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Mixed Metals Impact on Reliability

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Abstract
With the adoption of RoHS and implementation of Lead Free solders a major concern is how this will impact reliability. Both commercial and military hardware are impacted by this change even though military hardware is considered exempt from the requirements of RoHS. As the supply chain has moved to the new lead free alloys both markets are being forced to understand these impacts and form risk mitigation strategies to deal with the change. This paper documents the effect of mixing Leaded and Lead Free alloys on BGA devices and how this impacts reliability. Three of the most common pitch BGA packages are included in the study to determine if the risk is the same as pitches decrease. Metallurgical analysis was performed utilizing cross-sections and SEM to study the alloying of tin/lead and tin/silver/copper both separately and combined. MIL-STD-883 Method 1010.8 Temperature Cycling was used to accelerate fatigue life of the samples and testing of those samples was performed at regular intervals using a bed of nails tester. Various reflow soldering temperatures were used to assemble the different combinations of alloys. Under-filling of assembled BGA's was also studied as a risk mitigation strategy.

Introduction
Plastic Ball Grid array packages are now perhaps the most common integrated circuit packages used today. Processors, control chips, memory, switches ect. there are few if any assemblies designed today that do not have at least one BGA on board. The primary focus of our experiments was to evaluate the impact of using leaded solder and lead free BGA's together in a soldering system comparable to what is used in today's assembly shops. When mixing two different alloy systems which have two different melting points, the potential exists for non-uniformity of the finished solder connection which could have a negative effect on reliability. The mixing of solder alloy systems is common as many Military and Aerospace designs still call out leaded solder assembly although many of these designs will have BGA's that are available only in lead free versions. Some companies have elected to remove the lead free solder from these BGA's and replace it with leaded solder. This strategy has been utilized extensively in the industry but adds cost and time to the process while having its own set of potential impacts on reliability which are not discussed in this paper. The experiment design also evaluates the impact of different peak reflow temperatures on the finished solder alloying and how this might impact reliability. Three of the most common pitch BGA's, 1.0 mm, .8 mm and .5 mm were used in the experiment matrix to evaluate if any of the potential impacts effected one particular pitch more than another. Underfill was also studied in these experiments as a potential strategy for improving the reliability of both uniform and mixed alloy soldering systems.

Design Matrix
Table 1 details group 1 through 4.

Table 1 – Design Matrix Group 1-4

Group 1	**Pitch**	**Solder Ball Alloy**	**Solder Paste Alloy**	**Peak Reflow Temp**
	1.0 mm	Sn63Pb37	Sn63Pb37	220 C
	0.8 mm	Sn63Pb37	Sn63Pb37	220 C
	0.5 mm	Sn63Pb37	Sn63Pb37	220 C
Group 2	**Pitch**	**Solder Ball Alloy**	**Solder Paste Alloy**	**Peak Reflow Temp**
	1.0 mm	SAC305	Sn63Pb37	220 C
	0.8 mm	SAC305	Sn63Pb37	220 C
	0.5 mm	SAC305	Sn63Pb37	220 C
Group 3	**Pitch**	**Solder Ball Alloy**	**Solder Paste Alloy**	**Peak Reflow Temp**
	1.0 mm	SAC305	Sn63Pb37	235 C
	0.8 mm	SAC305	Sn63Pb37	235 C
	0.5 mm	SAC305	Sn63Pb37	235 C
Group 4	**Pitch**	**Solder Ball Alloy**	**Solder Paste Alloy**	**Peak Reflow Temp**
	1.0 mm	SAC305	SAC305	250 C
	0.8 mm	SAC305	SAC305	250 C
	0.5 mm	SAC305	SAC305	250 C

Table 2 details group 5 through 8 which are the same as groups 1-4 except that they are underfilled.

Table 2 – Design Matrix Group 5-8

Group 5	Pitch	Solder Ball Alloy	Solder Paste Alloy	Peak Reflow Temp	Underfill
	1.0 mm	Sn63Pb37	Sn63Pb37	220 C	Y
	0.8 mm	Sn63Pb37	Sn63Pb37	220 C	Y
	0.5 mm	Sn63Pb37	Sn63Pb37	220 C	Y
Group 6	**Pitch**	**Solder Ball Alloy**	**Solder Paste Alloy**	**Peak Reflow Temp**	**Underfill**
	1.0 mm	SAC305	Sn63Pb37	220 C	Y
	0.8 mm	SAC305	Sn63Pb37	220 C	Y
	0.5 mm	SAC305	Sn63Pb37	220 C	Y
Group 7	**Pitch**	**Solder Ball Alloy**	**Solder Paste Alloy**	**Peak Reflow Temp**	**Underfill**
	1.0 mm	SAC305	Sn63Pb37	235 C	Y
	0.8 mm	SAC305	Sn63Pb37	235 C	Y
	0.5 mm	SAC305	Sn63Pb37	235 C	Y
Group 8	**Pitch**	**Solder Ball Alloy**	**Solder Paste Alloy**	**Peak Reflow Temp**	**Underfill**
	1.0 mm	SAC305	SAC305	250 C	Y
	0.8 mm	SAC305	SAC305	250 C	Y
	0.5 mm	SAC305	SAC305	250 C	Y

There are 30 samples in each group and all were serialized.
One sample from Group 5-8 was cross sectioned and analyzed prior to temperature cycling.
One sample from each cell was cross sectioned and analyzed after temperature cycling.
All failures were cross sectioned and analyzed.
Samples were tested per MIL-STD-883 Method 1010.8 Temperature Cycling Condition B. -55C +0/-10, 125C +15/-0
Total Temperature Cycles Completed - 8876
Testing was performed on a bed of nails test platform.
Test frequency was ~ 100 Cycles
Data was collected for each test.
Analysis was performed on data collected.

PCB Design

PCB was designed in-house in order to accommodate all of the test requirements. The design was built with lead free compatible laminate meeting the IPC- 4101/26 requirements. The PCB was 4.0 x 3.0 x 0.062 thick and 4 layers with immersion silver finish. Figure 1 and Figure 2.

