CBGA/PBGA Package Planarity and Assembly Reliability

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ABSTRACT

Jet Propulsion Laboratory (JPL) is currentl y assessing (he use of Ball Grid Arrays (BGAs) for National Aeronautics and Space Administration (NASA) spaceflight applications. This work is being funded through NASA Headquarters, Code Q. The objectives are to demonstrate the robustness, quality and reliability of BGAs technology, and to assist in the development of the rapidly growing industrial infrastructure for this technology. JPL has solicited industrial, academic and other related consortia to work together to leverage the related efforts into a synergistic cooperative effort. Package dimensional characteristics of nearly one thousand plastic and ceramic packages were determined using a 3-D laser system. More than one hundred test vehicles are currently being thermall y cycled and cycles 10 failure data are being gathered. The results of these activities will be summarized and presented in this paper.

OBJECTIVES

Many aspects of BGAs were investigated. The objectives of the BGA project were to demonstrate the robustness, quality, reliability, and to assist in the development of the rapidly growing industrial in frastructure for this technology. BGAs are electronic packages used for higher I/O (input/Output) counts that also provide improved electrical and thermal performance, as well as more effective manufacturing and case of handling, compared to conventional Surface. Mount (SMT) leaded parts.

To meet requirements of the NASA community, including JPL, for highly re.liable assemblies in an Ultra-Low Volume (ULV) environment, an integrated system approach was used. The foci included identification of BGAs' critical manufacturing parameters, evaluation and development of inspection techniques, and determination of the effects of manufacturing defects on solder joint reliability. The Quality Assurance (QA) procedures developed will then be integrated into design and manufacturing so that critical parameters can be bounded and controlled.

JPL solicited industrial, academic and other related consortia (References 1-3) to work together to leverage their resources and expertise into a synergistic effort. All participants furnished in-kind contributions. The wide industrial use of BGA technology will afford NASA as well as consortium] industries inexpensive access to this technology and support miniaturization thrusts for their next generation applications.

The consortium objectives were to complete the characterization of BGAs in the following areas:

- Processing/assembling Printed Wiring Boards (PWBs) using BGAs. Variables included PWB material types and surface finishes, and use of ceramic and plastic packages with different ball populations and I/Os.
- Identifying inspection and Quality Assurance (QA) methods for ascertaining the process controls, acceptance methodologies, and final quality of BGA assemblies.
- Characterizing package properties such as coplanarity, inspection for solder joint quality, damage progress during environmental exposure, and defect/reliability correlation, as well as estimating solder joint life.
- Investigating the reliability of BGA assemblies in several different environments (thermal and dynamic).

BACKGROUND

Introduction

The production of surface mount assemblies (SMAs) now surpasses assemblies using through bole technology ('1'111'). In SMT, components are mounted and terminated directly onto PWB surface. One of the most important component parameters is the lead pitch, which is continuously decreasing to meet the need for higher 1/0 count.

The usc of tine and ultra fine pitch (FP and UFP) components with less than 0.020 inch pitch is growing, often resulting in more than 200 leads for a single device. Typically, these components have gull wing leads. FP and UFP components, in addition to being extremely delicate and easily damaged during handling, arc also difficult to process and rework, and arc prone to misalignment with the associated reliability implications,

BGA is an important emerging technology for utilizing higher pin counts, without the attendant handling and processing problems of the peripheral array packages (PAP). Unlike PAPs, BGAs have balls, covering tbc entire area, or a large portion of the area on the bottom of the package.

BGAs offer several distinct advantages over FP and UFP SMCs that have gull wing leads, including:

- High pin counts, generally > 200.
- Larger lead pitches, which significantly reduces the manufacturing complexities for high 1/0 parts.
- Higher packaging densities, since the lead envelope for the gull wing leads dots not apply to BGAs; hence, it is possible to mount more packages pcr board.
- Faster circuitry speed than gull wing SMCS because the terminations arc much shorter.
- Better heat dissipation than gull wing leaded SMCs because of providing lower path from dic to PWB for heat dissipation.

