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Double Reflow-Induced Brittle Interfacial Failures in Pb-free Ball Grid Array Solder Joints

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ABSTRACT
Assembly defects can effectively shorten reliability lifetimes in addition to lowering manufacturing yields or creating premature service failures. This paper describes and characterizes an unusual open circuit failure mechanism in Pb-free ball grid array (BGA) solder joints. The failure occurred during Pb-free solder assembly of a 31 mm, 1.27 mm pitch, perimeter array, SAC305 (Sn3.0Ag0.5Cu) BGA. Due to design constraints, it was necessary to assemble some BGA components during the first reflow cycle. Following the second reflow operation, some solder joint opens were detected on the BGA component which had been subjected to the atypical second reflow exposure. Metallographic cross sectional analysis indicated that the open solder joints initially were well-formed but the failure resulted from a brittle interfacial fracture at the package side of the solder joints. The failure mechanism and possible root cause is discussed in terms of the combined impact of stress induced by component and board warpage and the lower inherent strength of the solder joint near the melting and solidification temperatures.

INTRODUCTION

The electronics industry continues to identify and uncover potential performance and reliability risks associated with the transition to Pb-free design and manufacturing. This is a particular concern for complex product designs requiring high reliability and extended service life. The continued integration of printed circuit board assemblies (PCBA) using more complex packages, smaller solder joints, diminishing pitch and complex components mounted on both sides of the PCBA has resulted in increasing yield and reliability challenges. Among those issues is the emergence of solder defects that appear to be related to higher assembly temperatures due to the use of Pb-free solders. These assembly defects can effectively shorten reliability lifetimes in addition to lowering manufacturing yields or creating premature service failures.

In the mid-1990's there were published reports of brittle interface failures of surface mount solder joints that had been subjected to a second soldering operation. The first reported case occurred subsequent to a wave soldering operation [1] but there was another case reported subsequent to a second surface mount reflow operation [2]. Because brittle interfacial solder joint failures were observed during a second reflow soldering operation they were called "Double Reflow" failures. There have been no additional published cases of Double Reflow Failures since those early occurrences. However, the increasing complexity of electronic assemblies coupled with the transition to higher temperature Pb-Free soldering has given rise to another case of brittle interfacial failures induced by Double Reflow.

This paper describes and characterizes electrically intermittent, brittle interfacial solder joint failures in a Pb-Free ball grid array (BGA) subjected to two reflow cycles. The failed BGA is a 1.27 mm pitch, perimeter array with a body size of 31 mm and SAC305 (Sn3.0Ag0.5Cu) solder balls. Due to the presence of several surface mounted daughter card modules on the non-BGA side of the board, the BGA-side of the printed circuit assembly was soldered first. In effect, this constraint put the BGA components atypically on the bottom-side during the second reflow. The solder joint failures were characterized with metallographic cross sectional analysis using optical microscopy and scanning electron microscopy. The failure mechanism and possible root cause are discussed in terms of the combined impact of stress induced by component and board warpage and the lower inherent strength of the solder joint near the melting and solidification temperatures. The primary objective of this work is to document this new case of Double Reflow failure to enable a heightened awareness of the failure mode. These assembly defects are difficult to detect and shorten reliability lifetimes in addition to lowering manufacturing yields and creating premature service failures. This also emphasizes the importance of reviewing and checking the assembly quality and reliability of assemblies before shipping product.

ASSEMBLY AND MANUFACTURING DETAILS

Figure 1 shows the layout of the printed circuit board assembly (PCBA) that contained the soldering defects. Table 1 provides detailed component descriptions for all the area array devices assembled onto the PCBA. All the BGA components with the exception of Component K were subjected to two reflow cycles. Due to the properties of the printed circuit board (PCB), soldering was done using two vapor phase reflow cycles, instead of the more typical hot air convection reflow cycles. Following the second reflow, the assembly exhibited parametric failures at test. The parametric failures were traced to the plastic ball grid array component (PBGA) labeled Component A and designated by the red box in Figure 1. Component A, which is a perimeter array BGA, 31 mm^2, 304 I/O solder balls of 1.27 mm pitch and 0.76 mm diameter, exhibited intermittent solder joint electrical opens. There were no indications of solder joint electrical opens on any of the other components on the PCBA.