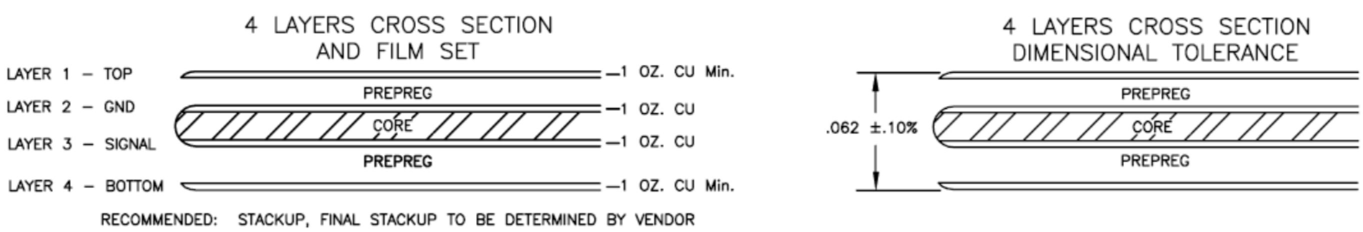

Figure 1 – PCB Stackup

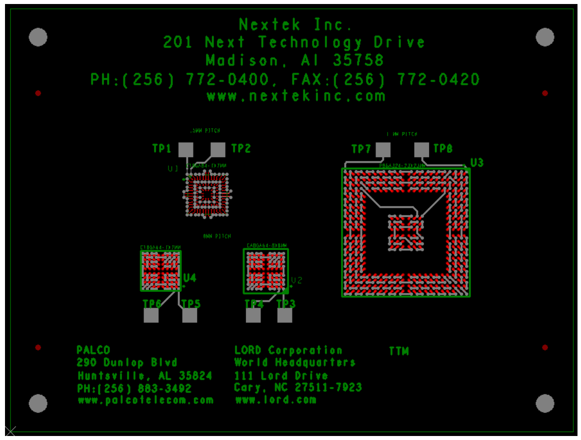

Figure 2 – Test PCB

Components

Components selected for this experiment were daisy chained plastic BGA's in three different pitch configurations. The intent was to see if pitch played a role in the reliability of the different groups. Daisy chained devices were used in order to allow for electrical continuity testing of the individual parts during temperature cycling and to assess failures. The parts were selected in the three most common configurations that we see being used in day to day assembly, 1.0mm, .8mm and .5mm. Details of the individual packages are listed in Table 3.

Table 3 - Components

A-PBGA324-1.0mm-23mm-DC
A-PBGA324-1.0mm-23mm-DC-LF-305
A-CABGA64-.8mm-8mm-dc-lf-305
A-CTBGA64-.8mm-7mm-dc
A-CTBGA84-.5mm-7mm-dc
A-CTBGA84-.5mm-7mm-dc-lf-305

Reflow Temperatures

The PCA's were reflowed in a 7-Zone, forced convection, nitrogen purged reflow oven. Three reflow profiles were used in the experiment. Profile 1 was a linear ramp reflow profile for leaded solder, peak ~ 220C, time above liquidus ~ 60 sec. Profile 2 was a modified version of profile 1, peak ~ 235C, time above liquidus ~ 110 sec. Profile 3 was a linear ramp profile, peak ~ 245C, time above liquidus ~ 60 sec.

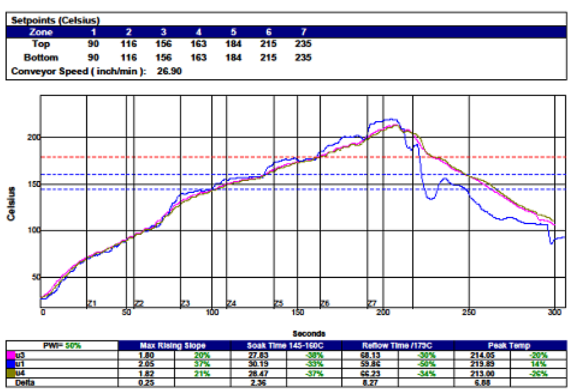

Figure 3 – Profile 1

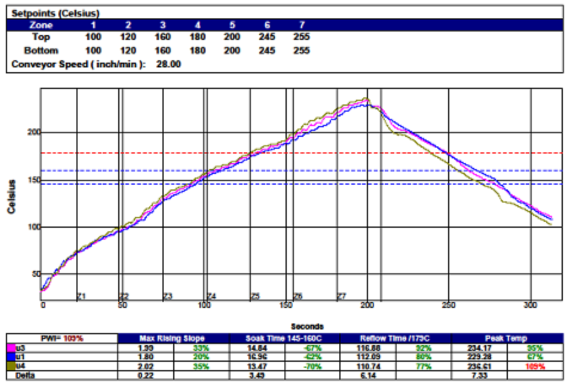

Figure 4 – Profile 2

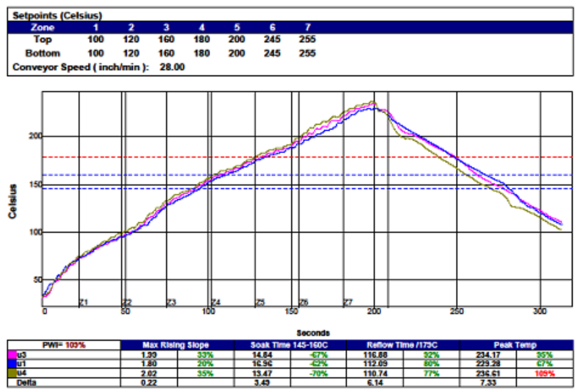

Figure 5 – Profile 3

Assembly and Verification

All of the test assemblies were built in one consecutive run. Printing and solder paste inspection were performed on the production line and placement was performed on high speed modular placement platforms with +/- 30 micron accuracy. After reflow the parts were inspected 100% with X-Ray to verify no shorts or excessive voiding was present. Figure 6-9 are representative samples of the devices after reflow.

