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Investigation of the Manufacturing Challenges of 2577 I/O Flip Chip Ball Grid Arrays

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Abstract
Higher I/O Ball Grid Arrays (BGAs) are high speed, high pin count, and high performance array packages. These BGAs are also more complex in structure than "standard" BGAs and are generally targeted toward network and server class products. Higher I/O BGAs follow an industry trend identified on multiple industry roadmaps and vendor data sheets. Today, component manufacturers are introducing higher I/O BGAs into the market.

Along with the speed and performance benefits, these higher I/O BGAs also incorporate additional manufacturing and reliability challenges. For example, these larger sized BGAs are considered more susceptible to component warping and large temperature deltas during reflow because of their large size. This paper will discuss overcoming these challenges in regards to one new type of high I/O BGA: a 2577 I/O, 1.0mm ball pitch, 52.5 x 52.5mm body size, PTFE carrier, Flip Chip BGA (FCBGA).

The main objective of this study is to describe and discuss the component characterization, test vehicle design, assembly, rework, and accelerated temperature cycling testing that were done with the 2577 I/O Hyper BGATM. Component warpage, overcoming large temperature deltas during reflow, reworking techniques, and analysis of the accelerated temperature cycling will be discussed.

Another objective of this study is to discuss process considerations for assembling and reworking the 2577 I/O Hyper BGA.™

Introduction
The 2577 I/O Hyper BGA™ is one of the largest, commercially available solder array packages in the market today. It is targeted for use on high-performance and high-speed networking and telecommunication systems. Jabil decided to pursue process development and 2nd level reliability assessment in collaboration with Universal Instruments in response to industry trends and key customers identifying probable use of this package. The key objectives of this project were to:

Study and document the 2577 I/O package mechanical and thermal characteristics
- Design a printed circuit board test vehicle that would provide assembly, rework and 2nd level reliability information.
- Develop and document the assembly and rework process.
- Perform 2nd level reliability testing and associated failure analysis of the test vehicle assemblies.
- Discuss process and rework considerations for the 2577 I/O package.

The various assembly and solder paste rework studies were conducted at the Jabil AMT (Advanced Manufacturing Technology) lab in San Jose, California. The flux-only rework and ATC (Accelerated Temperature Cycling) and associated 2nd level reliability assessments were performed at Universal Instruments Lab in Binghamton, New York.

This paper includes the assembly and rework process description and results, ATC test description and results and considerations for developing a process for assembling and reworking the 2577 I/O package.

Note: the description for the 2577 I/O Hyper BGA will also be referred to in this paper as 2577 I/O part/device or the 2577 I/O FCBGA.

Component Description
The 2577 I/O device that was the focus of this project is a full area 1mm pitch array that measures 52.5mm square.

The package design/construction includes the following (see Figure 1):

- Daisy-chain/thermal flip chip die
- Depopulated corners (6 solder balls missing from each corner)
- High-Pb flip chip bumps with Sn63/Pb37 solder attach to interposer
- Cu/Invar/Cu Inner ground plane
- Low stress PTFE organic multi-layer laminate
- Cu thermal lid.
- Integrated decoupling capacitors.

Note: the 2577 I/O components used for this study were designed by IBM specifically for performing assembly, rework and 2nd level reliability studies using daisy chain interconnects between the device and the printed circuit board test vehicle.

The flip chip die attach to the PTFE laminate carrier is done with high Pb bumps on the die being soldered to the via-in-pad using Sn63/Pb37 solder. See Figure 2.

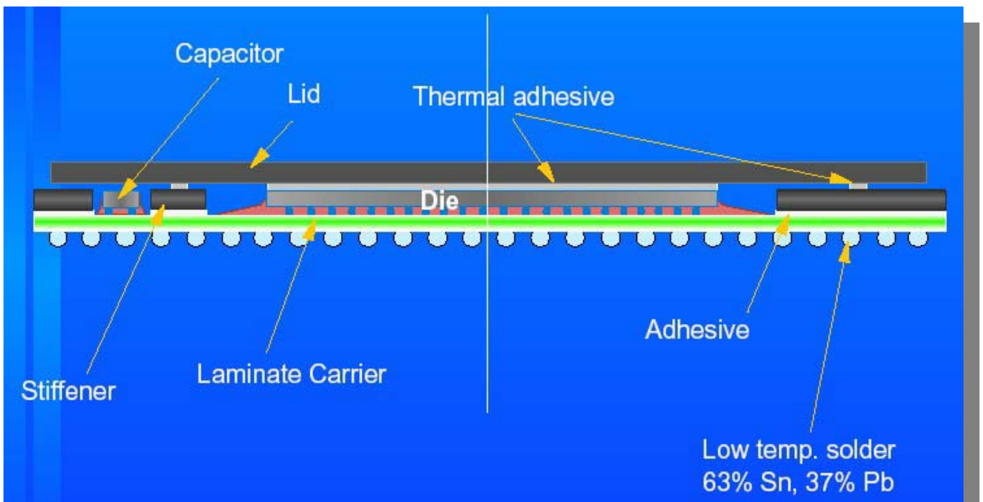


Figure 1 - 2577 I/O BGA Pictorial Cross-Section (IBM Packaging ASIC Overview (April 2001)).