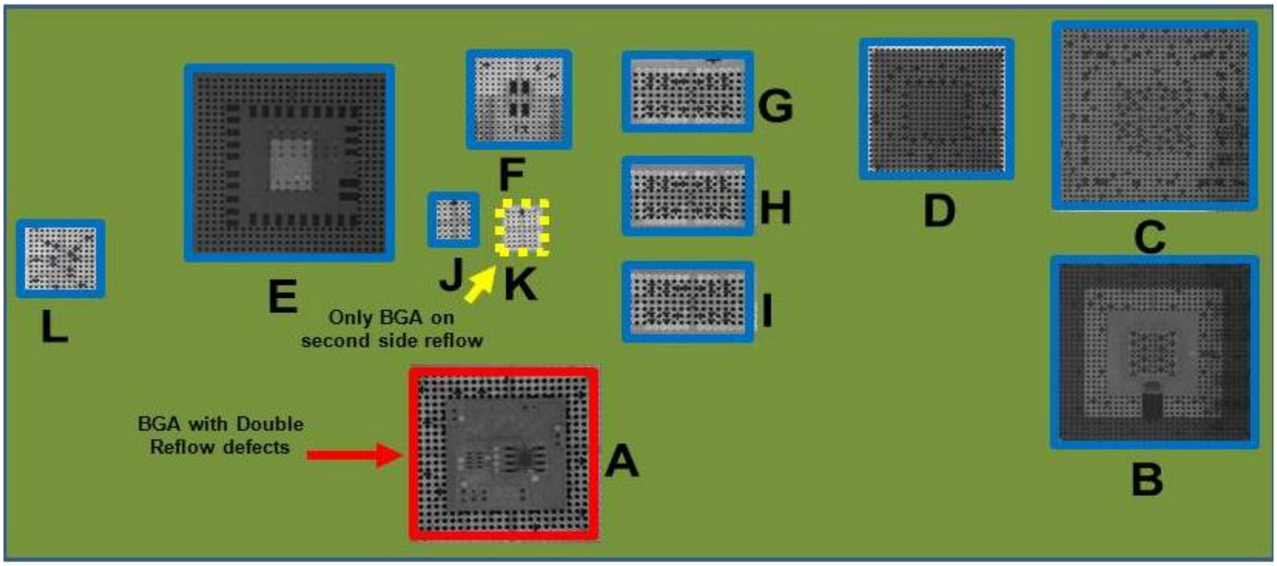

Figure 1: PCBA BGA Component Descriptions, Locations and Reflow Process.

Table 1: Detailed BGA component descriptions for PCBA shown in Figure 1.

Component Designator	Body Size (mm)	Package type	Ball Count (I/O)	Pitch (mm)	Ball Count (I/O)	Pitch (mm)	Ball Diameter (mm)
A	31 x 31	Perimeter PBGA	304	1.27	304	1.27	0.76
B	31 x 31	Full array BGA	964	1.27	964	1.27	0.76
C	27 x 27	Full array FCBGA	676	1.0	676	1.0	0.60
D	25 x 25	Full array TEBGA	576	1.0	576	1.0	0.65
E	31 x 31	Perimeter TBGA	352	1.27	352	1.27	0.75
F	15 x 17	Full array PBGA	256	1.0	256	1.0	0.50
G, H, I	12 x 9	Full array PBGA	119	1.27	119	1.27	0.75
J, K	8 x 11	Full array PBGA	64	0.8	64	0.8	0.62
L	13 x 13	Full array PBGA	144	1.0	144	1.0	0.60

A preliminary failure analysis of Component A at the factory suggested poor adhesion of the ball to the substrate, with possible inner row solder ball separation at the component side. The root cause was suggested as solder ball “de-wetting,” rather than solder joint fracture. Additional failed PCBAs were analyzed using transmission X-ray, dye and pry testing, and metallographic cross sectioning. Warpage measurements of the component and PCBA were done using thermal shadow Moiré [3]. Additional metallographic analyses were conducted to determine the failure mode.

FAILURE ANALYSIS

Background and Methodology

Solder joint quality inspections inherently are difficult to perform on BGA components and the detection and characterization of intermittent defects using nondestructive test (NDT) methods is even more problematical. Correlating electrical parametric test data to failed interconnection locations likewise can be difficult with complicated product designs. These factors make physical failure analysis challenging, particularly when the analysis is restricted to small sample sizes or unique product samples. The protocol used in this analysis was to perform all the typical NDT inspections regardless of the expected outcomes prior to initiating destructive analysis.

There are a number of distinct BGA solder assembly defects that can appear symptomatically as intermittent electrical failures. Intermittent failure modes occur at either the package or board side of solder joints and they include different types of brittle interfacial fractures, variations of Head-on-Pillow (HoP), non-wet opens, inadequate solderability (poor joint formation), microvoid-assisted fractures, and de-wetting. All of these failure modes are caused by some type of physical or metallurgical anomaly in the soldering process or soldered structure that interacts with a sufficient applied stress to cause defect initiation and ultimately failure of the interconnection.

The preliminary electrical test data at the contract manufacturer site indicted Component A as the single failed device on the PCBA. The test data indicated the possibility of multiple failure locations along the inner rows of the BGA. However, definitive identification of failed sites could not be made solely on the basis of the electrical test data.

Defect Detection

Because the suspect failure locations were not in the outer rows, defect detection by visual and low magnification optical inspections was unsuccessful. Transmission X-ray inspection also was unable to detect or image failed solder joints. This is expected since conventional, transmission X-ray cannot resolve fine cracking or thin planar defects that are nothing more than air gaps in the soldered structure. Consequently, destructive analyses were initiated starting with the “dye and pry” (DnP) method. The primary objective of the DnP was to determine if the solder joint had failed at the package or PCB side of the joint. Dye intrusion occurred at multiple solder joint sites and dye penetration was observed at the component side of all failed solder balls. A typical image of a DnP surface is shown in Figure 2. It was also noted that incomplete dye penetration was observed at some locations. This is indicative of either incomplete initial solder joint formation or subsequent cracking through only a fraction of the intended attachment area.

