to the solder but is actually resting in a depression in the solder without actually making a connection to the bulk solder.

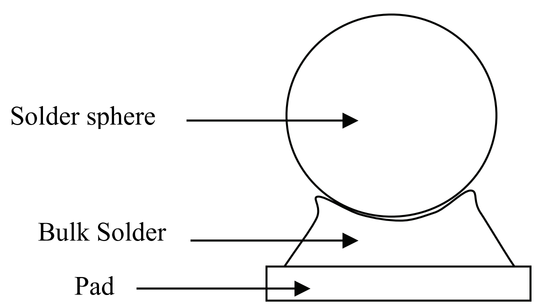

Figure 1 – Side view of Ball-in-Socket defect

Foot-in-mud defects are similar to the ball-in-socket defects described above, except that these non-contact failures occur on large quad flat packs (QFP) instead of BGA components. Figure 2 demonstrates the appearance of a typical foot-in-mud defect. Again, the component lead is sitting in a depression within the solder but not actually metallurgically connected to the bulk solder.

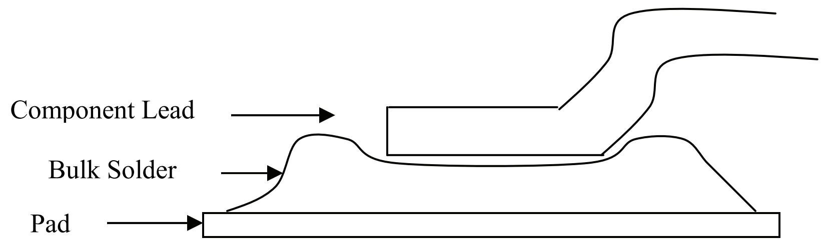

Figure 2 – Side View of Foot-in-Mud Defect

Of considerable concern to customers experiencing these defects, they are not always caught at the inspection level or at the functional test level. Due to the formation of the defect often resulting in a partial contact between the bulk solder and the component lead (or the ball in a BGA device), the final circuit often passes functional, optical and in circuit testing. However, since there is no real metallurgical connection (with the appropriate intermetallic layer and wetting action onto the leads), such weak connections will fail quickly if they do pass through all post-soldering testing. Circuit boards with ball-in-socket or foot-in-mud defects often fail during post-soldering assembly processes, shipment, upon thermal expansion and contractions, or actual product use. The possibility that these defects are being produced and not easily caught is particularly troubling to assemblers and their customers alike.

Electronic assemblers often generate this defect and have little idea regarding the potential root cause. Among customers that have experienced this defect, the most common belief is that such defects are caused by some combination of a tough-to-solder component (or component contamination) along with a solder paste that is not sufficiently active enough to wet the component surface. However, solderability tests on raw components rarely support this claim. As this defect commonly occurs in some of the easiest soldering applications (wetting of SnPb solder onto SnPb-plated components or SnPb solder spheres), it seems particularly unlikely that poor component solderability and/or weak flux activity could be the culprit in this case.

It has also been proposed that this defect can occur as the result of random paste deposits that are not of sufficient height and/or volume. Such paste deposits may lack the height for the component lead to be placed properly into the paste. This could occur due to a clogged aperture, poor paste release, or stencil damage, among other potential reasons.

Another commonly proposed root cause of this defect is the co-planarity of the QFP leads or the BGA solder spheres. Such co-planarity issues may be a factor in foot-in-mud and ball-in-socket defect formation as it can result in the solder and the component losing contact with each other during the soldering process.

However, in many cases, the proposed root causes above can often be eliminated based on the repeatability of the defect in a particular location on the component. If the defect always occurs on the same side or same corner of the device, it would become unlikely that the defect would be caused by a solderability issue, uneven paste deposition or component co-planarity problem. However, if the defect occurs randomly across the entire component, solderability issues, paste deposition and component co-planarity need to be strongly considered.

Charting the location of the ball-in-socket or foot-in-mud defects across a particular BGA or QFP often leads one to discover that the defect does happen much more frequently on one side or corner of the component than the opposing side or corner. In many of these cases, customers have noted that over 95% of the defect occurrences occur on the same corner or side of the component. As example of a typical defect map on a BGA is shown in Figure 3.