BGAs are also robust in processing. This stems from their higher pitch (0.050 inch typical), better lead rigidity, and self-alignment characteristics during reflow processing.

BGAs, however, arc not compatible with multiple. solder processing methods and individual solder joints cannot be inspected and reworked using conventional methods. in ultra low volume SMT assembly applications, e.g. NASA's, the ability to inspect the solder joints visually has been standard and is a kcy factor for providing confidence in solder joint reliability.

Consortium Team Members

At the start of the project, in January of 1995, a core of consortium (cam members was formed. Its members included Hughes, Boeing, and 1<1'1'. In weekly teleconferences, the consortium defined their needs, shared their experience and strengths, and knowledge gained on BGA technology through their independent literature searches. Consortium members visited companies with experience in BGAs to better understand the state of the technology and the areas that the consortium could address to add value to the advancement of technology.

JPL organized a workshop on 3 March 9S to have face-to-face information exchange among the core consortium team members and ncw participants. Participation by Interconnection Technology Research Institute (1'1'1<1) and SEMATECH, a visionary organization in electronics technology, permitted further narrowing of the project focus activities. 1'1'1<1, a focal point for the collaboration among the industries, was key in facilitating future expansion of the consortium into the commercial sectors. The consortium shared invaluable information, and built further confidence in BGA technology. Variables for the test matrix definition were ranked based on the current and future needs of the consortium.

The test matrix went through many revisions as ncw members joined and was finalized by September '9S when Altron agreed to fabricate both FR-4 and polyimide PWBs and Celestica agreed to assemble most of the test vehicles. The organizations that have been an integral part of tbc consortium activities arc as follows:

- **Military** sectors- Hughes Missile Systems Company (HMSC) designed the PWBs, Boeing Defense and Space Group performed environmental testing for military applications. Loral (Lockheed-Martin), Canada, offered to assemble and test validated the reliability of an additional 200 test vehicles using the consortium test matrix and test vehicle design,
- **Commercial facilities**- Amkor/Anam Electronics, inc. provided more. than '700 plastic packages, Altron Inc. fabricated 300 PWBs using FR-4 and polyimide materials, Celestica, Canada, assembled 200 test vehicles, Electronics Manufacturing Productivity Facility (EMPF) performed environmental testing, American Micro Devices (AMI)) provided resistive die, IBM provided ceramic packages at a minimum charge, Nicolet assisted in X-ray, and View Engineering measured coplanarity and warpage of packages using their 3-D laser scanning equipment.
- **Infrastructure**- ITRI established by the Institute for Interconnecting and Packaging Electronic Circuits (IPC) has provided a vehicle for collaboration among the various

sectors of electronic interconnection industries.

- Academia- Rochester Institute of Technology (RIT) assembled 35 test vehicles. More than 20 industrial advisors including people from JPL are helping to redirect the RIT metal manufacturing laboratory into a Computer Integrated Electronics Manufacturing (CIEM) facility to better meet the current national demand for electronics manufacturing engineers.

CERAMIC AND PLASTIC PACKAGE DIMENSIONAL PROPERTIES

Packages

Packages cover the range from OMPAC to SuperBGAs from Amkor/Anam. In SBGA, the IC die is directly attached to an oversize copper plate providing a better heat dissipation efficiency. The copper plate also acts as a stiffener and ground plane for the package. The solder balls for plastic packages arc eutectic (63 Sn/37Pb).