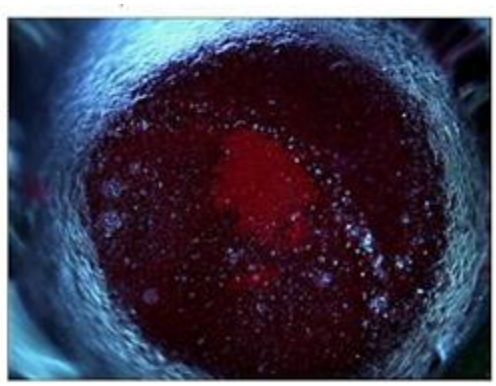

Figure 2: Optical photomacrograph of a failed solder ball surface after dye and pry (DnP) testing. This surface has fractured between the solder ball and BGA package pad (at the component side). The red color on the surface is from the dye intrusion that occurs prior to the mechanical prying.

Figure 3 shows the a composite map of failure locations taken from three different Component A samples overlaid on a low magnification transmission X-ray micrograph of the package ball pattern. The pattern of indicted sites is asymmetric within the package array and is concentrated in proximity to the inner row of perimeter ball array. This inner row failure signature is atypical for many of the intermittent failure modes discussed in the previous section. Those types of failures tend to manifest in the outer rows at the corner and near-corner locations that are known to be the highest stress-strain locations in BGA packages. However, exceptions to this trend can be found in PBGA packages that exhibit certain specific warpage signatures. It is common for warpage stresses to be high at the corner sites, but they also can be high in the die shadow region due to the high CTE mismatch between the package laminate and the silicon die.

Asymmetric failure patterns (Figure 3) are not common but when they occur, they are believed to result from mechanically or thermally unbalanced structures in either the PCB or the package that affect CTE and thermal transfer.

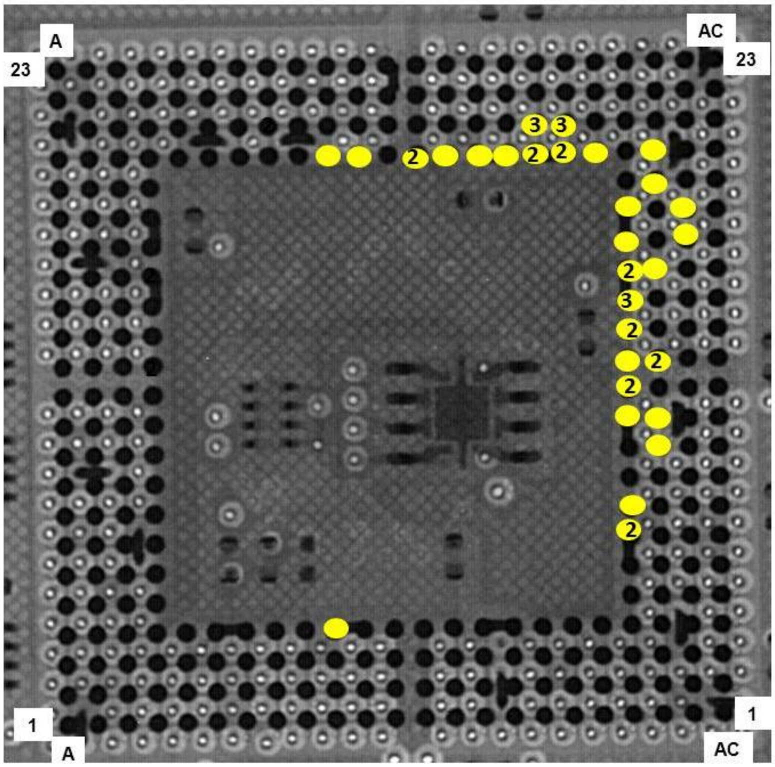

Figure 3: Failure location map from dye and pry test data overlaid on a transmission X-ray image of BGA Component A. This map is a composite of failures for Component A taken from three different PCBAs.

Additional optical and SEM micrographs of failed solder joints at the component side are shown in Figures 4 and 5. These failures initially were diagnosed as ball de-wet or ball drop, pointing to the assembly process as the root cause.

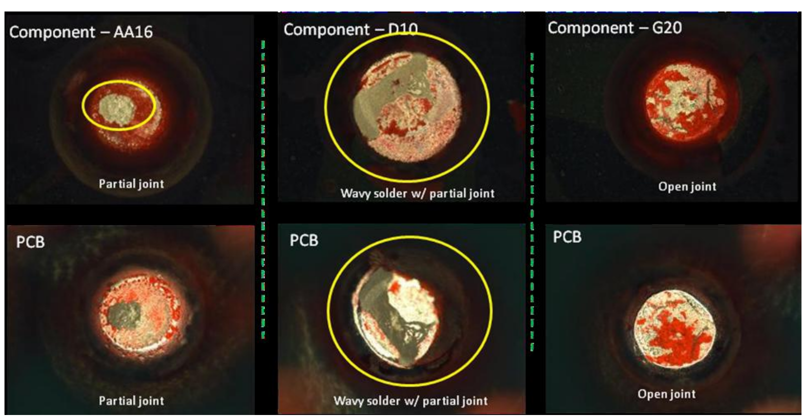

Figure 4: Optical photomacrographs of various fracture surfaces after DnP testing.