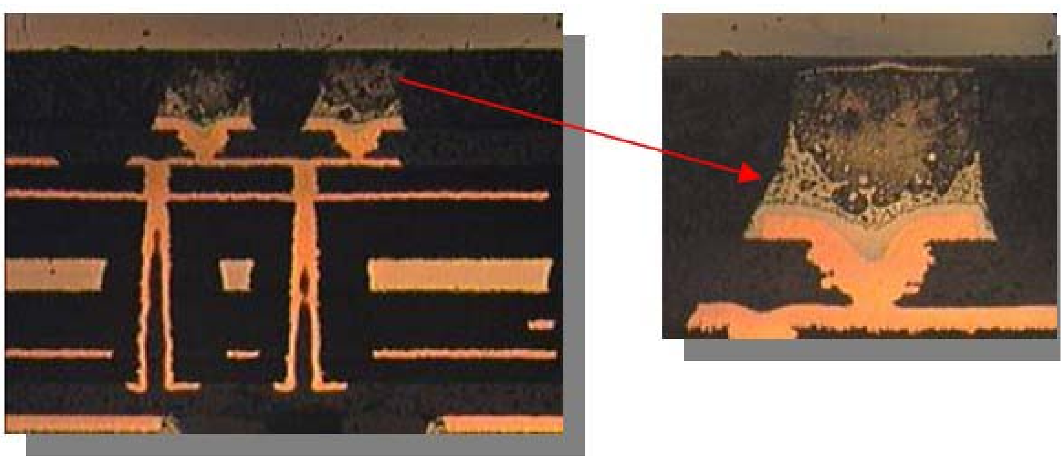


Figure 2 - Cross-Section of the 2577 I/O BGA High-Pb Flip Chip Bump Using Sn63/Pb37 Solder attach to PTFE Via-In-Pad

Pre-Assembly Component Characterization
The 2577 I/O devices were new packages with relative unknowns relating to mechanical features (i.e. co-planarity, flatness, etc.) and how the package would physically behave during a typical SMT solder reflow process. The measurements and tests performed included camber, ball height, ball diameter, and shadow-moiré. Average results for 100 parts measured are shown in Table 1.

Table 1 - Component Measurement Summary (100 parts measured)

Measurement Feature	Specification	Measurement Average	Standard Deviation
Ball Diameter	.028" nominal	.0276"	.000392"
Ball Height	.0197" nominal	.0197"	.00043"
Camber (1,3,5)	N/A	.0007"	.0017"
Camber (2,3,4)	N/A	-.0003"	.0018"

Shadow Moiré (Warpage @ Temperature) Analysis

Shadow-moiré analysis was performed at Universal Instruments Lab on a representative sample to measure the out-of-plane deflection during thermal loading. The orientation of the sample is ball-side up for the entire temperature range. Out-of-plane measurements were taken at room temperature, 100°C, 150°C, 200°C, 225°C and 240°C during heating and cooling. After peak temperature, the sample was cooled back to room temperature using cryogenic cooling. The curvature of the sample was found across the diagonals since that is the greatest length, and thus will have the highest deflection.

The initial deflection across the diagonals is 1.0 mil convex (orientation of ball side up). As it is heated, the deflection increased. At the peak temperature, the package the deflection was around 2.5 mils. It is then cooled back to room temperature. During cooling, there was a slow decrease in deflection, and the sample returned to its initial shape at room temperature. An example of the shadow-moiré deflection plot is shown in Figure 3.

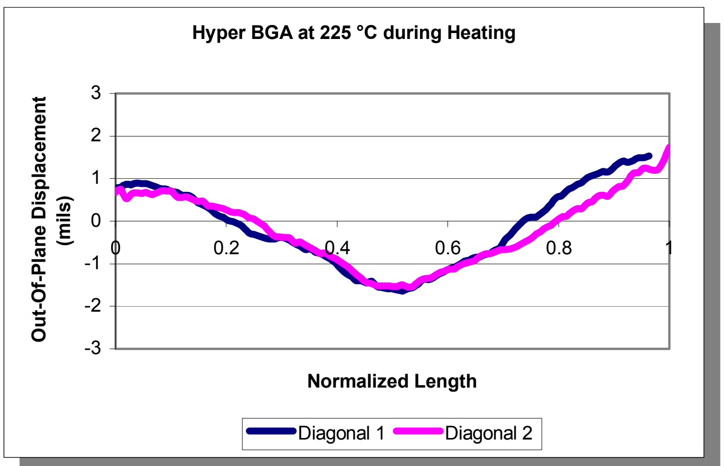


Figure 3 - 225°C Shadow Moiré Deflection Plot

Test Vehicle Design

The 2577 I/O printed circuit board test vehicle was co-designed by Jabil and Universal Instruments Consortium. The intent of the test vehicle was to provide information of the assembly and rework processes as well as 2nd level reliability assessment of these processes using Accelerated Temperature Cycling (ATC) with event detection monitoring. See Table 2 and Figure 4 for Test Vehicle Design details.