Note that all of the defect locations represented in Figure 3 have occurred in the top-left corner of the component. This type of repeatability in one geographical area of the component could not be caused by poor solderability, inadequate paste height/volume, or component co-planarity. Another root cause must be the culprit in this type of defect. The purpose of this work is to propose another potential root cause and identify a remedy for these defects.

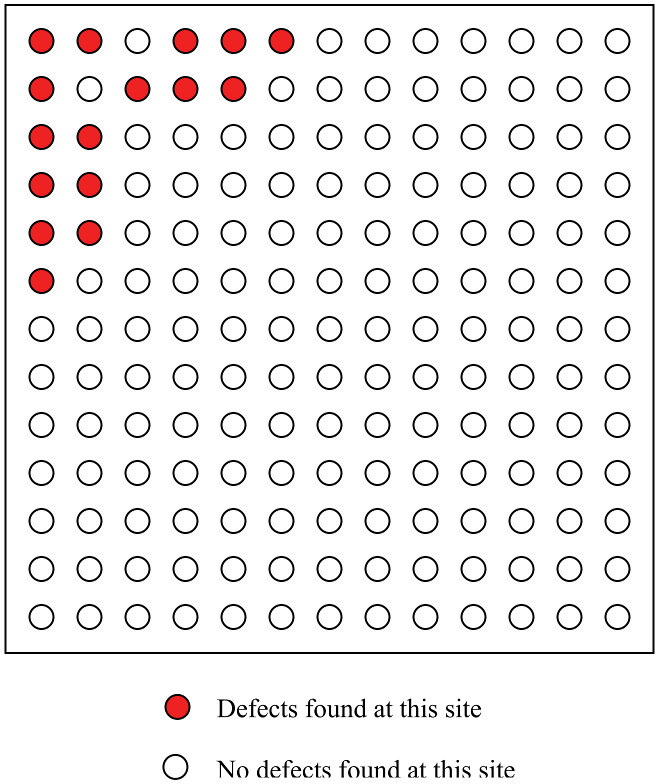

Figure 3 – Typical BGA Ball-in-Socket Defect Map

Introduction
Customers often approach soldering materials suppliers with a request for assistance in resolving ball-in-socket and foot-in-mud defects. Such defects do not always have an obvious root cause, and the defect rate is low enough that testing various hypotheses can prove difficult at most customer sites. Many customers experience the occasional defect of this variety and fail to investigate it properly due to the low rate of incidence and the difficulty in assigning root cause.

After careful consideration of the set of circumstances within several customer investigations of this type, it became clear that there was a misconception about the likely root causes for this type of defect. Component solderability, paste height variation and component co-planarity have often been considered within such investigations and, in nearly all cases, did not impact the defect level whatsoever. Based on the geographical defect location data, it was clear that another factor was causing the defect. While examining the boards in question, the defects often appeared on the side or corner of the component that would appear to be cooler than the opposing side or corner. Such conclusions about the cooler and hotter locations on the component are often educated guesses based on the sizes and locations of the components surrounding the component demonstrating the defect. Equipment that measures the temperatures on various parts of the board during the reflow process can substantiate such guesses. In these cases, thermocouples can be attached to all four corners (or sides) of the component to establish the thermal gradient (Delta T) across the device. The defects repeatedly occurred on the cooler corner of the component, meaning that the top-left corner of the component depicted in Figure 3 would have been cooler by at least a few degrees when compared to the bottom-right corner. This led to the hypothesis that the Delta T across the component may be generating the defect.

Based on this finding, many customers try to increase the temperature across the board, hoping to increase the temperature at the cooler portion of the component in question. Such efforts also did not reduce the ball-in-socket and foot-in-mud defect levels. This indicates that while the reflow profile is somehow involved with the defect formation, that the defect is not driven by the solder not fully melting or not having enough time to adequately wet to the component.