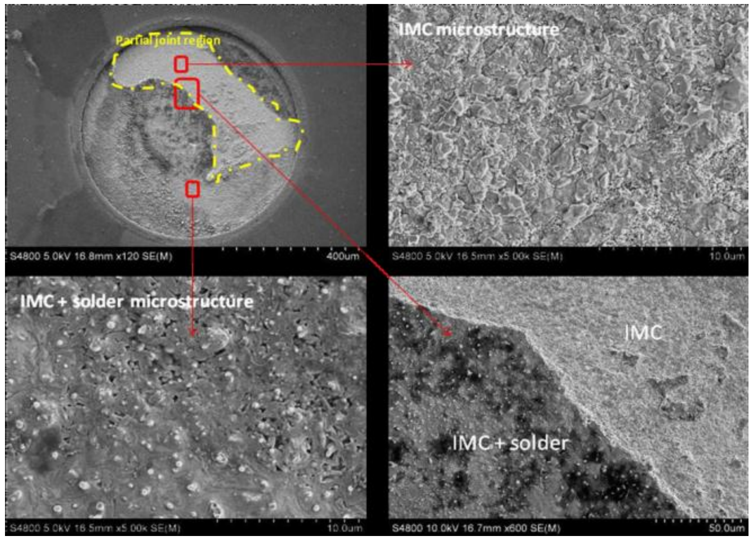

Figure 5: SEM micrographs of various fracture surfaces after DnP testing.

Destructive Cross Sectional Analysis

Destructive cross sectional metallographic analysis was performed to provide more detailed and conclusive failure mode data. The analysis was conducted on Component A from a PCBA sample that contained suspected solder joint opens. The component was cross-sectioned with row by row analysis and optical photomicrographs were obtained for multiple solder balls in each row. The photomicrographs in Figure 6 show cross sections of multiple solder balls across Row 20 in Component A. Row 20 is one of the inner rows of the "picture frame" of the BGA package pin diagram. The solder joint at pin location T20 does not appear to be formed properly and this is confirmed in the higher magnification image in Figure 7.

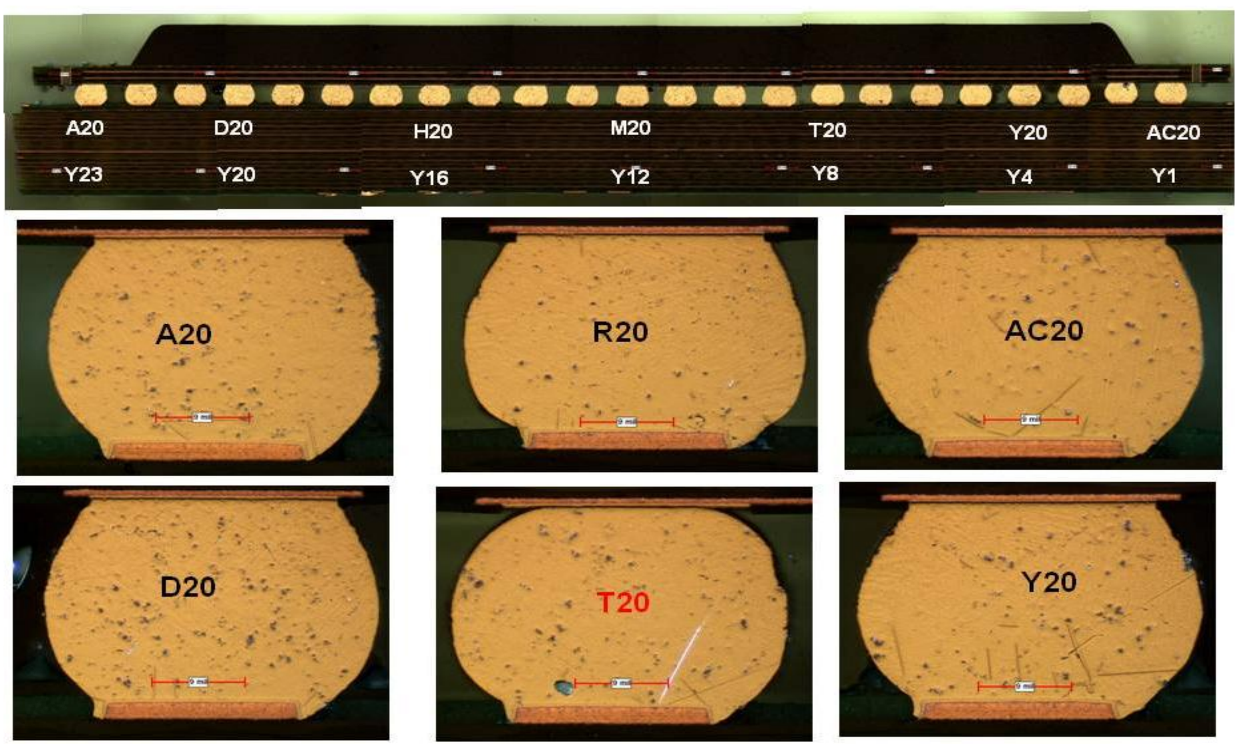

Figure 6: Multiple metallographic cross sections of solder balls in Row 20 of Component A.

