

Rework and Reliability of High I/O Column Grid Array Assemblies

Reza Ghaffarian, Ph.D.

Jet Propulsion Laboratory, California Institute of Technology

Pasadena, CA

Reza.Ghaffarian@JPL.NASA.Gov

(818) 354-2059

Abstract

Commercial-off-the-shelf column grid array packaging (COTS CGA) technologies in high reliability versions are now being considered for use in a number of National Aeronautics and Space Administration (NASA) electronic systems. Understanding the process and quality assurance (QA) indicators for reliability are important for low-risk insertion of these advanced electronic packages. This paper presents rework and re-column attachment of two high input/output (I/O) CCGA (CGA) packages (560 and 1144 I/Os). Subsequent to re-column attachment and isothermal aging, the integrity of tin-lead solder-column attachment was determined and presented. In addition, the process-control parameters for assembly of re-columned CGA packages using either vapor-phase or rework stations were established for both package types/sizes. Details of these process control parameters solder paste-print uniformity as well as quality assurance indicators based on visual inspection before and during thermal cycling tests are presented. Qualification guidelines generated based on these and additional optical photomicrographs, X-rays, SEMs, and destructive cross-sectioning of thermally cycled, reworked, re-columned, and re-assembled test vehicles of these CGAs are presented in detail.

Key Words: column grid array, CGA, CCGA, rework, re-column, thermal cycle, FPGA, solder joint reliability

Introduction

This author has addressed assembly reliability behavior of numerous ceramic column grid array (CCGA or CGA) types in previous investigations [1]–[3]. In addition, package suppliers also provided some board level reliability data for their specific packages [4]–[8]. For high reliability applications, CGAs with a 1.27-mm pitch (distance between adjacent ball centers) or lower are now replacing surface mount leaded packages, such as ceramic quad flat packs (CQFPs). In addition to size reduction, CGAs also provide improved electrical and thermal performance; however, their solder columns are prone to damage, and it is almost impossible to rework defective solder joints. Rework, re-column, and re-assembly may be required to address solder defects due to processing or column damage prior to assembly due to shipping and mishandling. This paper presents test results for column attachment process and integrity as well as assembly reliability for two different CGA package sizes/styles/I/Os, one with 560 and the other one with 1144 I/Os. Re-columned packages were assembled on printed circuit/wiring boards (PCBs/PWBs) using tin-lead solder paste that were reflowed either by vapor-phase machine or rework station. Optical microscopy and scanning electron microscopy (SEM) was used to capture damage progress of column and solder interconnection due to thermal cycling at intervals. Results performed under different thermal cycling ranges along with optical photomicrographs, X-ray, SEM, and X-sections are also presented.

Assembly, Rework, and Re-assembly of CGA560

A CGA package with 560 columns was selected for assembly and subsequent rework, re-column, and re-assembly, and reliability evaluation. Figure 1 depicts a photomicrograph of the CGA560 package with interposer attached and its interposer layer alone on top of package. The CGA560 package had a few key characteristics that are considered to be ideal for the rework process optimization. These special features included:

- Package availability: Individual virgin packages as well as test vehicles (TVs) with package assemblies were available, and the effect of additional rework on thermal cycle behavior after re-columning and re-assembling could be compared.
- Large ceramic package: The package is relatively large since it was designed to simulate its plastic counterpart version with the identical configuration, I/O counts, and 1.27-mm pitch. It is a peripheral array rather than a full array which is a common configuration for CGAs.
- Large CTE mismatch: The package had an added ceramic interposer for absorbing CTE mismatch to improve assembly solder joint reliability. This thin ceramic interposer was removed prior to re-columning in order to introduce maximum stresses due to CTE mismatches during thermal cycling exposures.
- Large columns: Possibly because of the package size and interposer, solder column diameter is unusually larger than standard diameter; therefore, the re-columned version had lower diameter requiring smaller PCB pad sizes for assembly.
- Assembly rework: Assembled packages were removed by rework station. Also utilized two pad designs using the initial TVs, one for CGA and the other for PBGA.

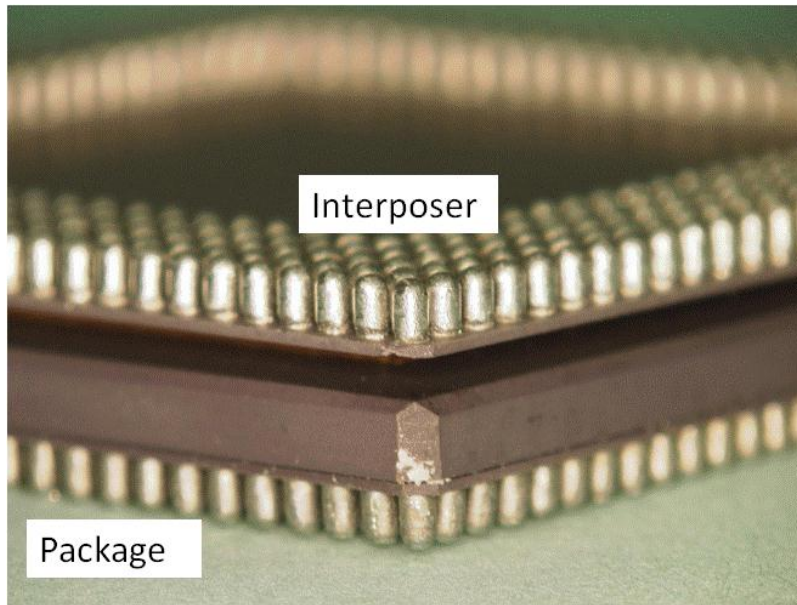


Fig. 1. Optical photomicrograph of a virgin CGA 560 I/O package before re-columning with interposer (bottom) and an interposer layer alone on the top.

Key Rework Parameters

A design of experiment (DOE) technique was utilized to cover many aspects of re-columning and re-assembling that are considered unique for this package configuration. The following parameters were part of the DOE matrix even though, in some cases, because of re-assembly processing issues, they could not be evaluated for subsequent thermal cycling behavior characterization as it was planned originally.