Table 2 - Test Vehicle Design Features

PCB Test Vehicle Design Feature	Specification
Material type	Fr-4 T_g =175°C min.
Dimensions (x,y,thickness)	9.35”x4.5”x.093”
Layer Count	14
Cu thickness (outer)	½ ounce
Surface Finish	Immersion Ag
Hyper BGA Cu defined pad sizes	A4 (.0225” dia) A1 (.020” dia)
Parts placed	2 2577 I/O BGAs: A4, A1 2 µBGA’s (46 I/O)
2nd level test capability	Daisy chain/all I/O Thermal heater in die for power cycling Edge connector interface to event detector cable

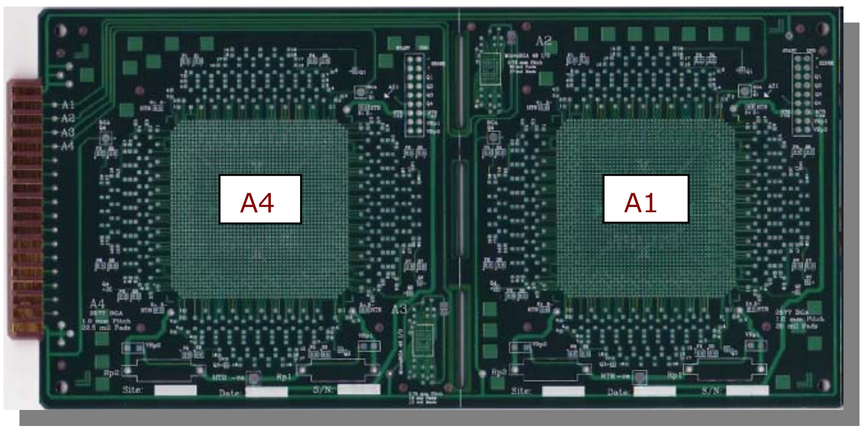


Figure 4 - Picture of the 2577 I/O Test Vehicle (Component Side)

Assembly

The assembly development for the 2577 I/O utilized current Jabil production equipment and processes. (See Table 3.) Key considerations for development of the assembly process and verification included the following:

- Stencil Printing
  - Stencil design
  - Solder volume
  - Solder printing characteristics
- Component Placement
  - Ability to pick 52.5mm2 part
  - Placement accuracy/repeatability
  - Ball Inspection (optional)
- Reflow
  - Characterizing thermocouple instrumentation of 2577 device
  - Optimizing lowest temperature differential between 2577 I/O device and other components (µBGA). Also optimizing lowest temperature differential across the 2577 I/O device
  - Repeatability
- Assembly verification
  - Electrical continuity measurements
  - 2D X-RAY
  - 3D X-RAY
  - Cross Sections

Table 3 - Process Assembly Detail

Process Feature	Details	Remarks
Solder Paste Printing	-	-
• Solder Paste	N/C, Type 3 powder, 90% metals	No issues noted with paste performance
• Stencil	5 mil thick, stainless steel, laser cut	No issues noted with stencil fabrication
• Printer	Semi-auto/Vision alignment	Typical squeegee speed, squeegee pressure, metal blades etc.
• Solder Volume	Measured with SVS 8100	Met solder volume requirements (600-2000 cu. Mils)
• Yield	33/33, 100% Print Yield	Verified visually and with SVS 8100
Component Placement	-	-
• Vision	Center of device determined using outside columns/rows of balls	Vision system was capable 100% ball inspection not performed
• Placement Force	200 grams	No issues noted with paste displacement or component misalignment
• Yield	66/66, 100% Placement Yield	Verified placements visually with Cu alignment marks and X-RAY.
Reflow	-	-
• Oven Type	Nitrogen, 10 zone forced convection	Typical new oven configuration
• Test Vehicle Instrumentation	6 thermocouple (TC) locations on test vehicle. 2577 I/O device was also thermo-coupled at 5 locations	See Figures 5 for TC locations at 2577 I/O device. See Figure 6 for TC locations across test vehicle.
• Peak Temp	(2577) 203-215°C (µBGA) 225°C	Acceptable results
• Yield	65/66, 98.5%	1 solder bridge @2577 I/O device (22.5mil Cu pad)

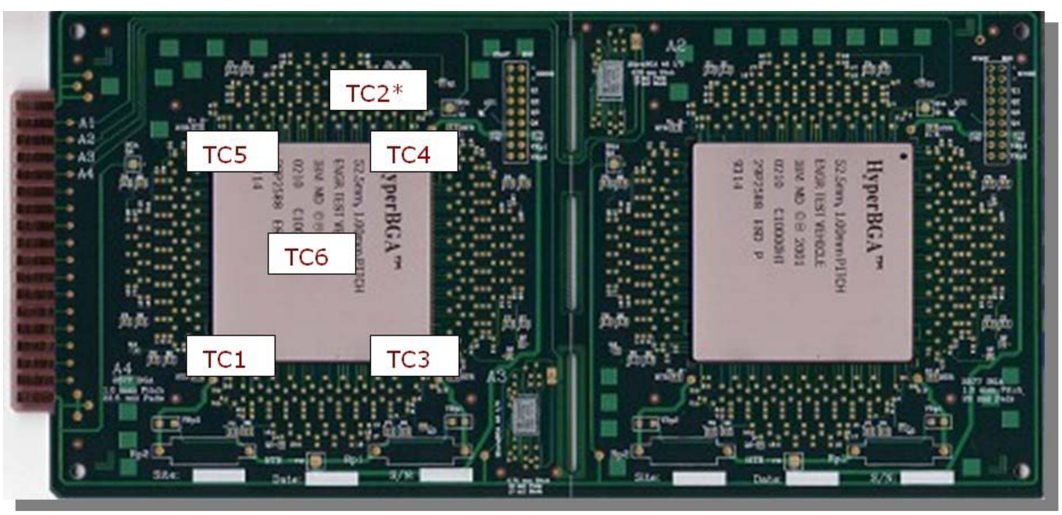


Figure 5 - Thermocouple Locations – 5 Locations @ 2577 I/O device

TC1: Leading Corner of A4
TC2: *Bottom of Board
TC3: Trailing Corner of A4
TC4: Trailing Corner of A4
TC5: Leading Corner of A4
TC6: Center of A4

The thermocouples at locations 1, 3, 4, 5, and 6 were inserted through drilled holes from the bottom-side of the test vehicle to record the ball temperature. The drilled holes were epoxy sealed.
TC2 (Bottom of Board) was placed on the bottom-side surface of the test vehicle. The TC was epoxy sealed.