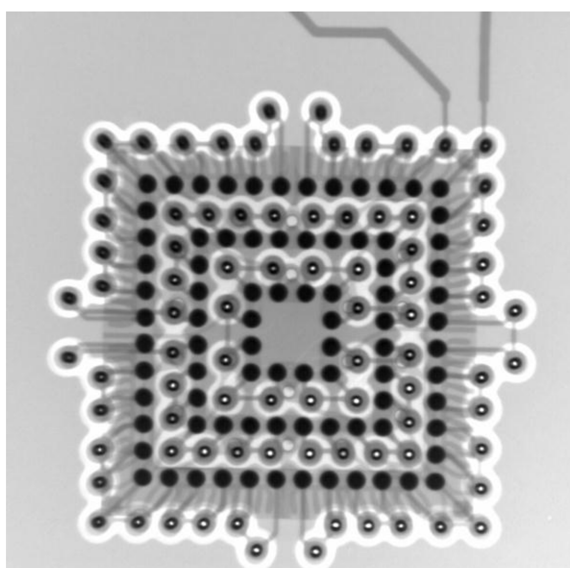
Figure 6 – U1 X-Ray After Reflow

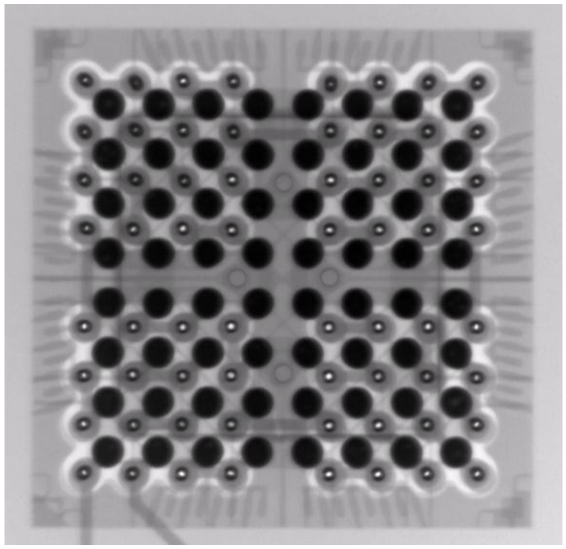

Figure 7 – U2 X-Ray After Reflow

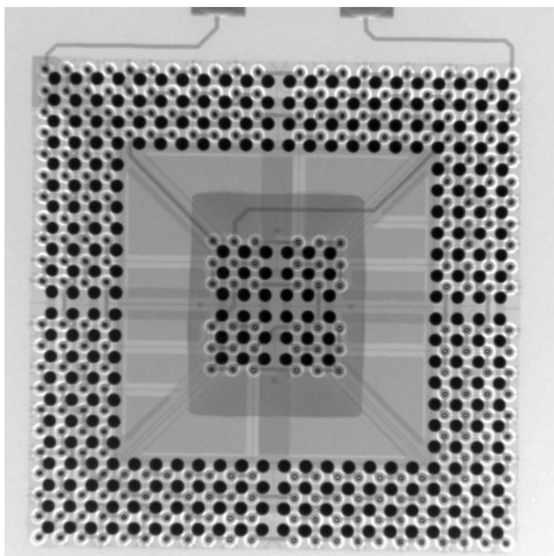

Figure 8 – U3 X-Ray After Reflow

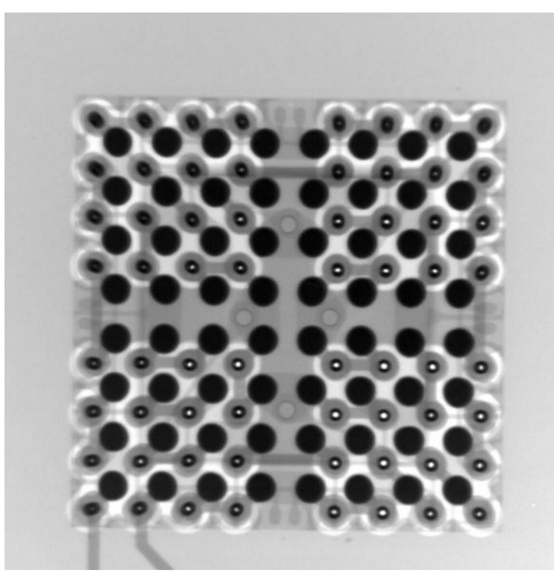

Figure 9 – U4 X-Ray After Reflow

After x-ray the assemblies were electrically tested on a custom test fixture that we designed and built for this experiment. The tester measures continuity of every device on each card independently and is the same tester used during the balance of the test to capture failures during temperature cycling. Assemblies in group 5 through 8 were underfilled after x-ray inspection in the class 10,000 clean room and cured in a convection oven. Cross-sections were performed on one sample assembly from group's 5-8 see figures 10-13. These groups were evaluated before thermal cycling to assess any differences in grain structure and to validate the underfill.