- CGA packages with and without corner staking were successfully removed from assembled TVs. In the first attempt, corner stakes induced minor damage to the board at corners away from the pads since the direction for removal was not clearly given to operator. Damage to board was minimized through providing a more detail procedure for reworking. Figure 2 depicts photomicrographs of packages after removal showing remains of columns on the interposer and daisy chain pattern for the exposed package pads.
- Ceramic interposer layers were removed both for virgin and reworked packages prior to re-column attachment on the new package with the land grid array pattern.
- These daisy chain packages had traces between many pads to accommodate full daisy chain resistance monitoring when assembled onto a board. Masking of these traces was considered before column attachment; however, the vendor was able to perform column attachment successfully with no evidence of shorts without masking the daisy chain traces. Tin-lead solder paste was used for column attachment.
- One re-columned virgin package was subjected to pull testing to assure quality of column solder joint attachments prior to committing to re-columning of other parts.
- Two additional re-columned virgin packages were subjected to isothermal aging and pull testing to determine quality of bond interfaces after aging exposures. One package had an additional simulated re-columning reflow to represent rework.
- Two mini-stencils were used for the two pad sizes: one designed for CGA pads, and the other designed for smaller pads for PBGA attachment. Mostly the CGA pad design was used.
- All packages were placed onto PCBs using a rework station. Both the rework station and the vapor phase reflow machine were used for reflowing solder pastes. The TVs with PBGA assemblies were also reflowed in place one more time during reflow of re-columned packages.
- A vapor-phase reflow profile for tin-lead solder with constant reflow temperature at 217°C for duration of 60 seconds was used.
- Acceptable reassembled TVs as well as those with known manufacturing defects were subjected to thermal cycling to detect early failures due to workmanship and damage progress with cycling for CGAs with acceptable quality.
- Optical photomicrographs, X-ray, and cross-sectioning were documented.

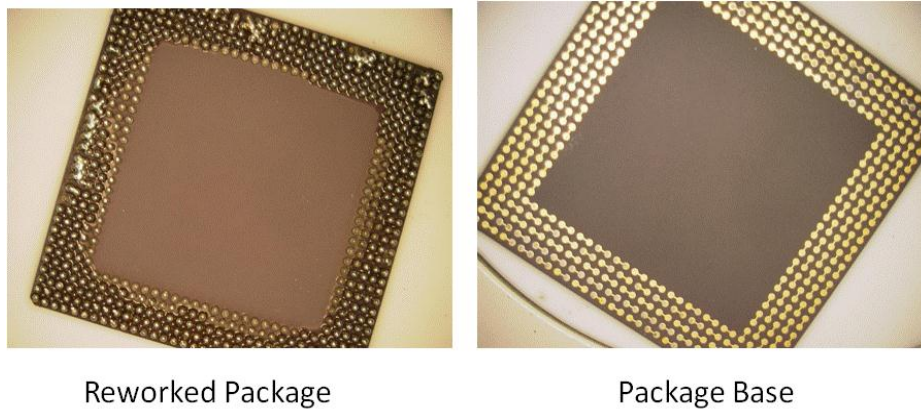


Fig. 2. Optical photomicrographs of a removed CGA560 package after rework showing removed/shorted columns (left) and package daisy chain pattern without interposer (right).

PCB/TV/Package CGA 560 I/Os

Figure 3 depicts the top and bottom of the board design for the CGA560 package assembly showing the daisy chain configurations, including PBGA560 probing pads. The PCB's pads had Hot Air Solder Level (HASL) tin-lead surface finish as specified in IPC [9] for the tin-lead solder assembly.

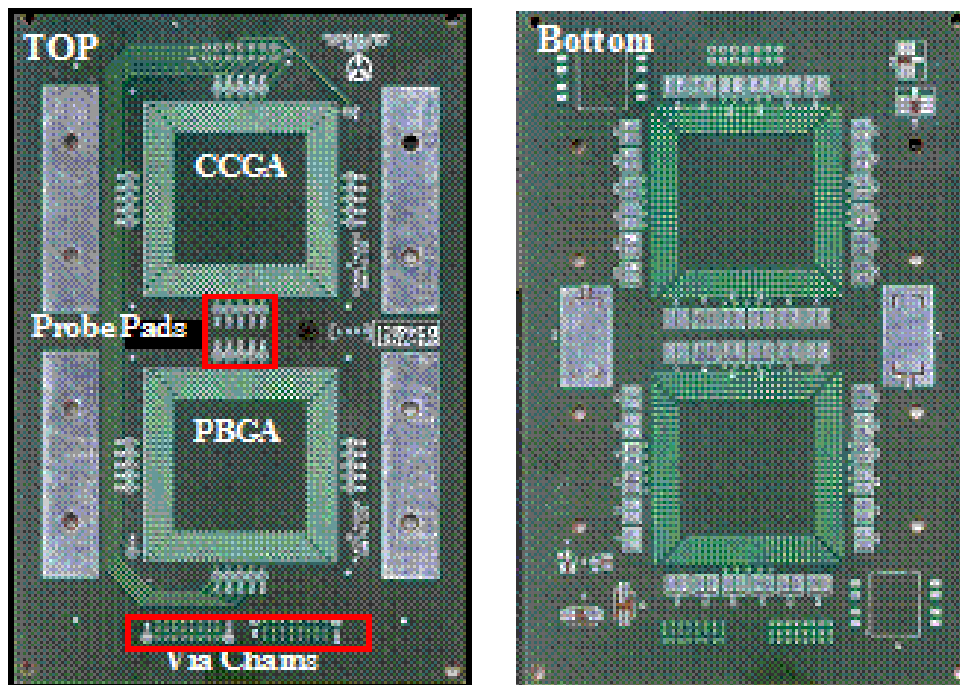


Fig. 3. PCB design showing package daisy chain, probing pads, and via daisy chains.

Re-assembly of CGA560 Results

A detailed test matrix for rework, re-column, and re-assembly of TVs was outlined at the start of the build. However, during subsequent re-assembly, it was recognized that on-the-spot modifications are required to achieve acceptable assemblies based on visual inspection of outer-row solder columns due to numerous assembly challenges. For example, Figure 4 includes two representative TVs after re-assembly of re-columned CGA560 packages. One has acceptable quality, but the other was rejected because of gross package twisting possibly occurred due to uneven nozzle heat flow. As stated, a rework station was used for both placement and reflow since it represents a more realistic condition.