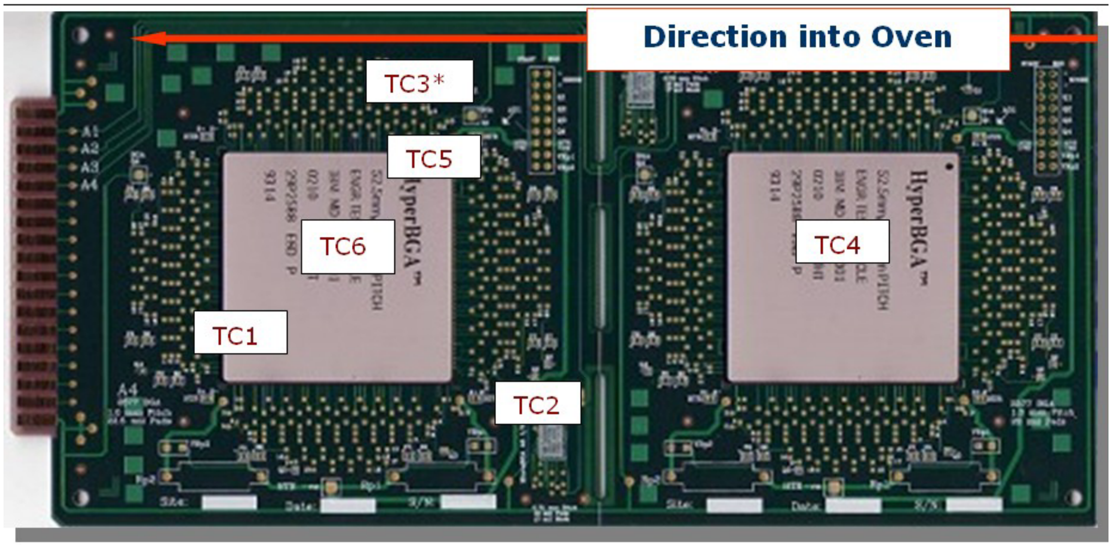


Figure 6 - Thermocouple Locations – Across the Test Vehicle

TC1: Leading Corner of A4
TC2: Center of A3
TC3: *Top of Board
TC4: Center of A1
TC5: Trailing Corner of A4
TC6: Center of A4

The thermocouples at locations 1, 2, 4, 5, and 6 were inserted through drilled holes from the bottom-side of the test vehicle to observe the ball temperature. The drilled holes were epoxy sealed.
TC3 (Top of Board) was placed on the topside surface of the test vehicle. The TC was epoxy sealed.

Process Verification

Post assembly process verification was done to verify assembly integrity. Work done included 2D X-RAY, 3D X-RAY, electrical continuity measurements, dye and pry, and cross sectional analysis (Figure 6). See Table 4 for process verification details.

Table 4 - Post Assembly Process Verification

Analysis	Detail	Remarks
2D X-RAY	125KV system with vision processing.	Recorded 1 solder bridge Minimal voiding. Met IPC Class II requirements
3D X-RAY	Production System	Met IPC Class II requirements
Electrical continuity	milli-Ohm 4 wire (Kelvin) bridge	~21.4 Ω average. No issues noted.
Cross Sections	Examined up to 1000X	Good solder joint wetting, typical intermetallic formation. Standoff height ~ .0147” See Figure 6a and 6b for detail
Dye and Pry	Examination of BGA and PCB pads after prying from PCB to observe for possible dye penetrant in solder joint structures	No dye ingress observed.

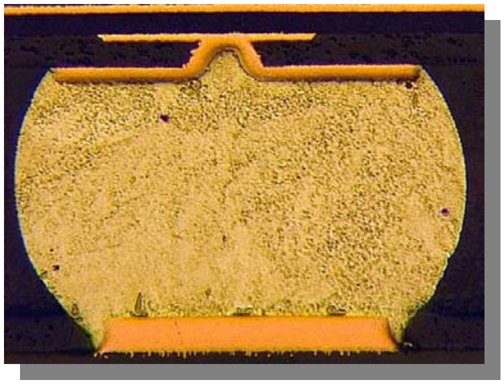


Figure 6a - Representative Solder Joint

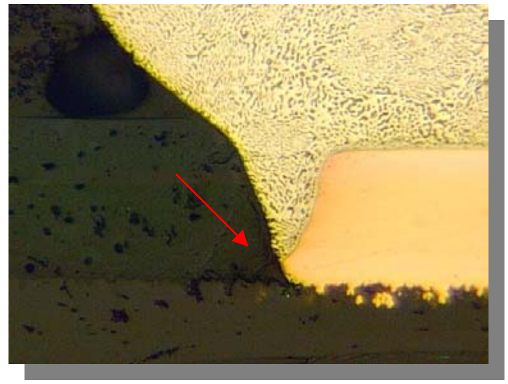


Figure 6b - Solder Mask Encroachment

Rework

The rework phase of the project evaluated two different rework processes for the 2577 I/O device. Rework process #1 used a flux-only process, N2 hot gas and board preheat. The flux was deposited onto the new part by dipping the replacement device into a N/C paste flux. Flux height control was accomplished by using a channeled squeegee that allowed for a precise height of flux after it was passed over a flat plate with pre-applied flux. The flux-only process was evaluated to understand the changes in the ball standoff height and also to evaluate reliability when subjected to accelerated temperature cycling.