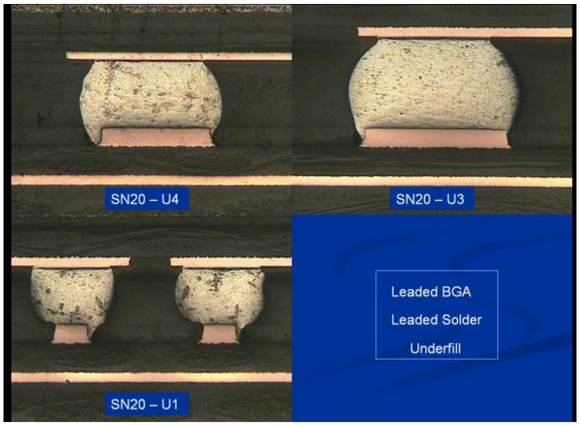

Figure 10 – Group 5

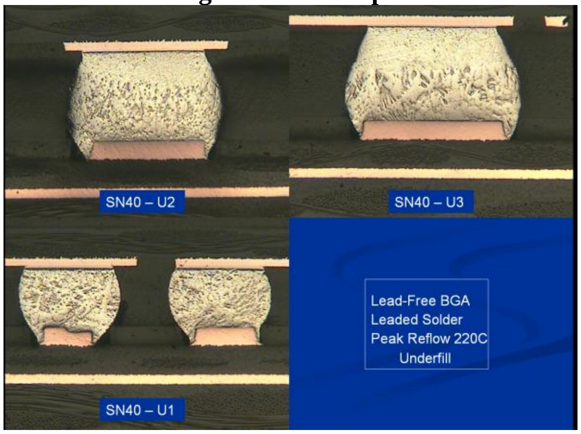

Figure 11 – Group 6

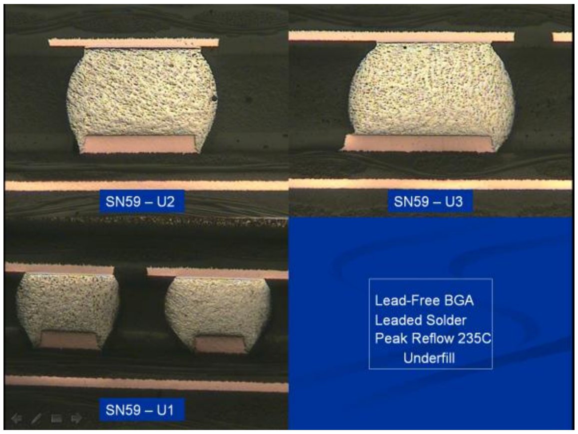

Figure 12 – Group 7

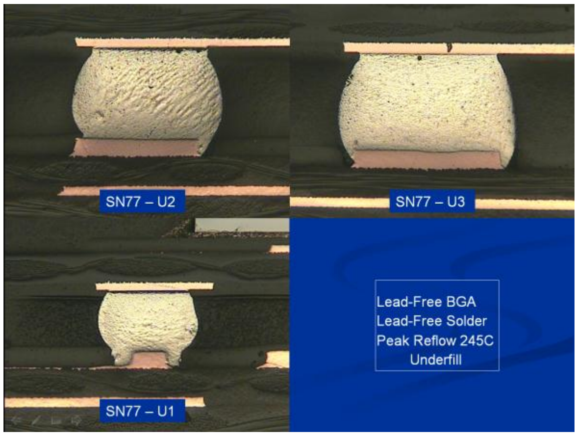

Figure 13 – Group 8

All of the samples showed good wetting to the PCB and complete reflow of the solder joint. Underfill in each of the samples showed complete fill and minimal voiding. The most interesting solder formations were in group 6 which exhibited a distinct demarcation line between the leaded solder from the solder paste and the lead free solder from the solder ball.

SEM/EDS

Scanning Electron Microscope (SEM) was used with Energy Dispersive Spectrometer (EDS) to determine the elemental makeup of the solder at two separate locations in each sample. Samples from groups 5 and 8 had only one alloy type involved in the solder matrix and were used as control groups. The EDS spectrum pulled for group 6 showed that the leaded solder at the circuit card did not alloy uniformly with the lead free solder ball when reflowed at 220C, see figure 14.

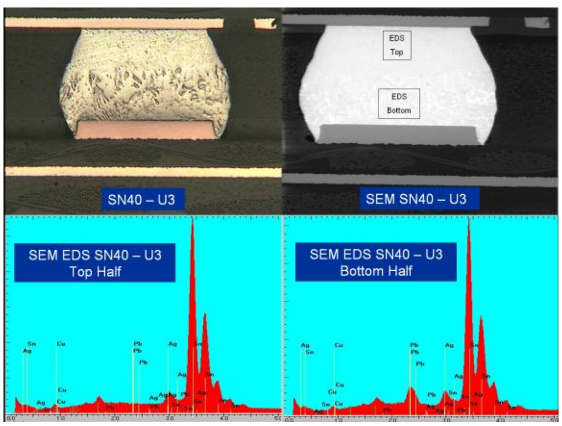

Figure 14 – Group 6

Group 7 which was the same as group 6, leaded solder with lead free solder balls but reflowed at 235C, showed uniform grain structure and alloying of the two solders, see figure 15.

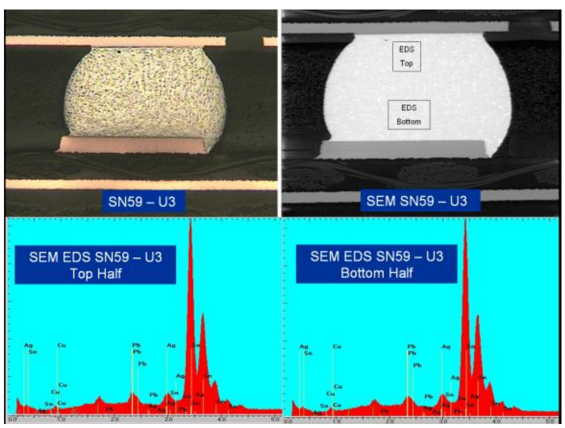

Figure 15 – Group 7

Temperature Cycling

Temperature cycling of all groups was performed over a one year period with testing of each coupon being performed at 100 cycle intervals. Test parameters were -40C to +125C with 10 minute dwell at each extreme. Ramp rates positive and negative were not specified but were as fast as the equipment could make the transitions which turned out to be .393C/sec on the positive slope and .145C/sec on the negative slope, see figure 12, 13. The total cycle time for each cycle was about 43 minutes, see figure 18.

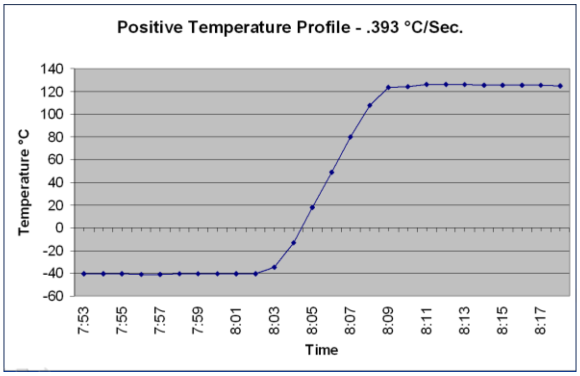

Figure 16 – Positive Ramp Rate

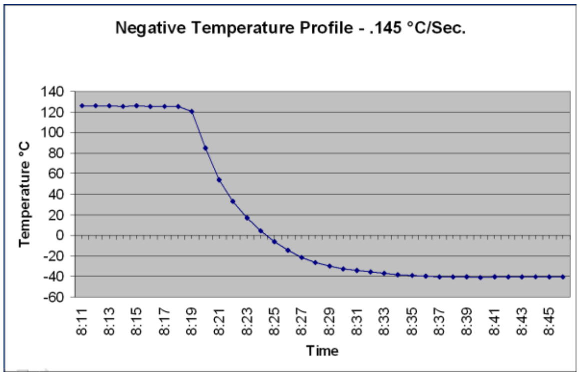

Figure 17 – Negative Ramp Rate

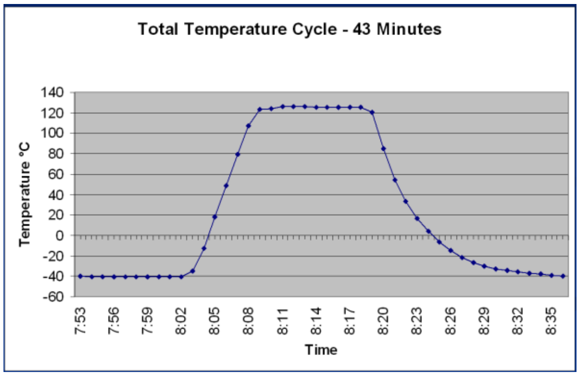

Figure 18 – Total Temperature Cycle

Non-Underfilled Failure Data

Failures were cataloged as they occurred and the failed component was pulled from the test coupon for cross section analysis and validation. Non-underfilled devices were evaluated first by component type/pitch; figure 19 details all of the failures.