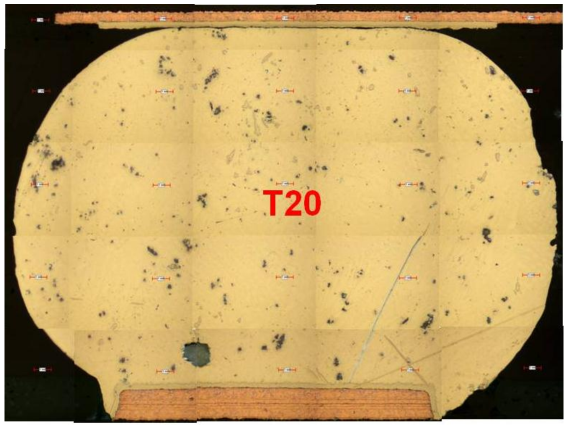

Figure 7: A higher magnification photomicrograph (initial magnification 500X) showing a defect that appears to be de-wetting at package location T20 in Component A. The ball seems to be detached from the package pad.

The initial indication from the high magnification photomicrograph in Figure 7 is that the T20 ball was never soldered to the BGA pad. At this low magnification, the solder ball appears to be de-wetted from the pad. However, an even higher magnification photomicrograph presented in Figure 8 shows that the T20 solder joint actually separated from the BGA pad at the interface between the Ni-Sn (nickel-tin) intermetallic compound (IMC) and the bulk solder. The presence of an IMC layer and a relatively small amount of solder on the PBGA pad confirm the solder ball had been previously attached to the pad. The spherical curved surface of the bulk solder at the perimeter of the solder ball also indicates melting. By all indications, the soldering reaction was successful initially and the solder joint was formed properly. In contrast, the top of the solder ball is flat and parallel to the component pad indicating that a brittle solder joint fracture occurred. This failure signature is consistent with that reported in the Double Reflow references [1, 2] and it is suggested that a similar failure mechanism can account for the T20 solder joint failure. As the solder joint temperature increased and approached the melting temperature during the second reflow, mechanical stress in the PCBA structure was sufficient to induce a brittle fracture at the IMC interface just prior to reaching the melting temperature. The source of the stress could be a combination of CTE mismatch in the package as well as PCB and component warpage. The subsequent melting of the solder ball moments later in the reflow process accounts for curved surface of the solder ball and de-wetted appearance at lower magnification.

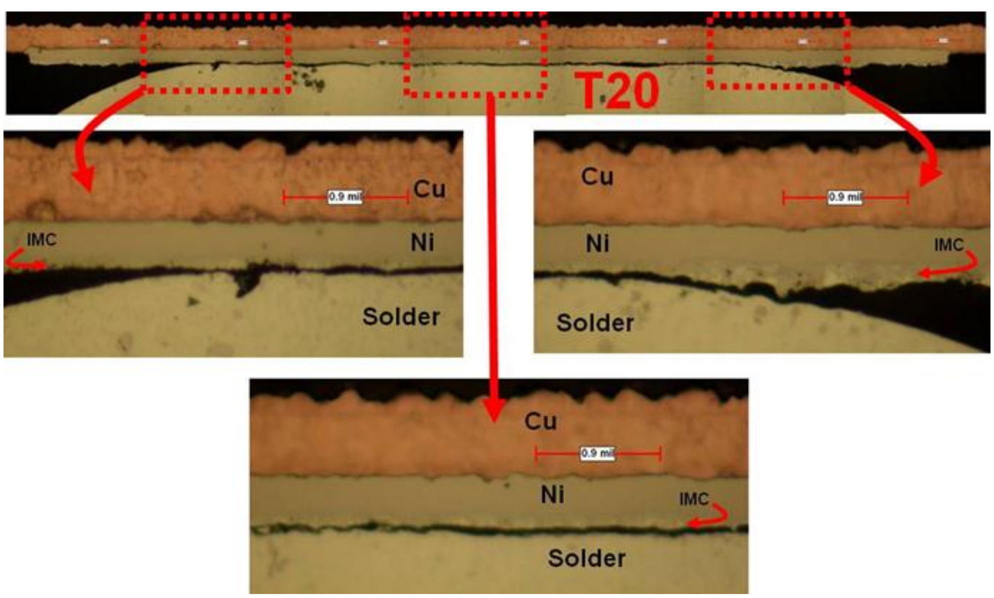

Figure 8: Higher magnification photomicrographs (initial magnification 1000X) adjacent to the T20 BGA pad area showing evidence of a prior successful soldering reaction on the BGA pad with subsequent fracture at the interface between the IMC layer and the bulk solder.