Rework process #2 used a solder paste print process, with similar N2 hot gas rework equipment. The solder paste was deposited onto the test vehicle replacement site using a micro-stencil and the same N/C solder paste that was originally used for assembly.

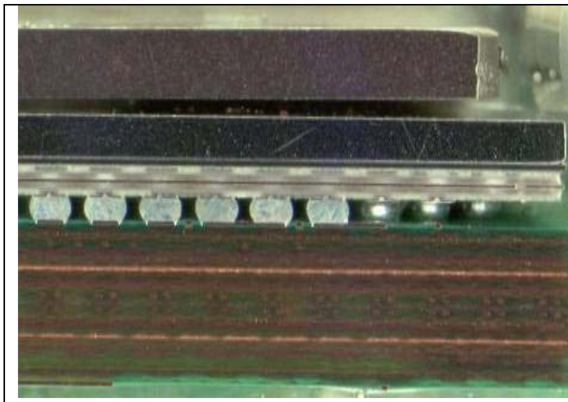
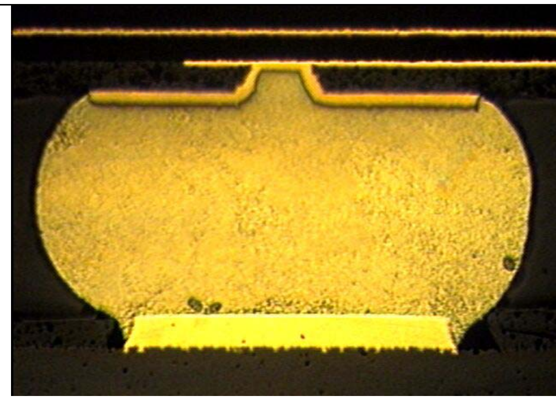
Both processes required good thermal characterization of the 2577 I/O device with multiple thermocouple locations.

Both rework processes included a "pre-bake" of test vehicle and components to minimize/eliminate moisture out-gassing as a process variable (i.e. delamination/solder voids, etc.). Both processes exhibited good process yield, electrical continuity, and solder joint structure. Electrical continuity, dye and pry, cross sections, and ball standoff measurements were performed. Please see Table 5 for additional rework detail including sample size, yield, standoff height, etc.

Table 5 - Rework Information

Process	Detail	Remarks
Flux-only	-	-
• Sample size	10 units (5 at each test vehicle Cu pad size)	
• Rework station	N_2 hot gas with high energy board pre-heat. Nozzle used was 55mm square.	Commercially available. Did not require modifications to do the 2577 I/O rework.
• Flux application	No Clean tacky paste flux, ~.008" deposition thickness. Part placed onto plate with pre-applied flux.	Tacky flux is commercially available
• Site "re-dress"	Semi-automated hot gas/vacuum station with automatic height adjustment Set unit to .005" clearance from end of vacuum nozzle tip to test vehicle board surface.	All sites successfully re-dressed. (No pad lifts or damaged solder mask) Observed uniform residual solder height on BGA pads after re-dress process.
• Thermal profiling	Peak Temp 204-212°C @ 2577 I/O solder joints (5 thermo-coupled locations)	Acceptable results.
• Yield	10/10 (100% yield)	Solder joints were uniform in shape with minimal solder voids observed.
• Stand-off height	.0139" average	Measurements included cross section. See Figure 7a and 7b.
Solder Paste	-	-
• Sample size	10 units (5 @ each test vehicle Cu pad size)	5 units in solder paste group were re-balled to look at re-balling feasibility, effects on post rework standoff height and performance during 2nd level Accelerated Temperature Cycle Testing
• Rework Station	N_2 hot gas with high energy board pre-heat. Nozzle size used = 55.3mm square using "open end" design	Commercially available. Unit required "in house" modifications to meet 2577 I/O rework objectives
• Solder Paste Application	5 mil mini-stencil SS, laser cut N/C solder paste (same paste type as used during assembly)	No printing issues observed on either pad geometry.
• Site re-dress	Traditional solder wick/soldering iron process	All sites successfully re-dressed (0 pad lifts or solder mask damage)
• Thermal profiling	Peak Temp 205-212°C @ 2577 I/O solder joints (5 TC locations)	Acceptable results
• Stand-off height	.0149" average (new parts) .0141" average (re-balled parts)	Measurements included cross section.
• Yield	5/5 (new parts) 5/5 (re-balled parts) Overall 100% yield	Solder joints were uniform in shape with minimal solder voids observed.

Note: The same verification methods used to verify post assembly assemblies were also performed on both rework groups including electrical continuity test, 2D X-RAY, 3D X-RAY, dye and pry and cross sectioning (Figure 7). All inspected assemblies and associated solder joints were comparable to the assembly verification findings and also met IPC 610 Class II requirements.