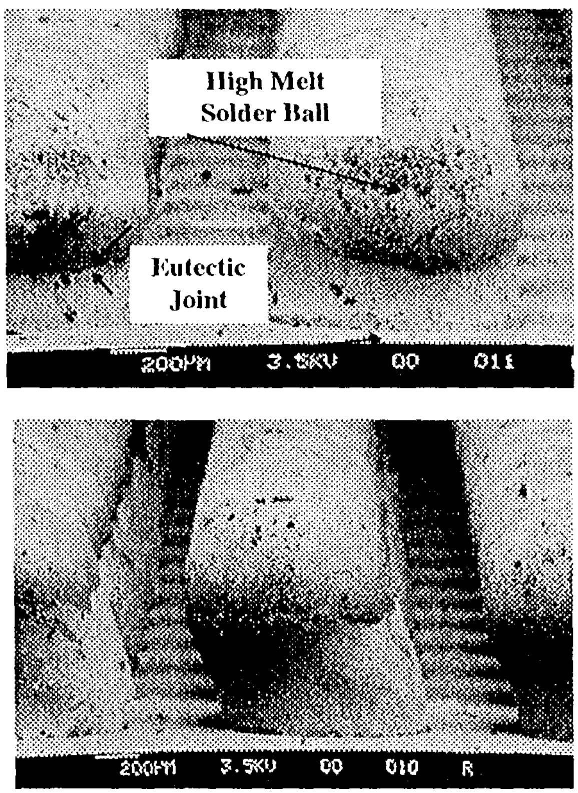


Figure 1 Solder Balls With no Tilting (top) and with tilting in 625 CBGA

Ceramic packages were from IBM. Ceramic solder balls have 0.035 inch diameters and have a high melting temperature (90Pb/10Sn). These balls arc attached to the ceramic substrate with eutectic solder (63 Sn/37Pb) material. At reflow, substrate eutectic material and the PWB eutectic paste reflow to provide the electro-mechanical interconnects.

Figures 1 shows Scanning Electron Micrograph (SEM) photos of ceramic package.s with 62.5 1/0s with straight and tilted solder balls.

Package Dimensional Characteristics

Package dimensional characteristics are among the key variables that affect solder joint reliability. Dimensional characteristics of all packages were measured using View Engineering 3-D laser scanning system. Output of measurements included solder ball diameter, package warpage, and coplanarity.

Package coplanarity is defined as the distance between the highest solder ball (lead for QFP) and the lowest solder ball. Coplanarity can contribute to the yield of surface mount manufacturing as well as long-term solder joint integrity. For leaded parts such as QFP, nonplanarity in excess of 0.003 inches is not acceptable. JEDEC specification for coplanarity y requirement was 0.006 inch which increased to .008 inch,

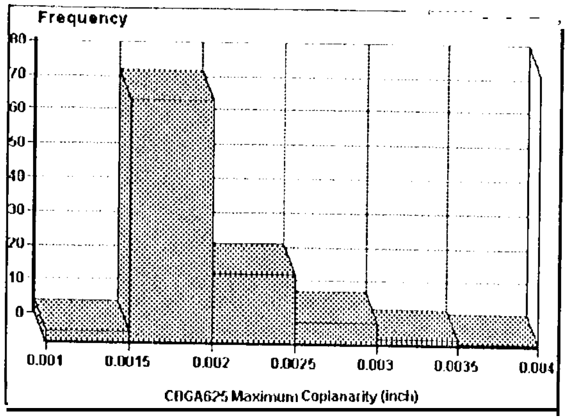
In this paper, the results of package properties for 625 CBGA and 560 Super BGA will be given only. These data are being used to determine the influence of these parameters on the solder joint number of cycles to failure.