To draw a distinction between the de-wet and brittle fracture modes, the solder joint separation surfaces (interfaces) must be analyzed carefully. In addition to the total separation shown in the T20 solder joint, the three adjacent balls P20, R20 and U20 shown in Figure 9 exhibit similar but partial separation of the solder ball from the Ni-Sn IMC. At first glance, the separations marked by the dashed yellow lines in Figure 9 look like the solder joint de-wetting failures. However the separated areas marked by the dashed red lines in Figure 9, show clear indications of cracking or fracturing rather than de-wetting.

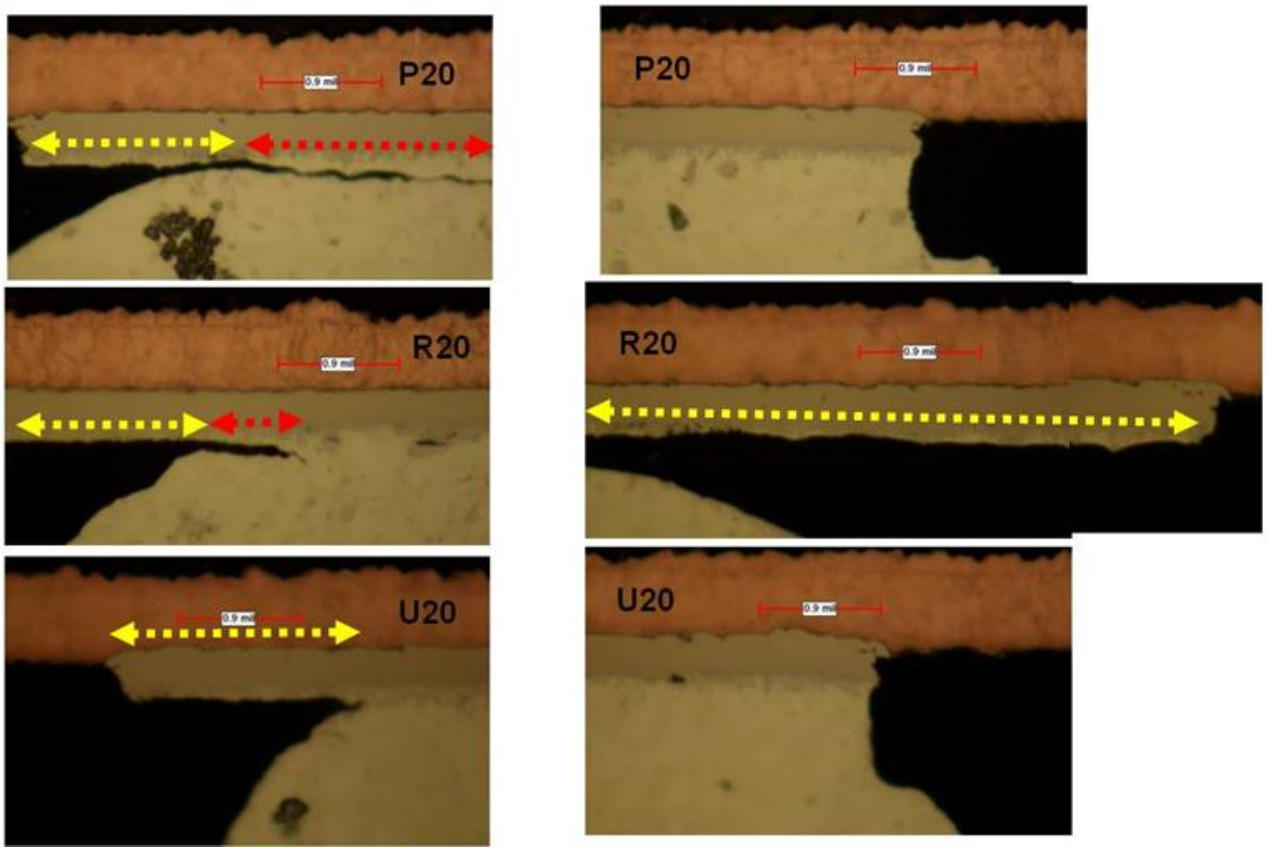

Figure 9 - Magnified cross section, 1000X, of PCBA, Component A, solder balls P-20, R-20, and U-20.

It is assumed that once Component A was attached to the PCBA during the first reflow process there was a good physical and metallurgical connection of solder balls to the PCB and package bond pads. During the subsequent second side reflow operation, the solder joints previously formed on Component A are subjected to an increasing thermal stress signature. It is reasonable to expect the mechanical strength of those solder joint interconnections to decrease as the temperature increases. Concurrently, stress and strain are induced in the solder joints due to the mismatch in coefficient of thermal expansion (CTE) between the composite structures of Component A and the PCB laminate. The stress in the joints could be exacerbated by any warpage in either the component or the PCB. If these stresses exceed the tensile strength of the solder joint, fracture will occur along the weakest interface. At higher temperatures near-reflow, the weakest link typically is the IMC/solder interface as indicated in Figure 8. Based on those cross sections, it is reasonable to conclude that fracture results from the increasing stress on the component solder joints during the second reflow process due to a combination of CTE mismatch and the component and PCB warpage.