Two customers were selected to participate in this work based on the mix of defects and the willingness to cooperate in the experimental reflow profile concept as a potential solution to their foot-in-mud and ball-in-socket defects. One customer (henceforth known as "Customer A") was a contract manufacturer building telecommunications equipment and experiencing a high incidence of ball-in-socket defects. The other customer (henceforth known as "Customer B") was an automotive subcontractor experiencing a high level of foot-in-mud defects on a large QFP. Both customers called their supplier with a request for assistance in reducing the incidence of these defects. Both companies attempted to reduce the defects through a handful of the aforementioned methods with no sustainable decrease in defect level. Neither assembler was able to sufficiently reduce the defects to an acceptable level to meet their customers' demands. The evidence accumulated at the two customer sites indicated that the defects created were random and no root cause was assignable. Despite the random designation of the defect, the customers had not necessarily verified the randomness of the locations of the defects.

Methodology
The two chosen customers had both indicated that their ball-in-socket and/or foot-in-mud defects were occurring at a rate of approximately 0.8 - 1%. Both indicated that they had examined several possible root causes, but the defects continued to occur randomly and at approximately the same rate.

Both customers provided a copy of their current reflow profile and analyzed the incidence level and locations of the aforementioned defects. It was immediately evident that the defects were not occurring randomly from a geographical standpoint on the component. Both customers reported that nearly all of the defect locations were clustered in one corner of component.

Customer A was using a reflow profile a similar to the one shown in Figure 4.