 **Figure 7a - Flux-Only Rework Cross-Section Overview**	 **Figure 7b - Magnified Flux-Only Cross-Section**

Accelerated Temperature Cycle Testing

The assembled test boards were subjected to 0/100oC air-to-air thermal cycling in order to drive fatigue mechanisms. Each thermal cycle was 20 minutes in length with 5-minute dwells at the temperature extremes and a 20oC/min ramp rate between the temperature extremes. Continuous in-situ event detection was used to determine failure. A failure was defined as the first cycle in which the net resistance of the test vehicle assembly exceeded 300 ohms for a minimum duration of 200 nanoseconds that could be confirmed by nine similar events within 10% of the cycle count as specified in IPC-9701.

Testing continued until 36 of 39 2577 I/O BGA devices failed. Failed components were removed from the thermal chamber following the identification of electrical events. Electrical discontinuities of the daisy chain were located using an ohmmeter and the earliest failures from each test cell were then subjected to failure analysis.

Failure Analysis

The first 2577 I/O BGA assembly failed at cycle 748. The device was located on PCB Site A1 (.020" diameter pads) and had been subjected to the flux-only rework process. The assembly was removed from the thermal chamber after cycle 850 and examined. The device was electrically open and the suspected failure location was isolated. The part was then cross-sectioned through the centerline of the solder joints located in the suspected failure region. The solder joints were examined and it was discovered that the failure was due to a "cold joint" or similar phenomena. The cold joint, shown in Figure 8, failed to fully wet to the PCB during the assembly process and separated from the PCB during thermal cycling. The joint is oblong, which indicates that the solder reflowed and collapsed while contacting the PCB. The reasons for cold joint formation are numerous and can only be speculated upon. However, the shape of the solder joint in cross section and the fact that the joint was electrically good following rework indicated that some degree of contact and even metallurgical bonding existed. Knowing that the assembly had been reworked using a flux dipping process, it is reasonable to assume that the bump did not receive sufficient flux to bond to the entire PCB pad. The failure was classified as an infant mortality due to a process related defect and was excluded from the reliability (lifetime) calculations. The next failure would not occur until cycle 3424 and the third failure until 5724 cycles.

Figure 8

The remaining BGA failures were selectively analyzed in order to determine the failure mechanisms encountered. Every failure was electrically probed and it was determined that two regions of the package were susceptible to failure. Most of the assemblies failed due to electrical discontinuity at the corner most region of the BGA device, but several assemblies failed due to electrical discontinuity in the central region of the package corresponding to the 16, 17, 18 or 19th row of solder joints.

Cross sectioning performed through the corner most solder joints successfully located solder fatigue in the 2nd level interconnects. Cracks were visible in the bulk solder material near the Non-Solder Mask Defined PCB pad. Figure 9 is a representative example of a fatigued corner joint. The solder microstructure displayed typical Sn and Pb phase coarsening in the crack region.

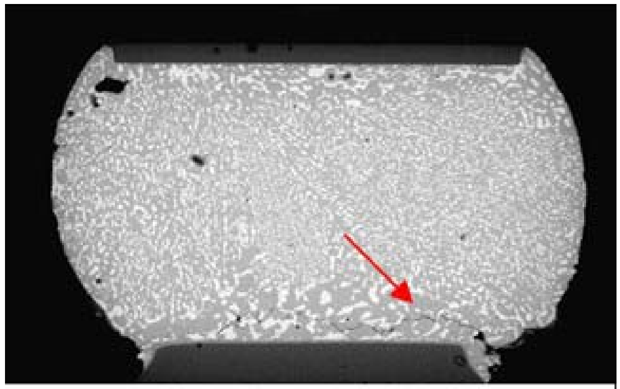


Figure 9 – Fatigued Corner Joint

Dye penetrant testing of other devices demonstrating corner joint failure confirms that significant solder fatigue was present in these BGA assemblies (Figure 10). These failures are primarily driven by stresses proportional to the solder joint DNP and CTE mismatch between the PCB and BGA body.

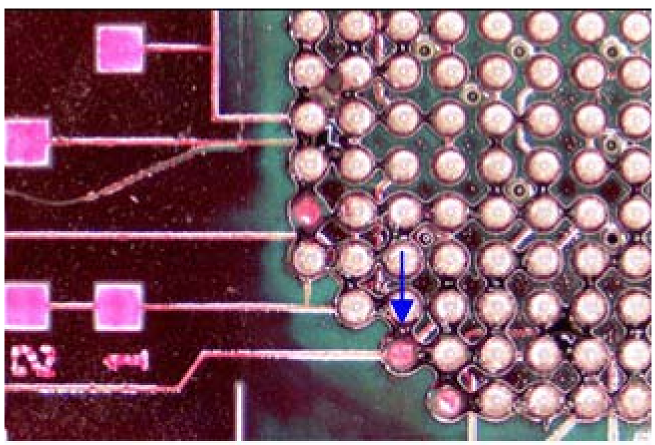


Figure 10 – Dye Penetrant Testing of Corner Solder Joints

Cross sectioning performed through the centrally located solder joints did not reveal solder fatigue. The 2nd level solder joints were electrically continuous in cross section and no visible explanation for the failures was apparent. Figure 11 contains an image of four consecutive solder joints that were located along the electrically discontinuous portion of the daisy chain. No fatigue cracks were present in the joints.