Dimensional Characteristics for CBGA 625

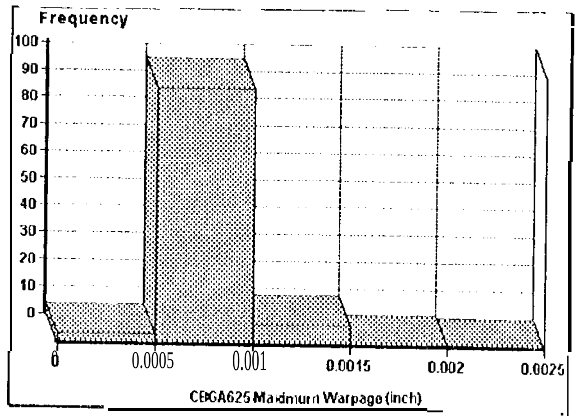
Figure 2 shows histogram plots of coplanarity and warpage distributions for 108 ceramics with 625 I/Os and coplanarity distribution for a package with the maximum coplanarity of 0.0042 inch. Results from these and similar plots arc:

- The balls' coplanarities were 0.0015 to 0.002. inches for 104 parts and 0.003 to 0.0042 inches for 4 parts.
- Maximum solder ball diameters were 0.0315 to 0.0334 inches with minimums 0.028 to 0.029 inches. Diameters were measured only for 36 parts.
- Maximum warpages were 0005 to 0.0029 inches.

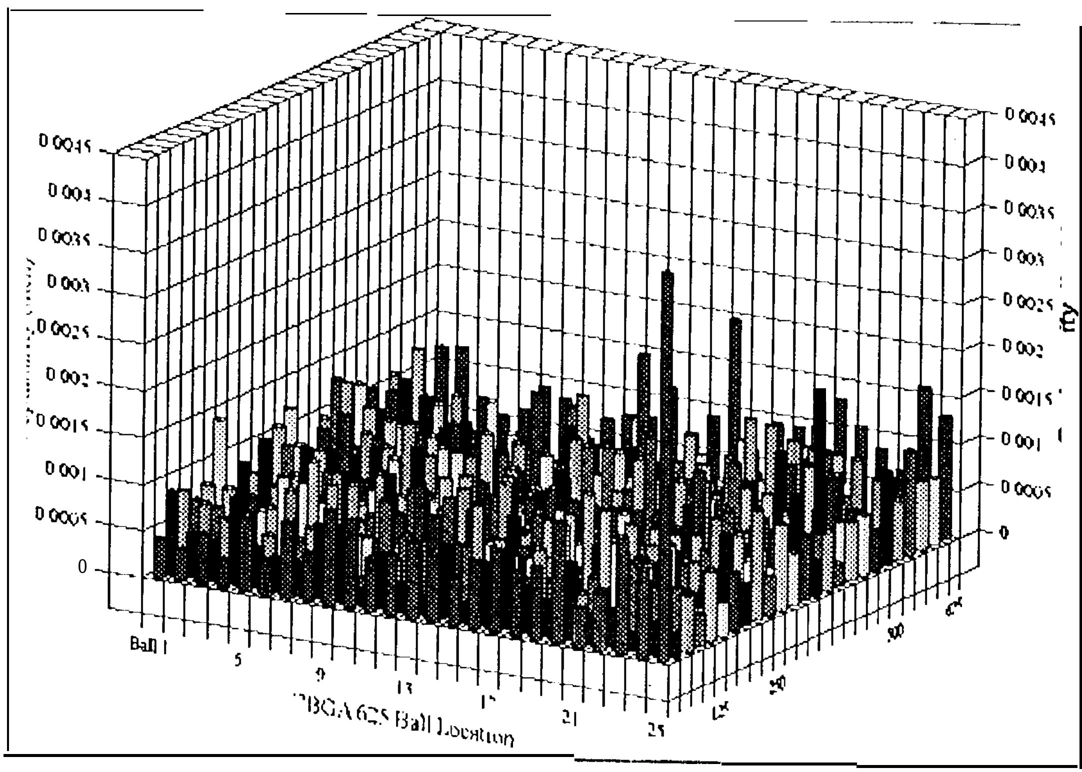
The coplanarity distribution plot for this part reveals that the solder bails were generally uniform in height with a few at two extreme levels that were randomly distributed.