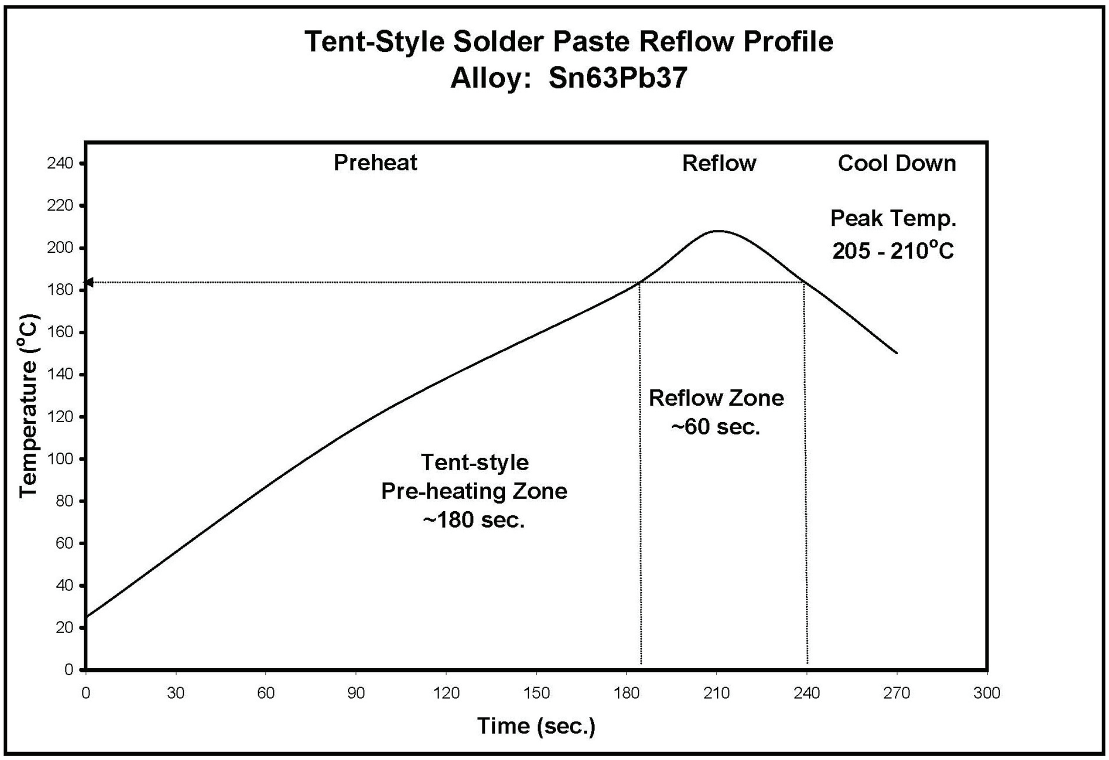

Figure 4 – Reflow Profile Used at Customer A

This profile is of the "ramp-to-spike" (or "tent") variety with no discernable soak zone. The ramp rate was a steady 0.9 – 1.0 ^{o}C/sec for the pre-reflow portion of the profile and the peak temperature was 205-210 ^{o}C. After measuring the temperature on all four corners of the component, it became evident that the ball-in-socket defects were occurring on the coolest corner of the component. Furthermore, the Delta T across the component was ~7 ^{o}C as the hotter corner reached the reflow temperature (183 ^{o}C), lending to a significant difference in melting times. This difference in temperature was driven primarily be the other components surrounding the large BGA, but was also exacerbated by the fact that the hotter corner was at the leading edge of the component and would therefore sooner experience the higher temperature of the subsequent reflow zones in the oven. A basic schematic of the board is shown in Figure 5.

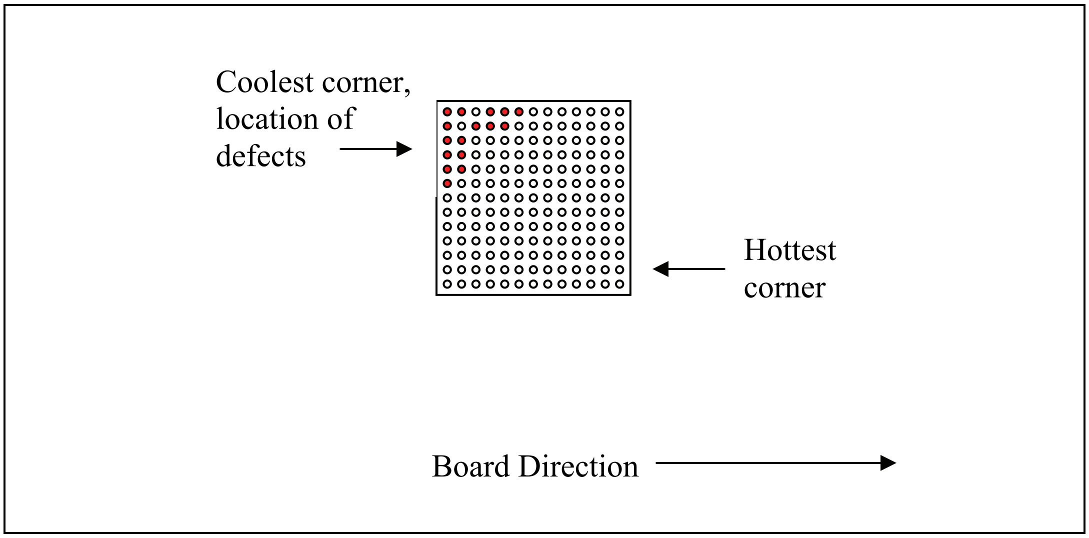

Figure 5 – Schematic of the Board at Customer A

Customer B was using a reflow profile with the general appearance shown in Figure 6.