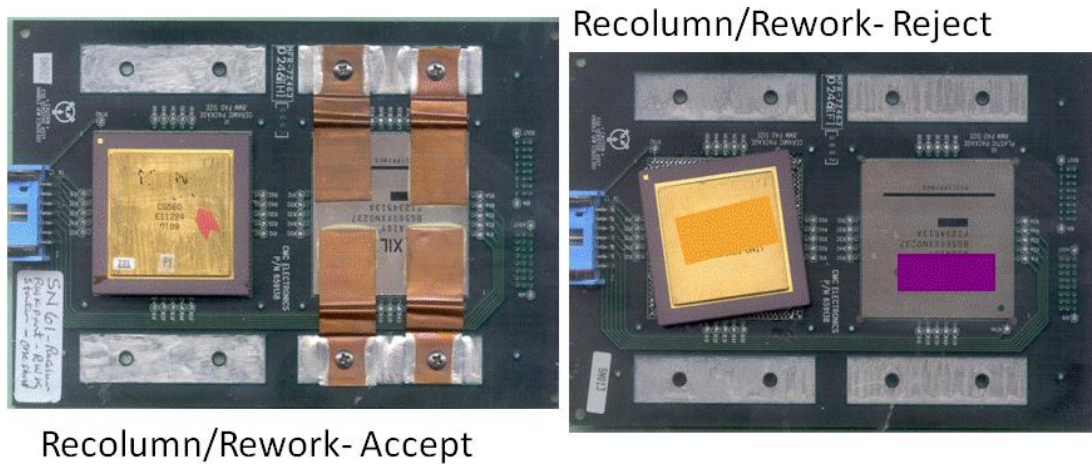
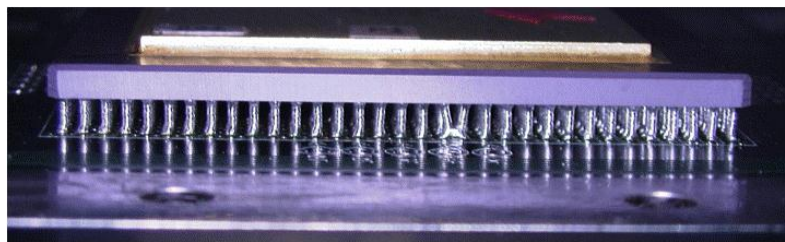


Fig. 4. Representative TVs after re-assembly of re-columned CGA560 packages: one with acceptable quality and the other rejected with gross package twisting occurred during solder reflow by a rework station.

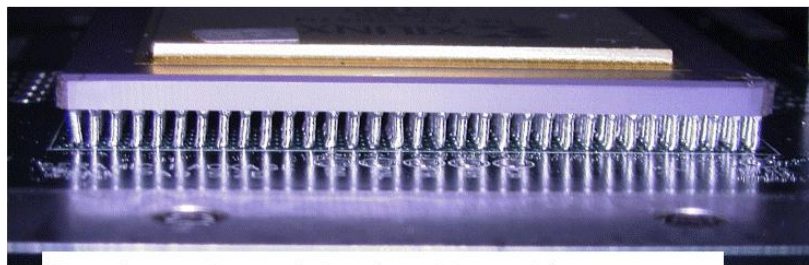
Inspection after Re-assembly of CGA560

Photomicrographs were taken after all test vehicles were reassembled to document quality of solder joints, including those with various workmanship defects. Figures 5 shows optical photomicrographs for re-columned CGA560 packages assembled under various conditions. Several processing defects are noticeable from these photos, including the following:

- Photomicrographs comparing quality of solder joints reflowed by vapor-phase machine or rework station. In a case where solder paste was not reflowed by rework, station was reflowed using reflow machine.
- Significant column shift when the package is assembled on relatively smaller pads designed for its PBGA package assembly.
- Solder short between the two columns in the middle of package outer row.
- Corner column shift and also the appearance of solder column separation at the package side (not shown at high magnification).
- Solder balls on the package in addition to the board side (photomicrographs not shown here); their source was not identified.



Recolumn-Rework Station



Recolumn-Rework Station- Vapor Phase

Fig. 5. Representative of optical photomicrographs for re-columned 560 I/O package assemblies.

The soldered column separation from the package side is a significant failure and is unusual. This might be due to the weakness in re-column attachment, which might have been exacerbated by another reflow during re-assembly causing solder separation at the pads. Note; however, that the new columns have much smaller diameter that are placed on relatively larger package pads allowing more movement of columns during reflow. Follow-on test results for strength reduction on re-columned packages with and without additional reflow and subsequent aging at 125°C all indicated lack of significant interfacial degradation. Consequently, the tensile test results reject the possibility of failure due to weakness of solder joints at interfaces. Another possibility is that the smaller re-column size relative to the large package size and weight causes elimination of self-alignment, which is a key advantage of the area array package. Daisy chain connections between the pads at the package side also are not representative of a working part and may contribute to such interfacial failure. Solder on daisy chain traces can possibly further facilitate column shifting to the neighboring pads during solder reflow.

RESULTS FOR CGA560

Thermal Cycle Conditions

Only a few assemblies had acceptable quality because of manufacturing challenges. Four assemblies considered to be acceptable were subjected to a cycle condition ranged from -55° to 100°C with a 2° to 5°C/min heating/cooling rate. Dwells at extreme temperatures were 15 minutes.

X-ray Characterization

A real time, 2-D X-ray system with a stationary microfocus source intensity and off-axis rotational capability was used to determine the damage states of re-columned CGA560 assemblies. Figure 6 shows an X-ray photomicrograph for an assembled CGA560 after thermal cycle exposure. The X-ray technique clearly detects abundance of solder balls but no indication of other defects; neither solder damage nor solder separation at pads due to thermal cycling.