There are two possible scenarios to consider. In the first scenario, the solder joint could be fracturing during the reflow ramp up. This could be happening at any point before the solder begins to melt. Stress of course cannot be transferred to the IMC interface once the solder has melted. Although vapor phase reflow is rapid and provides more uniform heating than forced convection IR reflow, temperature gradients will exist across components. Solder joints in the outer rows of the perimeter array are expected to reach the solder melting point a finite time before the inner rows. The differential melting may generate additional local stresses that could add to the any global stresses generated by differences in component and PCB CTE and warpage. Once the balls on the perimeter of the package melt, all the stress in the package is transferred to inner unmelted balls, which could result in fracture at those sites.

In the second scenario, the solder joint could be fracturing during the reflow ramp down. It is important to recognize that stress cannot be transferred to the IMC interface as the solder ball remains molten. Therefore, the solder joint fractures would have to occur at some time after the onset of solder solidification. Unfortunately, the actual solidification temperature is difficult to estimate given the degree of undercooling in Sn-based Pb-free solders [4, 5]. As in the first scenario, temperature gradients will exist across the component. However during cooling the joints in the outer rows of the perimeter array are expected to solidify before those in the inner rows. This differential solidification could also generate local stresses that could add to the stresses generated by differences in component and PCB CTE and warpage.

The first scenario, fracture during the reflow ramp up prior to solder melting seems more plausible because it is easier to envision stress being transferred to and concentrated at the inner, unmelted joints. Clearly, the stress distribution and the relationship between peak stress, temperature, and solder solidification must be complex so fracture during cooling may be possible.

Subtle differences in local solidification and stress could account for the observed inner row failures and the variations in the extent of the cracking from site to site along the inner row. The asymmetric failure pattern could be caused by thermo-mechanical imbalances in the package and PCB. The fact that fractures occur only at the package side of the joints is most likely related to the fact that a solder joint formed on a non-solder mask defined Cu pad (as on the PCB) is more resistant to tensile and shear loading than a solder joint formed on a solder mask defined Ni plated pad (as on the package).

It is inexplicable that only a single BGA component on the entire PCBA is affected by the double reflow failure mechanism. It can be speculated that this particular BGA component has sufficient dynamic warpage or a uniquely vulnerable warpage signature with temperature that precipitates the failures. Cross-sectional analysis of several other BGA components showed no evidence of brittle fracture. It is possible that brittle fracture occurs to a lesser extent in some of the other BGA components but it was never found to manifest as a failure nor detected in the failure analysis done on these parts.

Shadow Moiré Dynamic Warpage Measurements

Dynamic warpage was measured on an unattached (stand-alone) Component A and an entire assembled PCBA. A thermal shadow Moiré system was used to characterize warpage over a temperature range intended to simulate a solder reflow profile. Shadow Moiré uses geometric interference between a reference grating and its shadow on a sample to measure relative vertical displacement at each pixel position in the resultant interference pattern image. The thermal chamber is designed to enable measurements to be made during both heating and cooling cycles.

Dynamic warpage measurements were made on Component A and on the bottom side of the PCBA. Table 2 presents the warpage data as a function of temperature from room temperature to reflow at 245 °C and back down to 90 °C. These data show a maximum displacement (Δ) of >4 mils as the package ramps up to the solder melting point (220 °C) and as the package begins to ramp down to solder solidification. Examples of 3-dimensional warpage maps are shown in Figures 10 and 11. Figure 10 shows the warpage map for the overmolded region of the package. This is the region of the package that contained the failures (see Figure 3). This measurement was made during temperature ramp up at 220 °C. The maximum displacement over this surface is approximately -2.0 mils with out-of-plane bending in opposite corners (red regions). Figure 11 shows a comparable warpage map for the PCBA in the region of the Component A footprint. The maximum displacement of the PCB is +2.2 mils over this surface. Therefore, the maximum net displacement (warpage) of Component A relative to the PCB is 4.2 mils.

Table 2: Thermal shadow Moiré measurements showing maximum warpage across the overmolded region of BGA Component A and the bottom side of the PCBA opposite Component A.

Full Field Signed Warpage (mils)

	Temperature °C													
Sample	25	90	110	130	150	170	220	245	220	170	150	130	110	90
BGA “A”	-1	-1.6	-1.9	-2.0	-1.9	-2.0	-2.0	-0.8	-0.8	-1.4	-1.5	-1.6	-1.8	-1.7
PCBA	2.6	2.5	2.4	2.3	2.3	2.3	2.2	2.7	2.9	3.0	3.0	3.2	3.1	3.2
Max. Δ	2.7	4.1	4.3	4.3	4.2	4.3	4.2	3.5	3.7	4.4	4.5	4.8	4.9	4.9