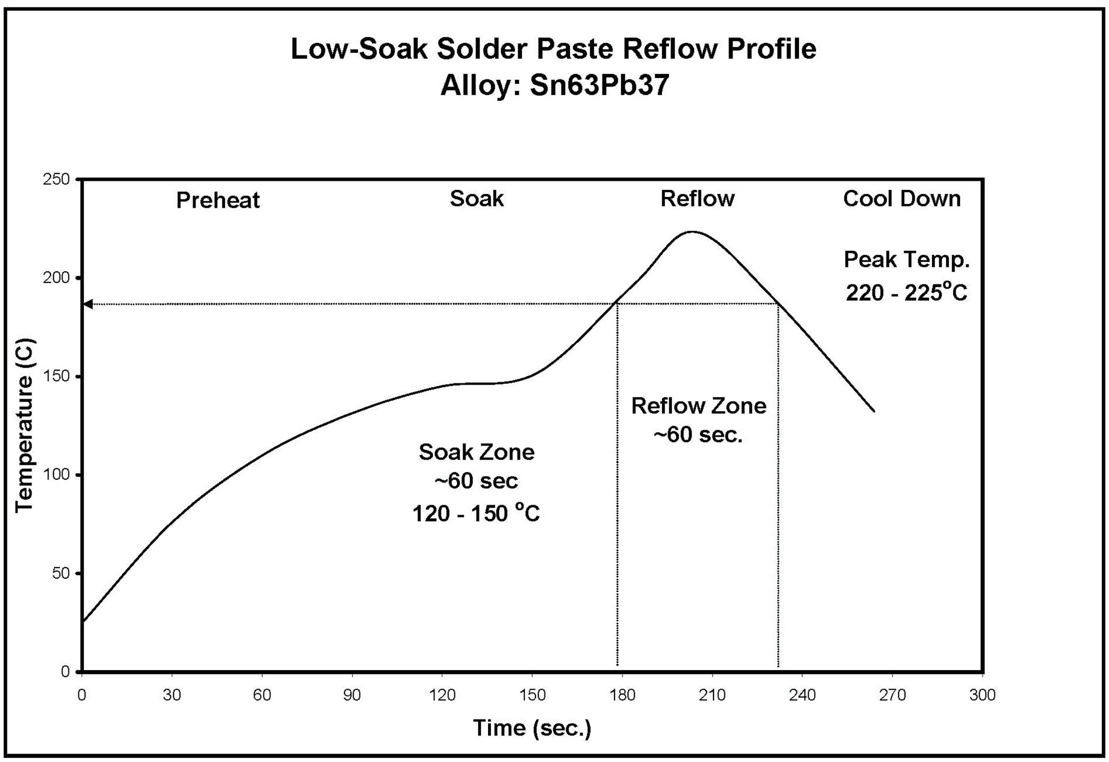

Figure 6 – Reflow Profile Used at Customer B

Note that the reflow profile used at Customer B is a "ramp-soak-spike" with a soak temperature of 120-150 ^{o}C and a peak temperature in the range of 220-225 ^{o}C. Upon performing a reflow profile specifically on the component demonstrating the foot-in-mud defects, it was found that the cooler corner of the component was the location of all of the foot-in-mud defects. It was noted that the Delta T from the cooler corner to the hotter corner was ~6 ^{o}C as the hotter corner reached the reflow temperature. This led to the hotter corner melting several seconds before the cooler corner.

With the knowledge that the defects were repeatedly formed on the coolest corner of the large components, both customers agreed to attempt to remedy the problem with a reflow profile adjustment. The hypothesis is that the Delta T issues are forcing some uneven wetting across the component, leading to some degree of component tilt. Component tilt may force the component leads in the coolest corner of the component to lose contact with the solder paste. This may only occur if the hottest corner is molten significantly before the coolest corner begins to melt and wetting to the component leads. The belief is that if the solder can be forced to melt at a more common time, such tilting will not occur and the ball-in-socket and foot-in-mud defects may be eliminated. A proposed profile that is believed to achieve this is shown in Figure 7.