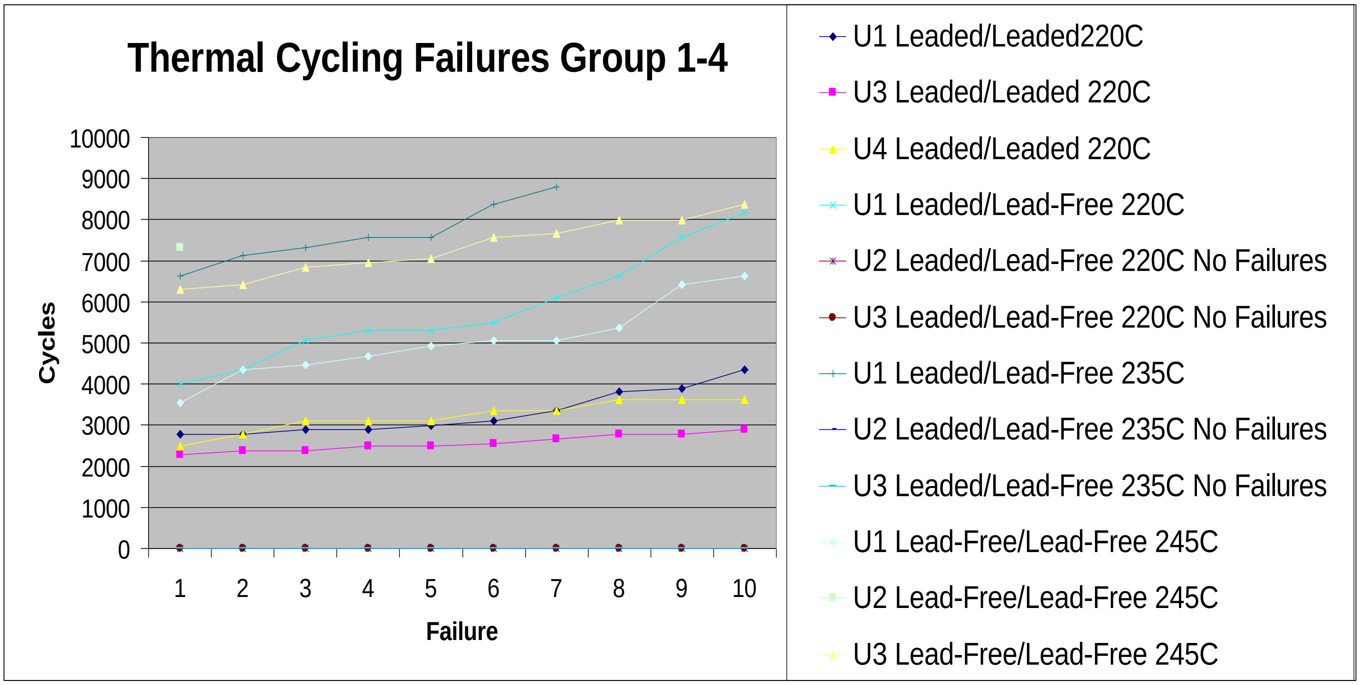

Figure 19 –Temperature Cycle Failure Data

As you can see from this data there were many of the devices that did not fail or had only one failure. In Group 1, Leaded/Leaded at 220C, there were 100% failures starting at 2285 cycles and ending by 4345 cycles. In Group 2, Leaded/Lead-Free at 220C, the U1 device had 100% failures starting at 4013 cycles and finishing at 8164 cycles. There were no failures in group 2 for U2 or U3. Group 3, Leaded/Lead-Free at 235C, had 7 failures at U1 from 6631 cycles to the 7th failure at 8786 cycles. Three of the U1 devices in group 3 did not fail by the end of the testing and no failures occurred at U2 or U3. Group 4 Lead-Free/Lead-Free at 245C, had 100% failures at U1 3552 to 6631 cycles and at U3 6312 to 8378 cycles but only had one failure at U2 which occurred at 7323 cycles. Breaking out the failures by device gives us a better view of how the different groups performed by pitch of the device. Figure 16 shows U1 failure data across groups 1 to 4. Figure 20 and 21 shows failure data for the U2/4 device and the U3 device respectively.

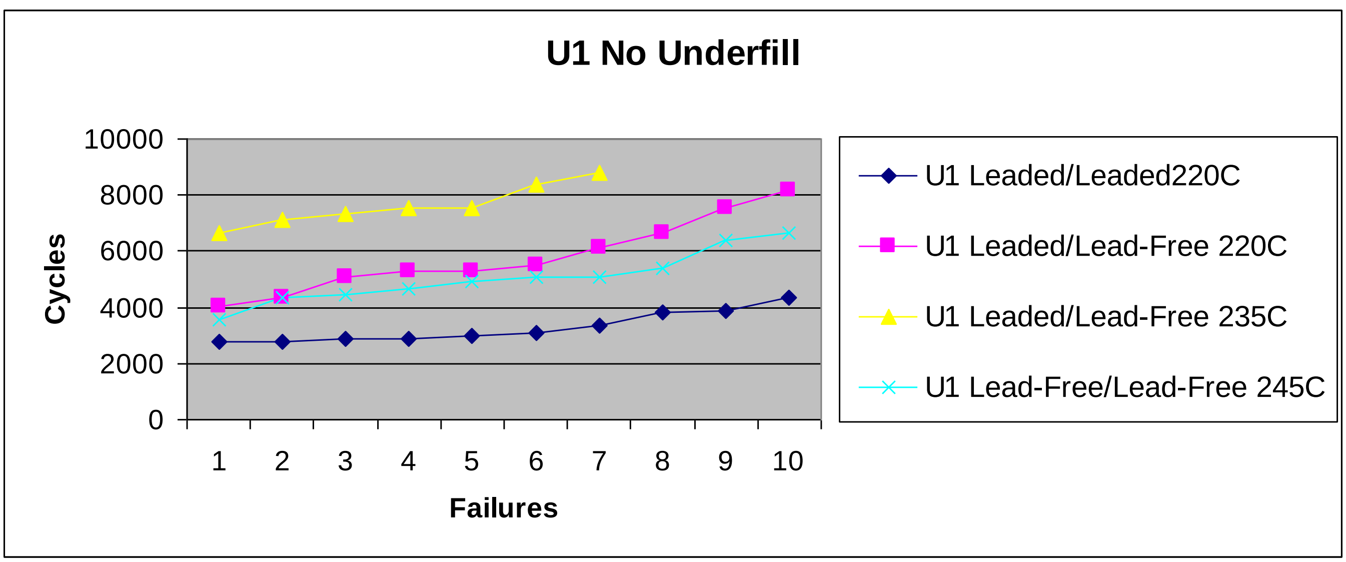

Figure 20 – U1 Failure Data

In the case of U1 it is clear that when mixing leaded and lead-free the best performance was achieved by reflowing at the 235C temperature. It is also interesting that the mixed metals soldered at 220C out performed the two control group samples.