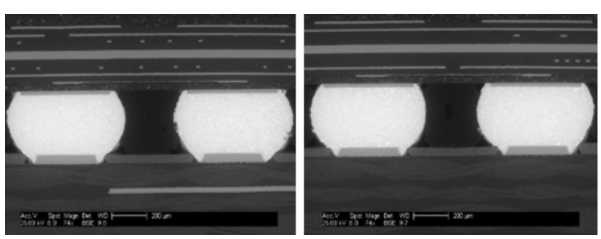


Figure 11 – Solder Joints without Fatigue Cracks

Dye penetrant testing also indicated that the centrally located solder joints were electrically good (Figure 12).

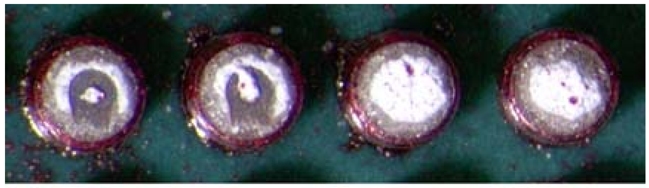


Figure 12 – Dye Penetrant Testing of Centrally Located Solder Joints

It is believed that the failures occurring within the central part of the BGA are due to an internal problem within the BGA routing that includes a large number of microvias as part of the daisy chain. Unfortunately, the exact location of each microvia was not included on the daisy chain map supplied by the manufacturer and it was impossible to cross-section through all the microvias in the failure region.

Overall, the internal failure was detected in at least 12 of the 39 BGA assemblies tested. The failure occurred within every test cell and appeared to be independent of PCB pad size and assembly/rework processing. The internal failure was associated with early failures and late stage failures –which indicates that the mechanism occurs in parallel with solder fatigue.

Lifetime Calculations

The cycle to failure data acquired from the thermal cycle test was plotted using a Weibull distribution and compared using Winsmith Weibull software version 2.0J. The Weibull software calculates the N01, N63.2, Beta and r2 value for each sample set. N01 is the projected number of cycles required for 1% of the sample population to fail. N63.2, or Eta, is the number of cycles required for 63.2% of the sample population to fail and is generally referred to as the characteristic lifetime of the sample set. Beta is the slope of the Weibull plot and describes the successive failure rate of the sample set. r2 describes the fit of the data to a straight line and is useful for determining multiple failure mechanisms.

The experimental data was divided into six test groups that were based on the PCB pad dimensions and assembly parameters including original paste assembly, flux-only rework and paste rework processes. The test group descriptions and results of the Weibull analysis may be found in Table 6.

A review of the data indicates that the flux-only reworked BGAs produced a significantly lower N01 and Beta than the remaining test cells. However, the N63.2 data for the sample set is on par with the other test cells. The low N01 and Beta were due to an early failure at cycle 3424. The 2577 I/O BGA assembly was evaluated and it was found that the failure was one of the internal failures and therefore was indicative of the package's performance and was used in the lifetime analysis.

Overall, the reliability of the 2577 I/O BGA far exceeded expectations. The device demonstrated an ability to surpass at least 3000 cycles without failure and produced a characteristic lifetime in excess of 6500 thermal cycles for all six test cells. Not surprisingly, the original paste assemblies exhibited the greatest reliability, but the 2577 I/O BGA assemblies were not significantly affected by the assembly + rework processes. The data also indicates that the PCB pad diameter was an important factor in determining the characteristic lifetime of the device. The larger PCB pads actually resulted in a greater lifetime. This is probably due to the fact that the solder fatigue failures were due to crack propagation along the PCB pad. The larger, .0225" diameter pads would require additional time for a crack to propagate around than would the .020" diameter pads. The .0225" pad is 12.5% wider and contains nearly 26% more solderable area than the .020" and it was found that the N63.2 on the larger pads was approximately 10 to 16% greater than on the smaller pads.

Table 6 - Weibull Reliability Data Summary

2577 I/O BGA	Assembly Process	PCB Pad Diameter	N01 (Cycles)	N63.2 (Cycles)	N63.2 @ 90% Confidence (Cycles)	Beta	r^2
Original	Paste	.020"	5285	6669	6589	19.77	0.917
Original	Paste	.0225"	5484	7792	7531	13.09	0.987
Rework	Flux	.020"	4555	6507	6298	12.09	0.754
Rework	Flux	.0225"	1527	6816	5152	3.075	0.830
Rework	Paste	.020"	4819	6866	6368	13.15	0.924
Rework	Paste	.0225"	5073	7227	6510	13.22	0.850

Considerations for Assembly and Rework of the 2577 I/O Package

The experiments associated with the assembly and rework process development of the 2577 I/O package revealed that an understanding of the component construction, materials, equipment and techniques is necessary for successful production manufacturing of product using a large device like the 52.5mm2, 2577 I/O package. Some of the considerations for the user who is going to use a very large BGA device similar to the 2577 I/O could leverage from the "lessons learned" that are described in this paper.