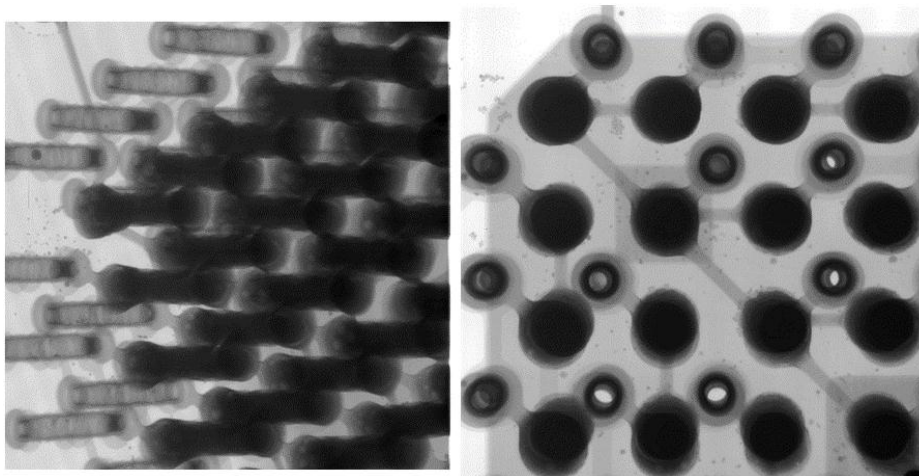


Fig. 6. X-ray photomicrographs for re-columned and re-assembled CGA560 after thermal cycle exposure showing solder balls, but no separation at package pads detected visually.

Damage Progress with Thermal Cycles

Damage progress with thermal cycling was established using optical microscope. Figure 7 presents a representative photomicrograph showing workmanship defects due to manufacturing as well as damage due to thermal cycling. Based on all inspected solder joints, there were various defects due to re-assembly that are categorized as follows:

- Solder balls at the package and board sides are apparent from low and high magnifications of re-column attachments. Coalescence of a large number of solder balls was observed at the package side at higher magnification. The sources of these solder balls are not clear, but they could be the result of solder splash from paste during solder reflow.
- Several displaced columns showing a larger corner column shift are apparent. Magnified photomicrographs clearly show signs of damage and microcracking due to thermal cycling at the package side.
- Several columns were shifted after thermal cycling. Photomicrographs of these at higher magnification clearly show pad separation from the package. This failure is unusual since microcracking generally occurs in the solder, as shown in the previous figure.

As discussed, soldered column separation from package side is considered an unusual and significant failure. Tensile test results exhibited no such failure mechanisms and no indication of interfacial weakness. Possible reasons for such a failure mechanism may be an unusual package size/weight and use of a smaller-column diameter.

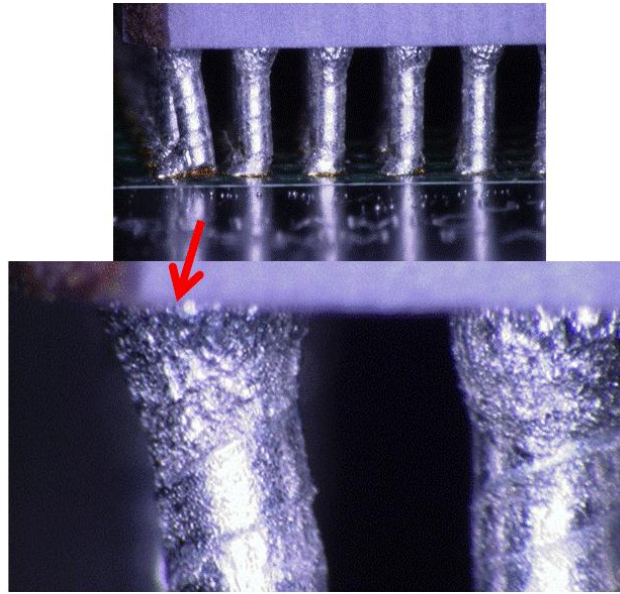


Fig. 7. Optical photomicrograph re-columned and reassembled CGA 560 I/Os after thermal cycles showing microcracks in solder at the package side.

SEM Photomicrographs and X-section

After thermal cycle completion, one sample was cut at its periphery in preparation for additional optical, SEM, and cross-sectioning. Figure 8 depicts representative optical photomicrographs of the assembly prior to cross-sectioning. Damage and microcracks exhibit better resolution since optical lenses now can get close to the package with no interference from the board. Figure 9 depicts representative SEM backscatter photomicrographs of column attachments at various magnifications up to 1,000 times. Cracks at the package side in solder interfaces are clearly apparent. Figure 10 depicts a photomicrograph at much higher magnification showing at least three types of microcracks. Potential mechanisms include: a) the large microcracks at the package interface surrounding the pad interface are due to the weak re-column attachment; b) the microcracks close to Cu spiral are due to weak Cu/solder interface and local CTE mismatch; and c) the microcracks parallel to interface between solder and column are due to the overall package/board CTE mismatch.

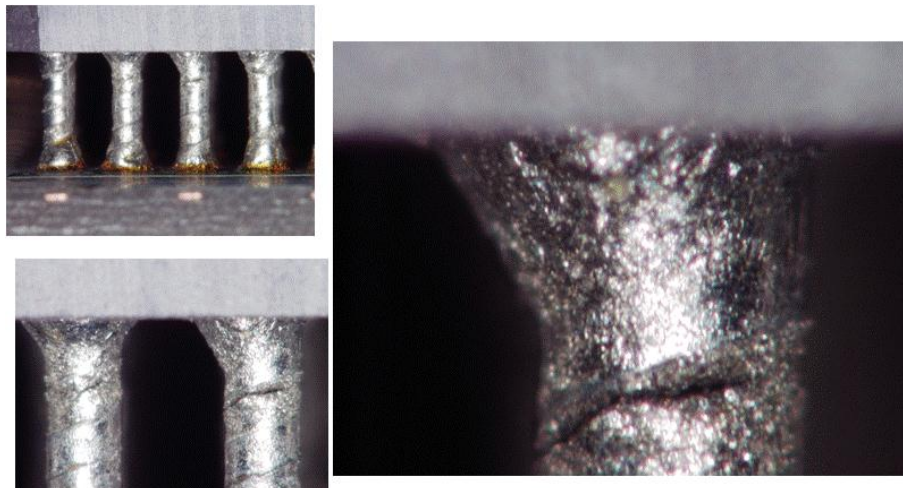


Fig. 8. Optical photomicrographs of re-columned and reassembled CGA 560 I/Os after thermal cycles and prior to X-sectioning showing microcracks in columns and solders at the package side.