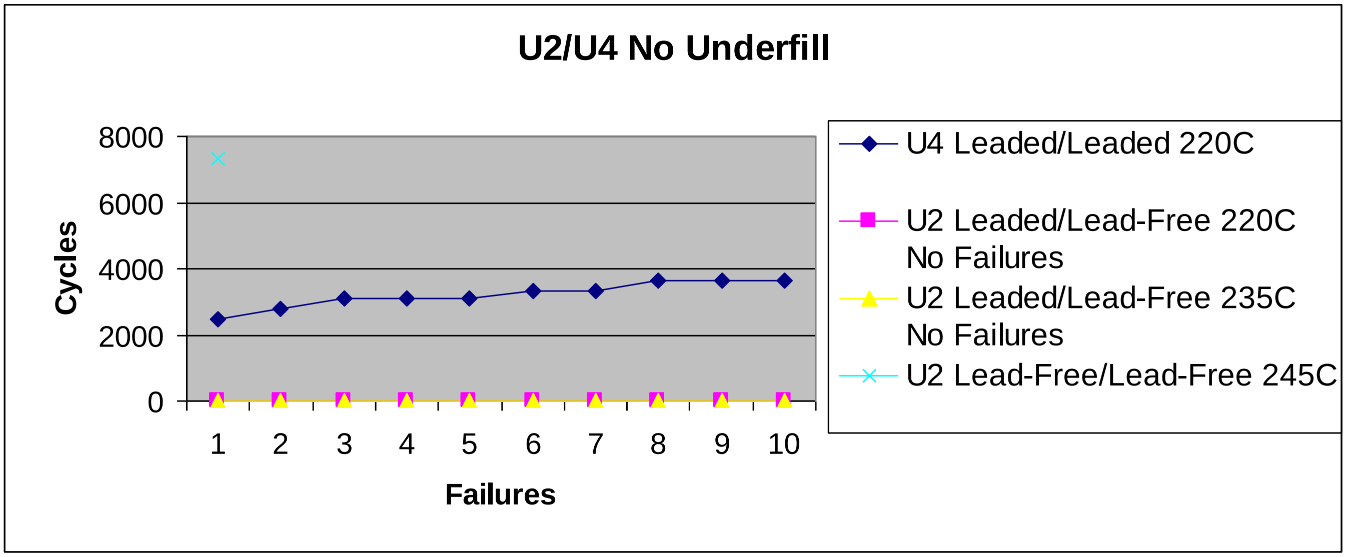

Figure 21 – U2/4 Failure Data

The U2/4 component failed in the leaded group 100% and only had one failure in the lead-free 245C group. The mixed metals groups have no failures.

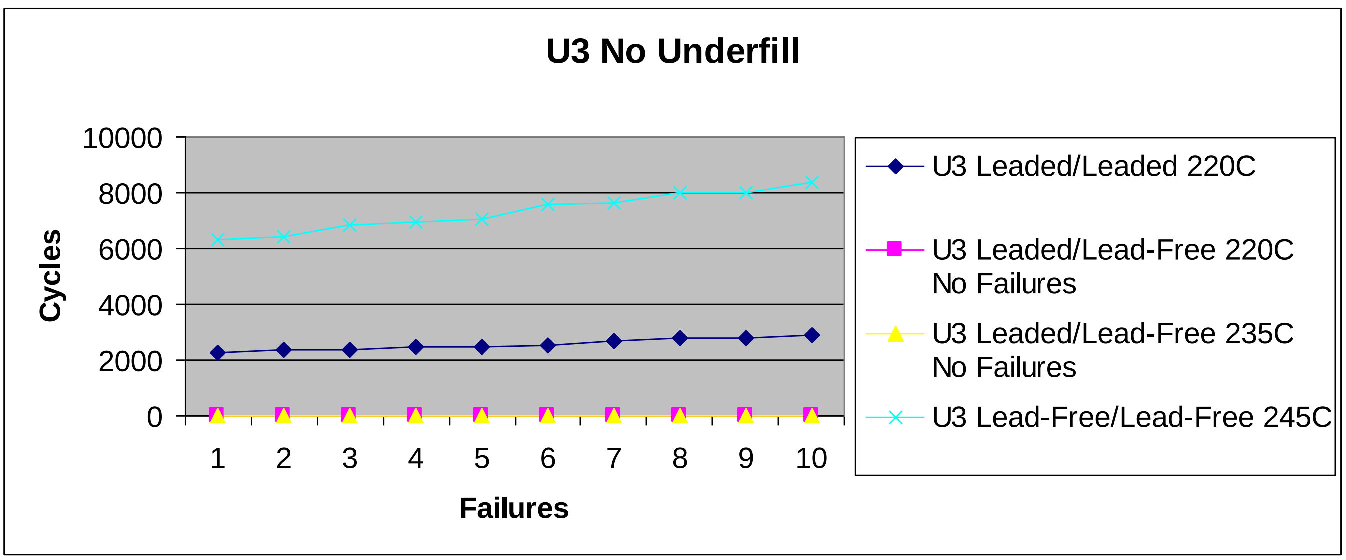

Figure 22 – U3 Failure Data

Failures in the U3 devices occurred only in the two control groups with no failures occurring in the mixed metals groups. This is an important trend that follows from package to package. The trend shows that mixed metals assemblies are outperforming the two control groups in every case.

Non-Underfilled vs. Underfilled Failure Data

As a part of the study underfill was evaluated as an additional strategy to improve overall reliability. The figures below detail the failure data by package/device location, figure 23-25.