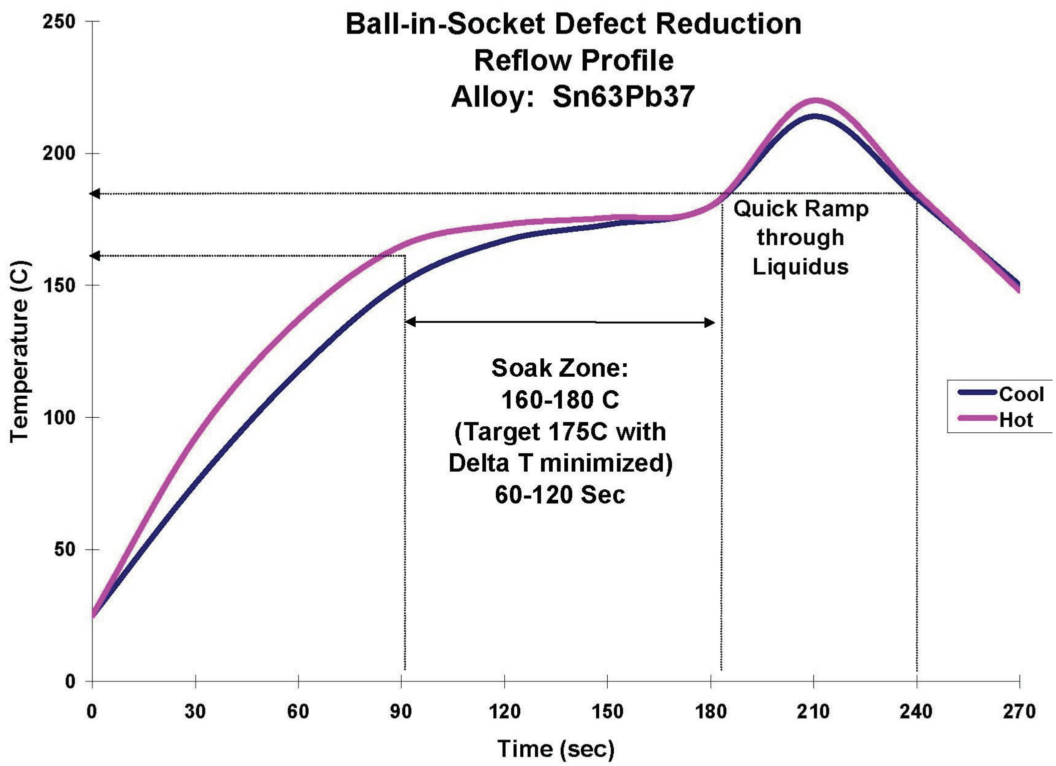

Figure 7 – Proposed Reflow Profile for Defect Reduction

Figure 7 includes reflow profile data for two locations on the board, which represent the hottest and coolest corners of the component where the defects are located. The first goal of the revised profile was to minimize the Delta T across the component as the solder reaches its liquidus temperature. This can be achieved by introducing a long, hot soak zone into the process. The target for soak time is 75+ seconds at 160-180 ^{o}C, with an ultimate goal of a soak temperature near 175 ^{o}C with a minimized Delta T.

The second goal of this profile was to quickly transition into the solder's liquidus phase. With a high soak temperature and minimized Delta T, the rapid heating between 175 – 190 ^{o}C is critical to force the solder to melt nearly simultaneously across the entire component.

The purpose of the revised profile was to make certain that the paste in the coolest corner and the paste in the hottest corner would melt at nearly the same instant. It is hypothesized that such a profile will eliminate the foot-in-mud and ball-in-socket defects that had been caused by uneven wetting forces driven by higher Delta T.

One of the customers met the reflow profile requirements described above with the following zone temperatures (all in ^{o}C): Z1: 130, Z2: 165, Z3: 180, Z4: 180, Z5: 180, Z6: 180, Z7: 180, Z8: 240, Z9: 260, Z10: 240. Note that there are five consecutive zones (zones three through seven) set at exactly 180 ^{o}C. This is an ideal approach to produce a reflow profile with a hot, long soak. Additionally, the eighth zone is set very high (240 ^{o}C) to induce a quick ramp through the liquidus phase of the solder across the entire component. While this temperature differential between two zones may be difficult for some reflow ovens to maintain, these settings give a general guideline to the type of approach that will yield a profile similar to the one shown in Figure 7.

Both customers implemented the experimental reflow profile without making any additional process changes. Solder paste alloy and chemistry were held constant at both locations. Both sites conducted a controlled experiment with engineering supervision over the process.

Data

Customer A had reported a defect level of ~1% with their original profile over a several week timeframe during which several thousand boards were built. After altering the reflow profile as described above, zero defects were found over the next week, during which over 1,000 boards had been built. Customer A has subsequently made a permanent switch to the revised profile on all assemblies that exhibited any level of ball-in-socket and foot-in-mud and has reported a reduction in defect incidence across several products.

Customer B had been experiencing a defect level of ~0.8% over a several month period during which over 10,000 of a particular assembly had been produced. As this was a foot-in-mud defect, the Customer B held the belief that component solderability and/or flux activity was the primary culprit. They had assigned additional inspectors to try to visually identify foot-in-mud defects and had decided to "live with" the defect because it couldn't be prevented. After converting to the revised profile, the foot-in-mud defect level was reduced to <0.1%. The customer found that these remaining defects were occurring randomly across the entire component and will ultimately deemed to be connected to sporadic contamination and/or solderability issues with the component itself. However, 90% of the foot-in-mud defects were eliminated by the transition from the profile shown in Figure 6 to the one shown in Figure 7. This indicates that the profile will not necessarily overcome other process variables, such as component co-planarity, clogged stencil apertures, and component solderability. However, by preventing component from tilting, the profile should be far more robust with respect to the occurrence of ball-in-socket and foot-in-mud defects.