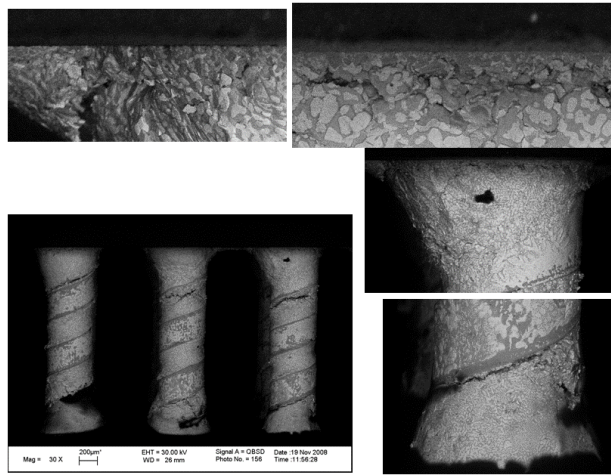


Fig. 9. SEM photomicrographs of re-columned and reassembled CGA560 after thermal cycles and prior to X-sectioning showing microcracks in columns and solders at the package side.

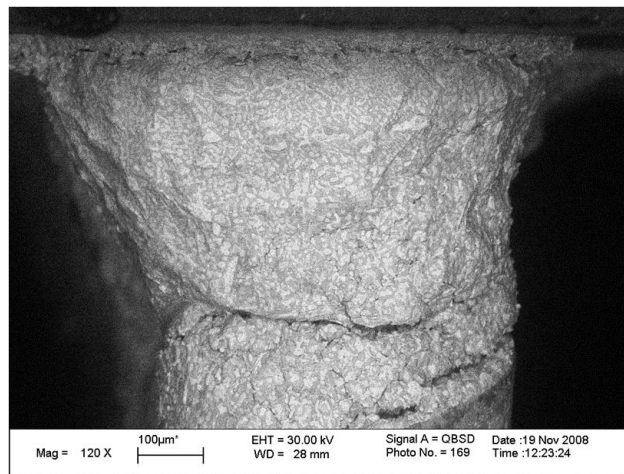


Fig. 10. SEM photomicrograph of re-columned and reassembled CGA560 after thermal cycles and prior to X-sectioning showing different types of microcracks in column and solder at the package side.

X-section photomicrographs for the three corner columns are shown in Figure 11. It clearly shows significant damage and minor-to-full cracking, more often at the package sides.

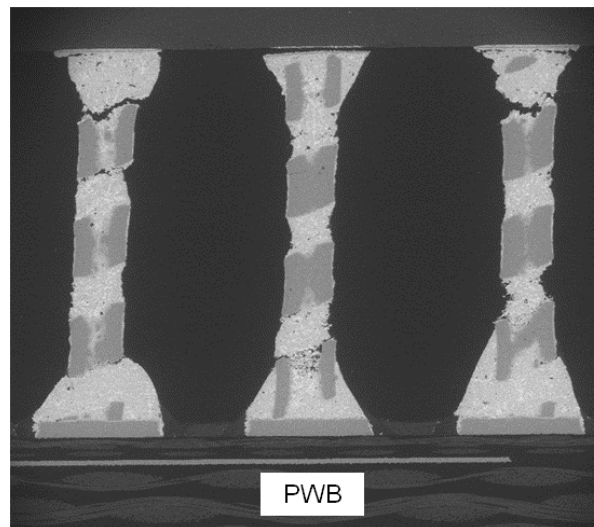


Fig. 11. X-section photomicrographs of re-columned and reassembled CGA560 after thermal cycling showing microcracks and separation mostly at the package side (top).

Figure 12 depicts SEM photomicrographs at higher magnifications, showing interfacial damage conditions both at the package and at the PCB sides. Separation at the package pad interface with minimum solder remnant at the pad is possibly an indication of weaker metallurgical bond due to re-columning and second reflow due re-work/re-assembly. More damage and cracking at the package side may also be due to a larger local CTE mismatch between the ceramic and solder at the package side in comparison to polymeric PCB and solder at the board level.

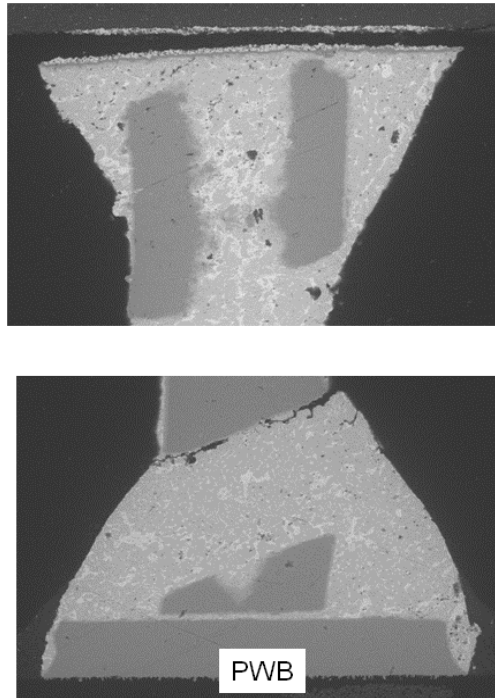


Fig. 12. X-section photomicrograph of re-columned and reassembled CGA560 after thermal cycling showing interfacial condition at package and PCB sides. Full cracking at the package side is apparent.

EVALUATION OF CGA 1144 I/Os

The purpose of this aspect of the investigation was to characterize assembly reliability of CGA1144. Eutectic tin-lead solder alloy was used for assembly. In contrast to the CGA560, this package had different pad configuration and column type. Differences include:

- Fully populated area array package rather than peripheral array
- Internal flip-chip die rather than wire bond
- 1-mm pitch rather than 1.27-mm
- 35-mm package body rather than 42.5-mm

Similar to other CGA packages, three columns from each corner were missing; they were intentionally removed by the package supplier in order to improve solder joint reliability. Corner solder columns usually fail first in thermal cycling because they have the longest distances to neutral point (package center).

The original column type in this package is also different from the CGA560; it uses Pb_{90}/Sn_{10} solder columns with no Cu wrap. Similar to re-columned CGA560, the Cu wrap columns replaced the virgin columns of high-lead composition. Both a typical and a smaller-diameter column were included for evaluation. Smaller-size columns can be used for the high I/O CGA since the package is smaller and lighter, reducing potential of column breakage due to overloading condition. Because of these significant changes, assembly processing parameters were different from the CGA560 packages; therefore, they required being tailored again for reflow optimization.