a) Maximum Coplanarity Distribution



b) Maximum Warpage Distribution



c) Coplanarity Distribution for a CBGA 625 Package

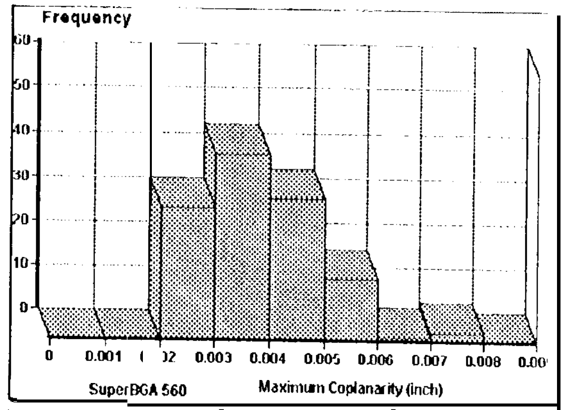
Figure 2 Package Dimensional Characteristics of Ceramic BGA with 625 1/0s

Dimensional Characteristics of SuperBGA S60

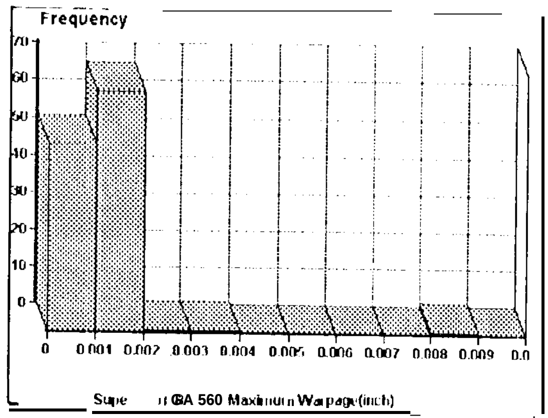
Figure 3 shows histogram plots of coplanarity and warpage for 120 SBGA560 and the coplanarity distribution for a package with the maximum coplanarity of 0.0054 inch. Results of these and similar plots are as follows:

- Ball coplanarities were 0.002 to 0.004 inches for 72 parts, 0.004 to .006 for 45 parts, and 0.006 to 0.00766 for 4 parts.
- Maximum solder ball diameters were 0.0275 to 0.0290 inches, minimums were 0.0213 to 0.0263 inches.
- Maximum warpages were 0.00165-0.0096 for 110 packages, 0.01012.-0.021 inches for 8 packages, and 0.034 inches for one package.

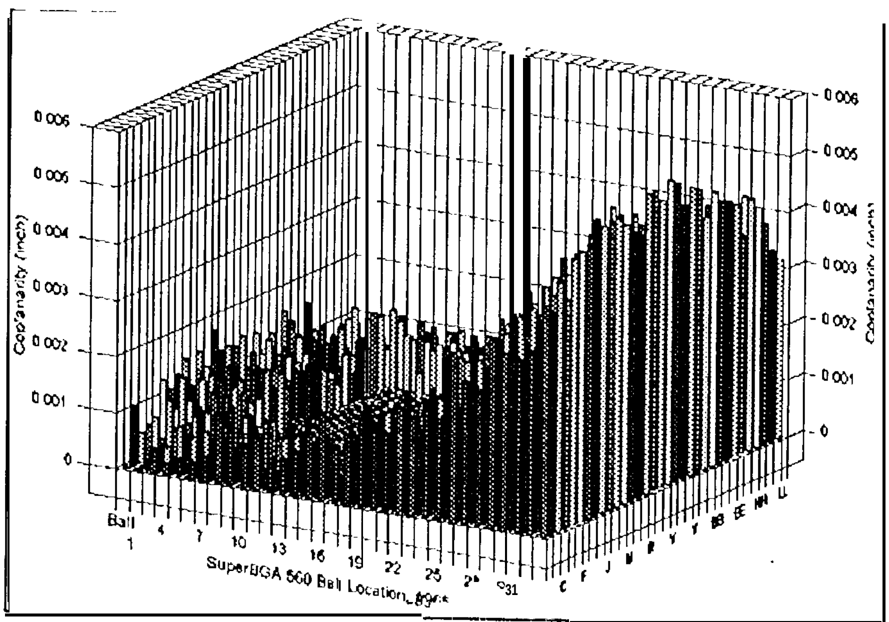
The coplanarity distribution plot for this part reveals a nonuniformity where one region shows higher heights than the other. Such nonuniformity could cause package lifting during reflow; thus, increasing the likelihood of manufacturing defect formation.