These considerations include the following:

1. Board Design.
   a. Use of a Cu component edge mark at each corner of the BGA site to assist with placement verification during assembly and rework of the device. See Figure 13.
   b. Use of a chevron solder mask registration feature to allow ease in verification of solder mask registration in relationship to critical Cu outer layer features. See Figure 14.
   c. Use of larger pads to enhance 2nd level reliability (see reliability data for .020" vs. .0225" diameter Cu mounting pads).
2. Component Placement.
   a. A single field of view camera to maximize placement cycle time.
   b. 100 % ball inspection to reduce risk of placing damaged components.
3. Reflow
   a. Use of > 10 zone convection oven to control temperature deltas across large components and also minimize T delta between different component sizes (i.e. 2577 I/O part and a 48 I/O µBGA).
   b. Careful thermocouple instrumentation of the package and adjacent areas to understand actual temperatures at various locations in the package and other areas of interest on the PCB.
4. Rework.
   a. The flux-only process must be carefully characterized before possible production use. Solder volume and standoff height must be characterized and understood for possible 2nd level reliability implications.
   b. Re-balling of devices needs to be carefully characterized before consideration as a production intent process. Considerations include mechanical strength of ball attachment, impacts to package integrity and possible degradation of package electrical performance.
   c. A 50mm field of view optics system was used on one of the rework machines in the study. Alignment was possible by use of the split mirror system. A single field of view optics system that captures the entire part without use of split mirrors would provide easier alignment of the part to the PCB.
   d. Thermal management. The rework machine that was used for the solder paste rework group required a modification to allow for better gas distribution. Our original experiments showed a very high T delta from the center to the corners of the 2577 I/O device. A diffuser was created to deflect the hot gas from the center and create better hot gas distribution. See Figure 15 for a schematic overview of the diffuser modification.

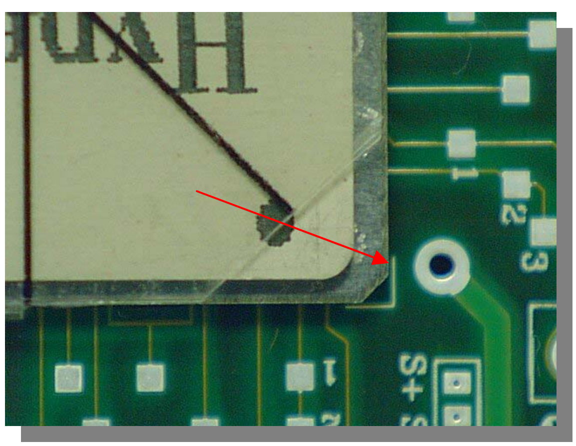


Figure 13 - Cu Alignment Mark

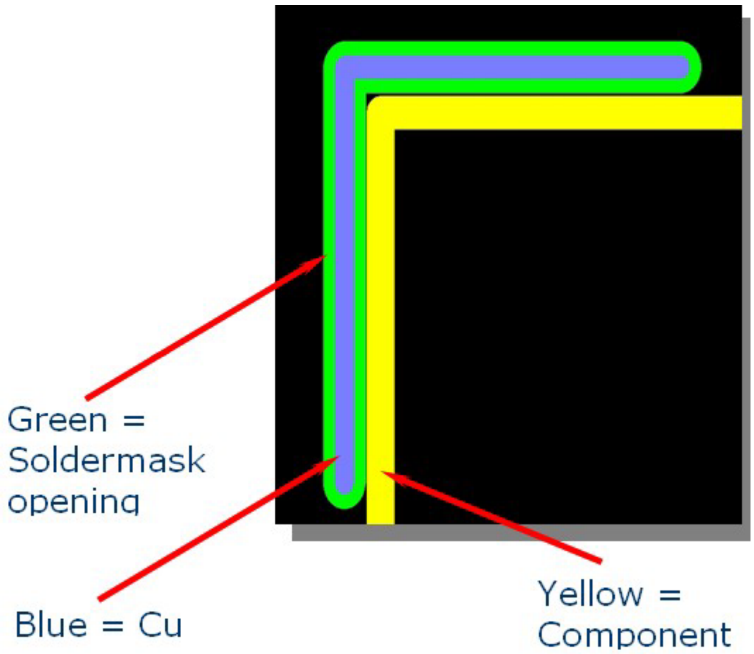


Figure 14 - Solder Mask Registration Mark

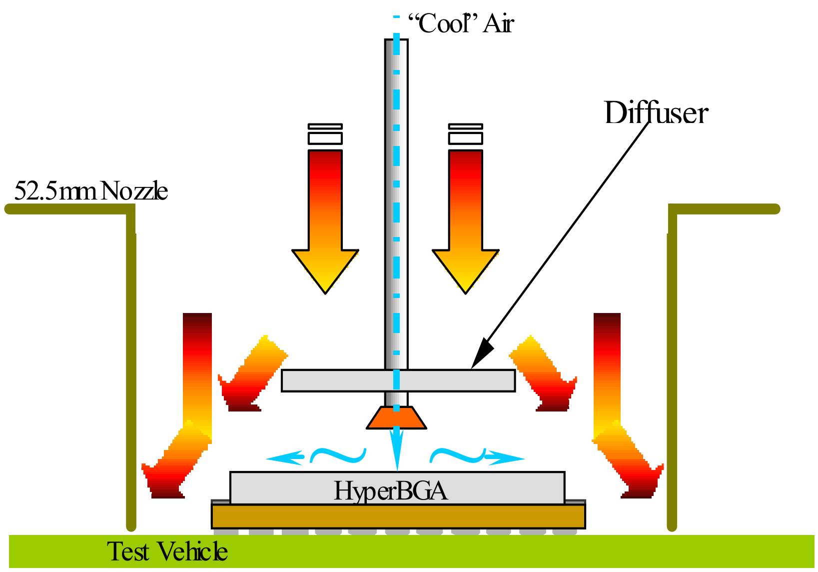


Figure 15 - Rework Reflow Schematic Including Diffuser

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