Discussion

Based on the findings, a logical mechanism for the defect formation can be proposed. When Customers A and B were using their previous reflow profiles, the Delta T across the component at the liquidus point of the solder forced the solder to melt on one corner of the component, creating wetting action between the solder and the component in one localized area. This wetting action exerts a downward "pull" on the component in the hotter corner, which can lead to a slight "tilt" to the component while the hotter corner is above liquidus and the cooler corner is below liquidus. It is assumed that this force is often not strong enough to uproot the component leads from the paste in the cooler (or else we may see this defect far more often), but in the case where the defect is formed, we must assume that the component leads in the cooler corner completely lose contact with the solder paste. If the component lead exits the paste "clean" (without any paste or flux remnants), the metallization is completely void of any oxidation prevention that would normally be in place due to the flux from the solder paste. This leads to rapid oxidation of the bottom of the component lead. Additionally, the as component lead leaves the paste deposit, the paste itself is suddenly free from a massive heat sink and can rapidly become molten before the component lead is forced back into the paste by the wetting action across the body of the component. Once the paste melts, the flux will promote the wetting of the solder onto the metallized surface in which it is in contact, meaning the flux will drop to the board level to promote spread onto the land and will likely not remain in place to prevent oxidation on the molten surface of the bulk solder. Once the component lead is finally driven back into the molten solder, both surfaces have become oxidized sufficiently such that the solder may not wet the component. The end result of this is a component lead that appears to be resting in the bulk solder, but the two surfaces would not be metallurgically connected.

It also follows that additional variables could easily affect the level of ball-in-socket and foot-in-mud defects in a typical assembly process. Since the component tilting effect is the real initiation of the defect formation, it is worth considering other variables that can reduce component tilt aside from controlling Delta T. It has been proposed that the wetting speed of the paste and alloy may affect the degree to which the component may tilt regardless of the Delta T conditions that exist. This may mean that alloys that wet slower or solder pastes with slower wetting speed can also reduce the formation of ball-in-socket and foot-in-mud defects. As an example, lead-free alloys may reduce the incidence of foot-in-mud and ball-in-socket defects through a more sluggish flow characteristic to the alloy itself. This would need to be the subject of future work as solder paste chemistries and alloys were kept consistent at both customers.

Conclusions

A reflow profile with a hotter and longer soak coupled with a quick transition into the solder's liquidus phase proved beneficial in reducing the ball-in-socket and foot-in-mud defects. This proves that many of the ball-in-socket and foot-in-mud defects that had been considered random do have an assignable cause, probable mechanism and corrective action.\

Based on the presumed mechanism, the Delta T minimization must occur such that the coolest and hottest corner of large QFP and BGA components melt nearly simultaneously, or at least close enough such that the coolest corner melts before any tilting action takes hold due to solder melting in the hottest corner. Only a profile that has Delta T minimized through the phase transition of the solder can eliminate the foot-in-mud and ball-in-socket defects formed via this mechanism. The profile shown in Figure 7 successfully eliminated 100% of the defects that were caused by component tilting at two different customer sites. This approach should eliminate ball-in-socket and foot-in-mud defects in situations where the defects occur repeatedly within a small geographic area on a component.

The ramp-to-spike profile will exacerbate these defects as it will drive higher Delta T across a component and induce component tilt. A ramp-soak-spike profile with a low soak temperature (<160 ^{o}C) will similarly worsen the ball-in-socket and foot-in-mud defects due to increased Delta T as the board is ramped up from soak to reflow temperatures. In general, any profile with significant Delta T across a large QFP or BGA through the phase transition of the solder may create ball-in-socket and foot-in-mud defects. This can be virtually eliminated by designing a profile with along, hot soak and increasing the temperature above the solder's liquidus temperature at a rapid rate.