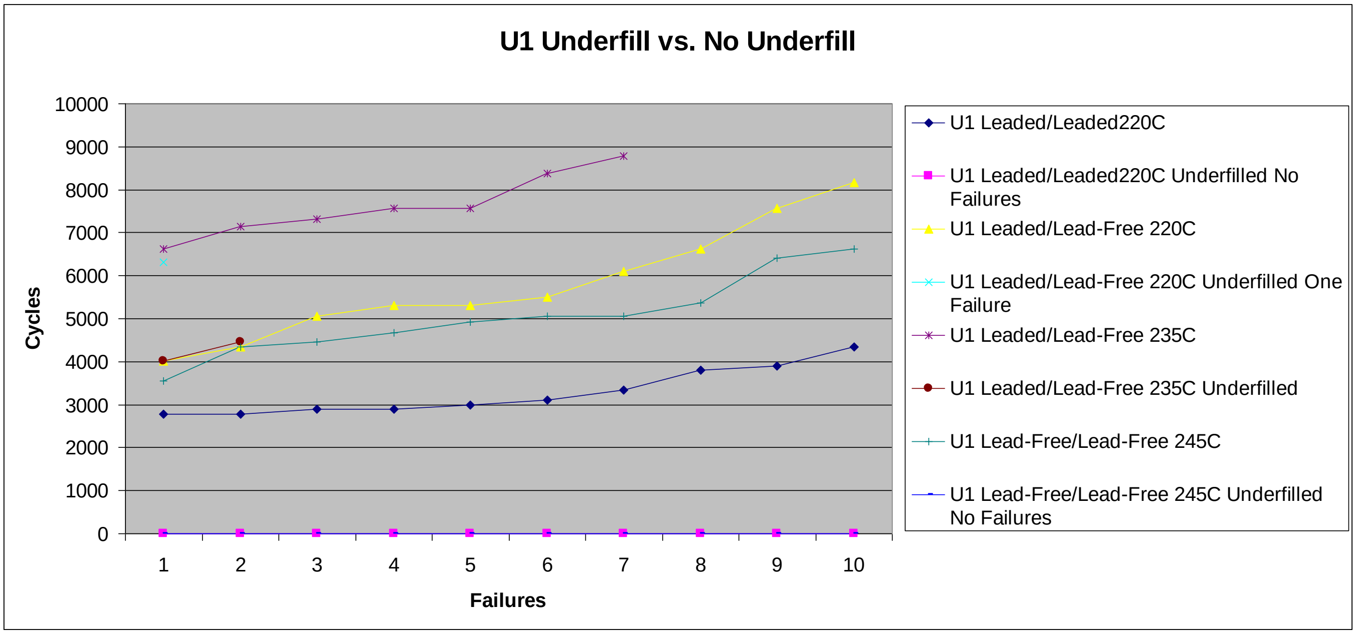

Figure 23 – U1 Underfill vs. No Underfill

The U1 package/location has three underfilled devices that experienced a failure compared to 100% of the non-underfilled U1 packages.

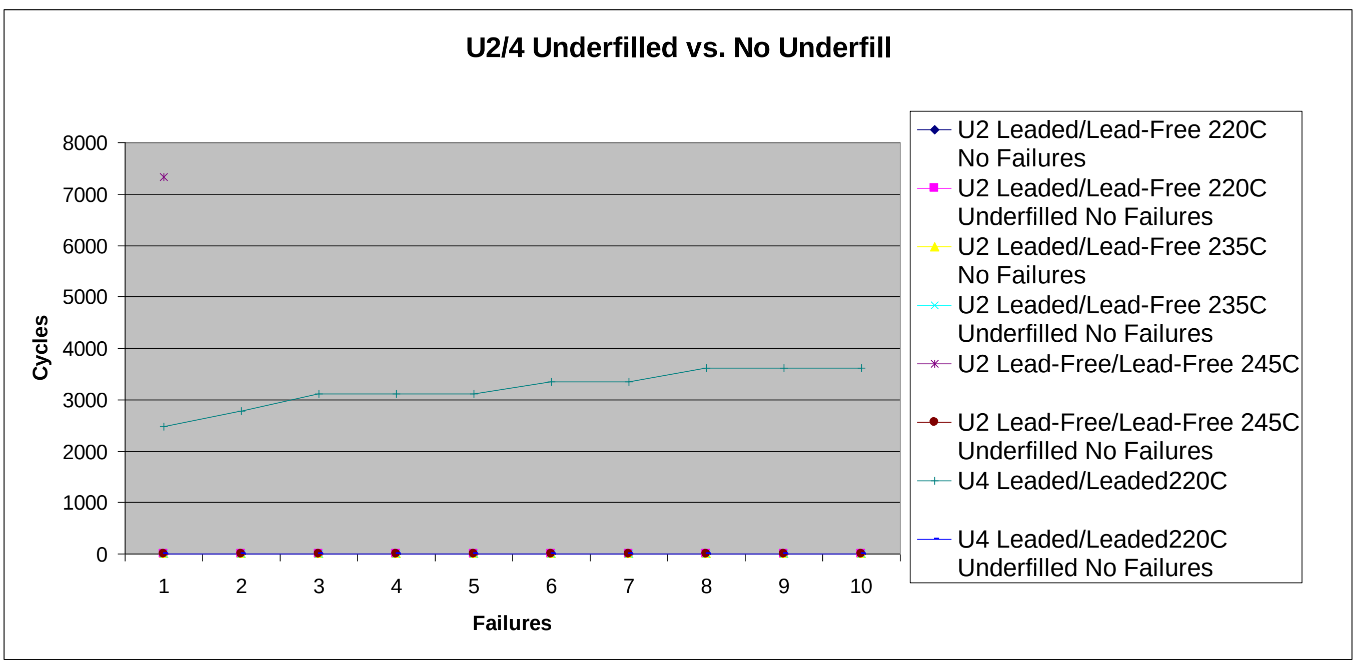

Figure 24 – U2/4 Underfill vs. No Underfill

The U2/4 package/location had no failures in the underfilled assemblies.