Suspected temperature and warpage range for double reflow defects

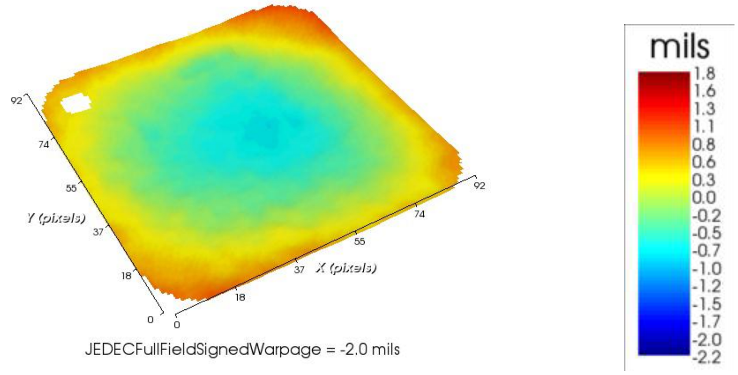

Figure 10: A warpage displacement map across the overmolded area of Component A measured during temperature ramp up at 220°C.

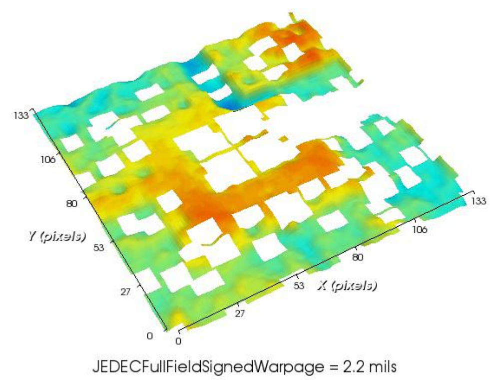

Figure 11: A warpage displacement map for the PCB footprint matching Component A. The measurements were made during temperature ramp up at 220°C.

The thermal shadow Moiré data in Table 2 indicate a net displacement or warpage of Component A relative to the PCB of approximately 4 mils during heating in advance of melting or during cooling before solidification takes place (shaded Max. $\triangle$ cells in Table 2). It must be acknowledged that there are uncertainties in interpreting these displacement measurements. First, these measurements may not reflect the component and PCBA behavior accurately as it would occur during an actual factory reflow cycle. More importantly, the amount of warpage needed to induce solder joint fracture is unknown. A similar amount of warpage can create other serious BGA defects such as head on pillow (HoP) but HoP is a completely different failure mode [6, 7].

In most applications 4 mils of warpage would be considered acceptable because defects like HoP and dropped ball would not occur. On the other hand, solder assembly defects due to warpage can appear with deviations in warpage as small as a few mils [8]. In the case of BGA double reflow, the magnitude of the warpage and induced thermal stress may not be the primary consideration. The more important factor may be the strength of the solder interconnection at higher temperatures close to the melting and solidification points of the solder. Consequently, it is conceivable that a small stress applied to the solder joint at high temperature when the joint has its lowest strength could cause a brittle interfacial fracture.

Corrective Action

The obvious path for elimination of the failures in this design was to subject the BGA-side of the PCBA to only a single reflow pass. This corrective action was implemented successfully. The soldering of the heavy daughter card modules on the non-BGA side of the board was achieved by modifying other aspects of the assembly process.

The root cause analysis and subsequent successful corrective action indicate that in order to prevent double reflow defects, BGA components should not be subjected to multiple reflow passes. These double reflow defects could be another manifestation of warpage-related assembly defects that are increasing across the industry. A risk assessment is recommended whenever double reflow assembly of BGA components is proposed. The assessment should include evaluation of dynamic warpage data for the BGA components used in the design.

In the current analysis, using vapor phase reflow may actually have mitigated the effects of warpage. If the more conventional IR convection reflow had been used, it may have exacerbated the component and PCB warpage and increased the severity of the double reflow defects.

Summary and Conclusions

A comprehensive failure analysis was performed on a complex electronic printed circuit board assembly (PCBA) that exhibited intermittent open circuit electrical failures following Pb-free solder assembly. The following observations and conclusions are drawn from the results of the failure analysis.

- The root cause of the intermittent open circuit failures was brittle solder joint fractures at the interface between the Ni-Sn (nickel-tin) intermetallic compound (IMC) and the bulk solder at the package side of the solder joint. The solder joint fractures could not be detected until destructive cross sectional analysis was performed.
- The fractures developed in a Pb-Free perimeter plastic ball grid array (PBGA) following exposure to a second reflow cycle. The failure signature is characteristic of the so-called Double Reflow failure mechanism that has been reported very sparingly in the literature over the years. This may be the first reported example of this failure mechanism in a Pb-free solder assembly.
- The most likely scenario for describing the failure sequence is that the solder joints fracture just prior to solder melting during the 2nd reflow. In this scenario, the solder joint strength is at a minimum prior to melting and brittle solder joint fractures are induced by a complex combination of CTE and warpage stress on the solder joint during its exposure to the second reflow cycle. Thermal gradients across the BGA package during heating may contribute to the stress.
- The brittle fractures were eliminated by process changes that allowed the BGA-populated side of the PCBA to be exposed to only a single reflow cycle.

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