Tailoring was performed based on previous experiences for similar packages. Additionally, the process was modified on the spot if required, this being possible because only twelve packages were assembled. Ease and consistency in paste deposition, condition of fillet formation after reflow, and solder joint visual appearance were a few important parameters used for tailoring process.

Key re-column and re-assembly parameters for processing and evaluation are as follows:

- Successfully re-columned eight CGA1144 packages with 20-mil column diameter. No fallout due to re-columning processes.
- Successfully re-columned four CGA packages with 15-mil column diameter; all solder joint column attachments exhibited acceptable visual quality.
- Prepared two boards for assembly, each having four and two packages with 20- and 15-mil re-column diameters, respectively
- Utilized two mini-stencils for solder paste printing, one with 7/23 (thickness/aperture opening) and the other with 8/26 configuration.
- Individually placed each package onto the board using a rework station with optical inspection capability for accurate placement of CGA package onto board pattern with paste deposition.
- Assembled ten re-columned, high I/O CGA packages using a vapor-phase reflow machine.
- Individually assembled two re-columned, high I/O CGA packages using a rework station to establish process steps for assembly and to determine if there are differences between the two techniques in terms of reliability and failures. A rework station is an option for assembly in a low volume manufacturing environment when generally only one or a few CGA parts are assembled onto board. Obviously, it is not an option for high volume manufacturing, but rework station still is used for rework of defected assemblies.

A fully populated board had 6 re-columned CGA1144 packages. All assemblies exhibited acceptable—although, in many cases, not ideal—solder joints at the board side, indicated by visual inspection and verified by daisy chain resistance measurement. Inspection of solder joints at the package side is more difficult to perform, but from what was observed, they also appeared to be acceptable. The two test vehicles built under various manufacturing processing conditions were subjected to thermal cycling. Only a representative test result is discussed below.

CGA1144 Package Re-column

Re-columning was performed using Cu-spiral columns at the same facility that CGA560 packages were re-columned. Two re-column sizes were used, one with 20- and the other with 15-mil diameter. Photomicrographs of the two re-columns at a low and a high magnification are compared in Figure 13; the right side shows the 20-mil diameter columns. Except for the column size differences, solder joints for both conditions have visually acceptable quality with shiny appearance and good fillets. No pull testing was performed; therefore, the tensile strength differences between the two column sizes are unknown.

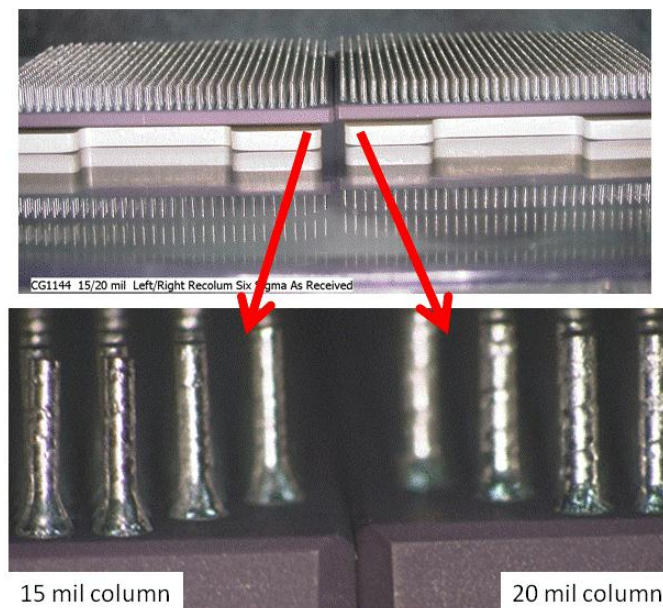


Fig. 13. Photomicrographs of the two sizes of re-columned packages (20- and 15-mil columns) at low and high magnifications.

Stencil Design, Paste Deposition, and Volume Measurement

The stencil thicknesses were 7 and 8 mils, and the two aperture openings were 23 and 26 mils for low and standard volume conditions, respectively. An RMA tin-lead paste was used for paste printing using automatic manufacturing parameters. Figure 14 depicts a photo of a board in which all six CCGA patterns were individually paste printed using a mini-stencil. After printing, each paste print on the PWB was visually inspected for gross defects such as bridging or insufficient paste. On

rare occasion, quality of paste deposition was improved by adding a small amount of paste when insufficient paste was detected. When bridging was discovered, solder paste was removed to open the bridge. In some cases, when the prints had offsets larger than acceptable levels, they were cleaned and reprinted for the second time. Figure 15 depicts optical photomicrographs showing acceptable paste deposition quality (left) and reject quality (right).

Solder paste volumes for selected pads were estimated using a laser profilometer with 3-D dimensional measurement capability. Solder paste areas and heights were measured for solder volume documentation. Measurements were made at numerous locations—including corner and center pads—to gather solder volume data and their corresponding distributions. An example of photomicrographs of paste deposition with 7/23 mini-stencil (thickness/opening) after paste printing, estimated/calculated solder paste volumes on each pad, and color-coded paste height distribution measurements are shown in Figure 16. Similar information for the 8/26 mini-stencil (thickness/opening) is shown in Figure 17.

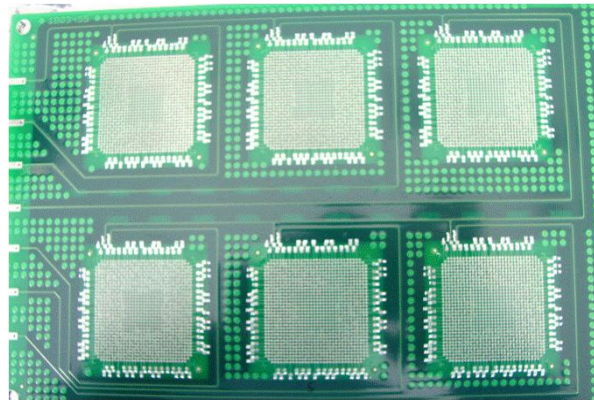


Fig. 14. Optical photo of a high I/O CCGA board after paste printing with a ministencil.