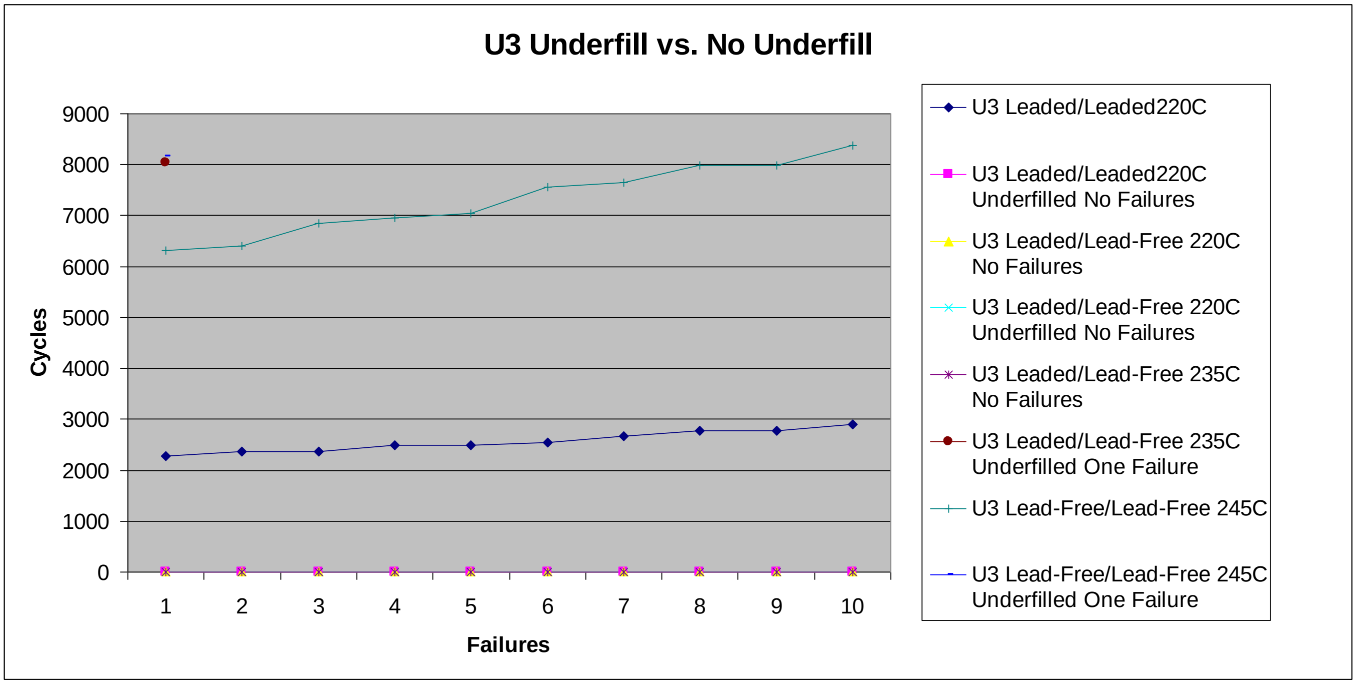

Figure 25 – U3 Underfill vs. No Underfill

The U3 package/location there were two failures in the underfilled groups and both were out beyond 8000 cycles. Across all groups underfill improves the reliability of these devices by 50% on average compared to not underfilling.

Failure Cross Sections

Cross sections of the failed packages were performed to evaluate where the failure occurred. On U1 device/locations across all groups the failures occurred 86% of the time at the package interface. 7% of the failures at U1 were at the PCB interface and 7% of the failures had fractures at both package and PCB interface. Failures on the other devices followed with similar results. The only group that had a full set of failures and was group 1, leaded/leaded at 220C, and they all failed at the PCB interface.

Sample of Cross Sections

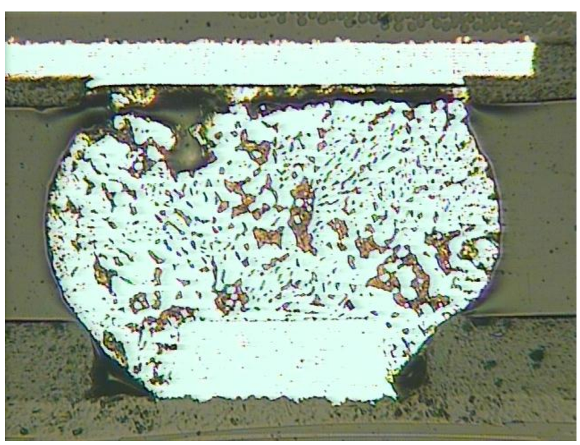

Figure 26 – Group 1 U1 Component Side Failure

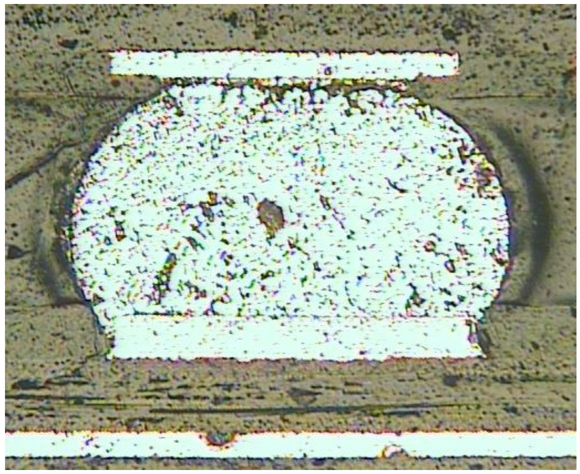

Figure 27 – Group 1 U3 Component Side Failure

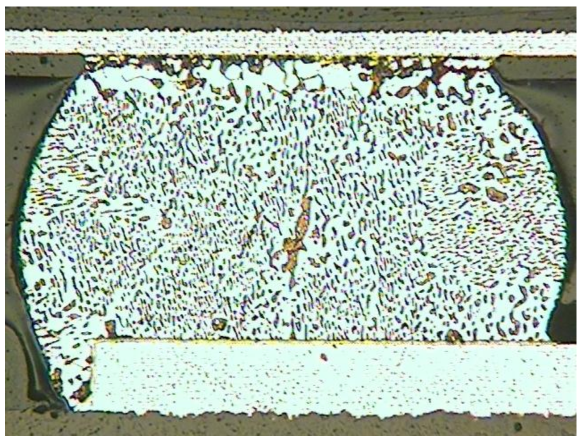

Figure 28 – Group 1 U4 Component Side Failure

Conclusion

The data from these experiments exposed several facts. First and most importantly we see that mixing of leaded solder and lead free BGA's is not a problem for reliability but in fact improves the reliability of the solder in temperature cycling. The data also shows that mixed alloy groups out performed single alloy systems across all packages. The average failure time for the leaded/leaded 220C group was 3021 cycles and was the lowest of all groups. The second lowest group was the leadfree/leadfree at 245C group with an average failure time of 6561 cycles.

The leaded/leadfree at 220 group had an average failure time of 7799 cycles and the best group was the leaded/leadfree at 235C with and average failure time of 8986 cycles. The data shows that group 3, leaded/leadfree at 235C, is 197% better than group 1, 36% better than group 4 and 15.2% better than group 2. Package pitch only appeared to be a factor in the .5mm devices as all of that package type failed during the test period. Failures in the .8mm package and 1.0mm package occurred only in the single alloy groups. Underfill of the BGA's improved reliability of the device regardless of pitch. The failure rate for non-underfilled parts is 55.8% and the failure rate of underfilled parts is 4.1%. Failure location across all groups is 86% of the time on the package side and did not appear to change behavior with pitch.