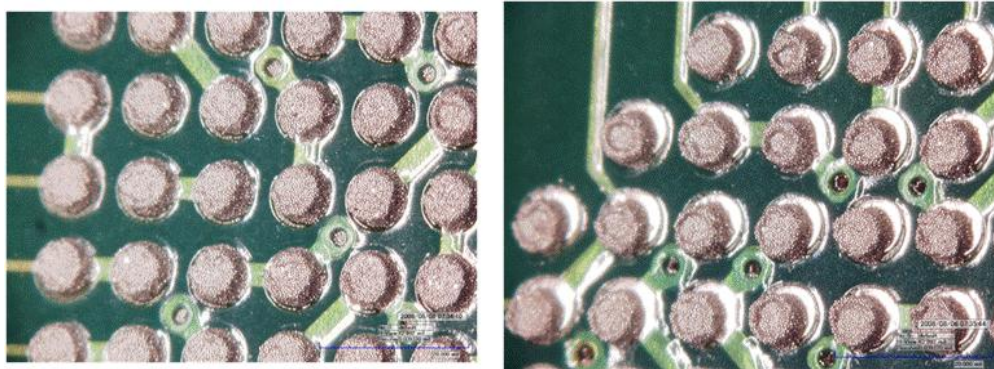


Fig. 15. Optical photomicrograph of paste deposition with mini-stencil with acceptable solder paste quality (left) and reject (right).

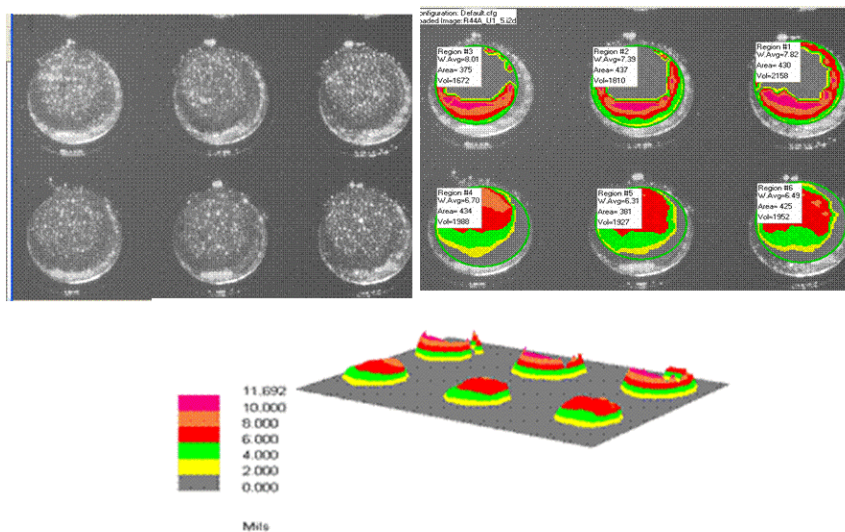


Fig. 16. Optical photomicrograph and measured/calculated solder paste information for paste print with minitencil with 7-mil thickness and 23-mil aperture opening diameter.

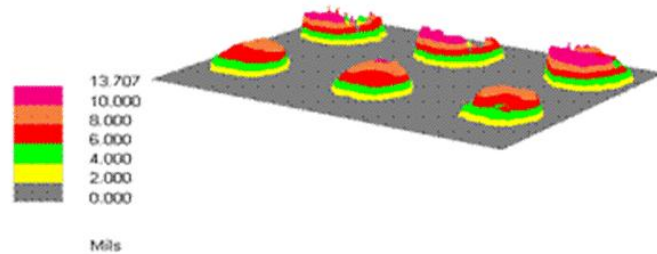
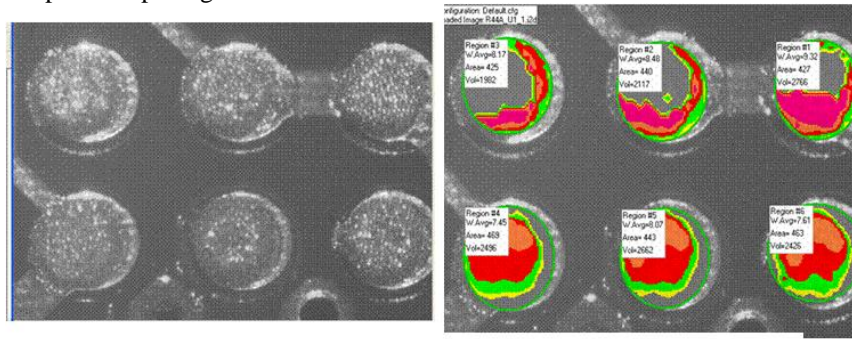


Fig. 17. Optical photomicrograph and measured/calculated paste information for paste print with minitencil with 8-mil thickness and 28-mil aperture opening diameter.

Figure 18 depicts an assembled test vehicle having six high I/O packages. Note the input and output traces extending to the board edge and also the probing pads at the package peripheral for manually detecting failures.

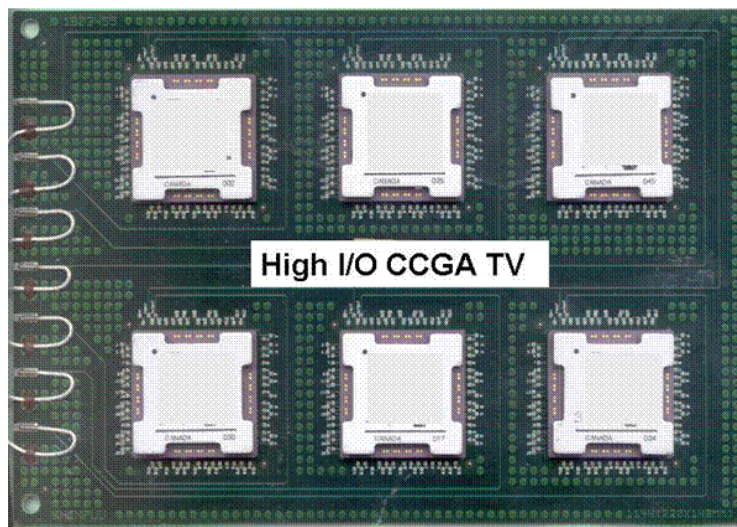


Fig. 18. Photograph of an assembled test vehicle having six re-columned, high I/O CGA packages.

Inspection before Environmental Tests

Visual inspection using an optical microscope was used during assembly to optimize processes based on the visible outer-row column solder conditions. Visual inspection was also performed prior to and during thermal cycling to determine quality of solder joints both at the package and at the board sides. The degree of damage progress in columns and solder joints with cycling was also monitored. Even though only peripheral column interconnections can be inspected, such inspection provides valuable information for CCGA assembly quality and reliability. It provides not only information on solder joint quality, but also on solder damage progress and failure mechanisms since generally CTE mismatch failures first occur in the corner and outer-row columns.

However; for re-columned CCGAs, it was soon recognized that interface close to the package pad are more critical than solder joint quality at the board side. It is more difficult to inspect and document solder joint quality and interface integrity at the package side because the large board area in package vicinity interferes with optical lenses. For this reason, after cycling,

boards were cut close to the package body and visually inspected for better identification of damage and cracking even though it is realized that this was not a representative of inspection for hardware. Optical and SEM photomicrographs were taken before X-sectioning.

Test Results after Thermal Cycling for CGA1144 Assemblies

Thermal Cycle Condition

Only the Cycle C condition, ranged from -120° to 85°C with about $5^{\circ}\text{C}/\text{min}$ heating/cooling rate and 10-minute dwells, was selected to characterize thermal cycle behavior of the two test vehicles, each having six high I/O CCGA package assemblies. To better characterize microcrack formation of re-columned package assemblies, two packages were cut close to the package body for optical, SEM, and cross-sectioning. Because of potential failure of re-columns at the package side, it is critical to be able to inspect them; however, it is generally difficult to inspect assemblies at the package side because of board obstruction. Inspection of solder joints at the board side is easier since solder joints are blocked only by package periphery. For this reason, a thorough optical inspection was performed for two package assemblies after cycling and cutting for X-sectioning. Representative optical photomicrographs of the solder joints at the package side from the cut sample are shown in Figure 19. This figure also includes the pseudo 3-D optical photomicrograph, which is a compilation of images from different optical focus layers. If the optical lenses are aligned correctly with solder joints at the package interface, it is possible to reveal finer microcracks that are generally difficult to detect for a non-cut package assembly.

Photomicrographs clearly depict damage at the package side and even microcracks near the pad interface taken at much higher magnifications. Note that these microcracks could not have been detected during routine optical microscopy evaluation since they are fine and also close to the package interface, making it difficult to detect, as mentioned earlier. Note that these microcracks were first revealed during SEM evaluation at much higher magnifications, and then searched for during an optical inspection.

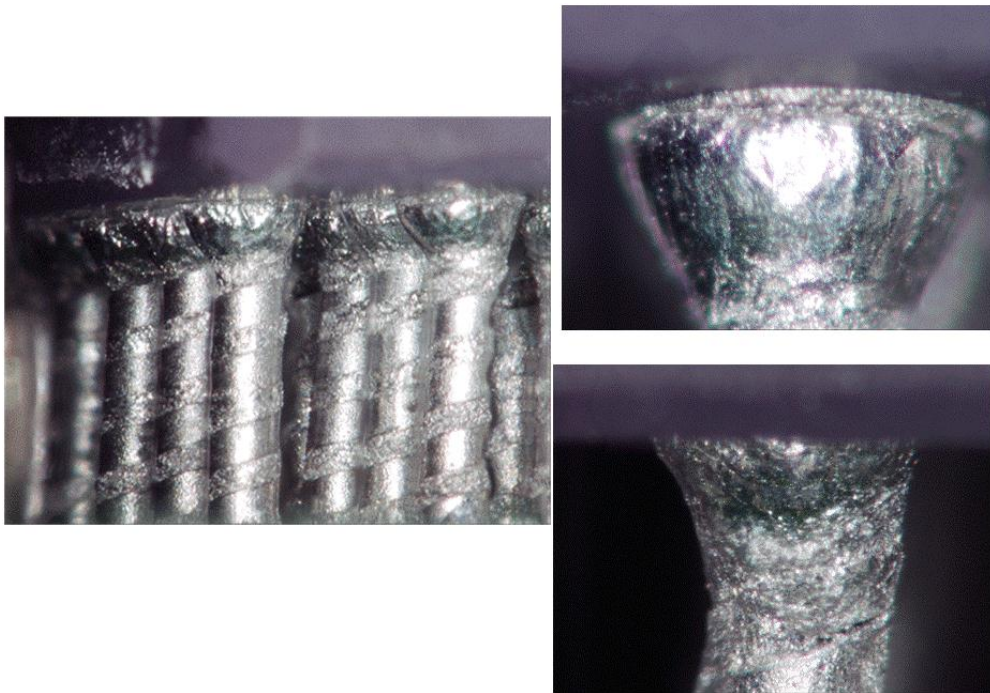


Figure 19. Representative optical photomicrographs, including those with pseudo 3-D optical photomicrograph, showing damage and microcracks at the package side.

CONCLUSIONS

Key findings based on column attachment and re-assembly of CGA packages onto PCBs which were subjected to a number of thermal cycles are as follows:

- The Cu-spiral re-column version of the CGA560 package without its original ceramic interposer layer exhibited good attachment interconnection strength as re-columned and after exposure to isothermal aging at 125°C up to 500 hours.

- Based on only a few test samples subjected to thermal cycling and visual inspection, it appears that re-columned CGA60 package with no interposer is a viable rework solution from an assembly perspective only. Further work is required to substantiate these test results for an active-die version.
- All CGA1144 assemblies with re-columned packages passed 200 severe thermal cycles ($-120^{\circ}/85^{\circ}\text{C}$) with no apparent visual damage or daisy chain failures.
- Based on limited thermal cycle test results and visual inspection during thermal cycling, it appears that re-columning of CGA1144 is a viable option from a solder attachment perspective only.

Acknowledgments

The research described in this publication is being conducted at the Jet Propulsion Laboratory, California Institute of Technology, under a contract with the National Aeronautics and Space Administration. Copyright 2012, California Institute of Technology. Government sponsorship acknowledged.

The author would like to acknowledge A. Mehta, N. Neverida, R. Ruiz at JPL for their support in test vehicle assembly, thermal cycling, failure analysis. Thanks also to column attachment manufacture's personnel for providing service and support. The author extends his appreciation to program managers of the National Aeronautics and Space Administration Electronics Parts and Packaging (NEPP) Program, including Michael Sampson, Ken LaBel, and Dr. Charles Barnes and Douglas Sheldon for their continuous support and encouragement.

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