a) Maximum Coplanarity Distribution



b) Maximum Warpage Distribution



c) Coplanarity Distribution for a SuperBGA 560 Package

Figure 3 Package Dimensional Characteristics of SuperBGA with 560 1/0s

Summary Of BGA Package Dimensions

Table 1 summarizes dimensional characteristics of two ceramics and five plastic packages. Five of package types were from Amkor/Anam, the largest manufacturer of plastic packages, cover the range from OMPAC to Super BGAs. Ceramic packages were from IBM. It is seen that depending on the type of packages i.e. ceramic or plastic and maturity of the package, the variations arc different,

Table 1 Dimensional Characteristics of Ceramic and Plastic Packages Determined by View Engineering 3-D Laser System

Package Type	Coplanarity Range (inch)	Warpage Range (inch)	Max. Diameter Range (inch)*
CBGA 625	.0015 -.002 for 104 .0030-.004 for 4	.0005 -.0029	.0315 -.0334
CBGA 361	.001 ?-.0022 for 102	.0005 -.0018	.0312 -.0335
S60 SuperBGA	.002 -.004 for 72 .004 -.006 for 45 006-.0077 for 4	.0016 -.009 for 110 .010 -.021 for 8	.0275 -.029
352 SuperBGA	.0014 -.0037 for 145 .0048,.0058,.0065,.00 91	.0013 -.003	.0278 -.0287
352 OMPAC	.0024 -.0057 for 128	.002 -.006 for 111 .006 -.010 for 17	.0275 -.0288
313 OMPAC	.002,2 -.0052/ for 140	.0021 -.0045	.0285 -<0296
256 OMPAC	.0021 - .0047 for 140	.00259 -.0047	.0276-.0289

* These values are lower than the solder ball diameter true values.

Solder Ball Diameters

Solder ball diameters as measured by View Engineering do not agree with the values reported by IBM. Ceramic packages usc high melting solder balls with 0.035 inch diameter. The values from the 3-D laser images for both 361 and 62,5 1/0s were lower than 0.035 inch. In IBM's recent random measurements of ball diameter measurements of SO out of 300,000, as part of their incoming inspection, the values were within their ball diameter specification.

One possibility is that even though the View Engineering system is accurate for measuring coplanarity and other dimensional parameters, it is not accurate for solder ball diameter measurement. A solder ball diameter is calculated from a mathematical curve which is fitted to the last.r image of the ball. Therefor c, the estimated diameter depends on bow well the fitted curve is representative of the actual shape of the. ball.

Another possibility could be duc to the tilt and skewness of solder balls as shown in Figure 3. The tilt could cause distortion in the image detected by laser scanning, resulting in different values than those reported by IBM. Diameter of solder ball were measured using the SEM as shown in Figure 3: it was found to be 0.0355 inch.

CONCLUSIONS ON BGA PACKAGE DIMENSIONS

- Solder ball planarities were significantly higher for plastic than for ceramic packages. PBGAs, however, arc more robust and the large planarity values might not be a detriment on the solder joint reliability. Some planarity differences among the balls arc accommodated by their collapses during the reflow process. This is not the case for CBGAs where high melt solder balls remain intact during reflow. The solder ball diameter controls the stand-off height which is a key factor to solder joint reliability.

- 3-1) laser scanning is excellent for characterization of package dimensions, but possibly not for solder ball measurement. It did read lower values for ceramic solder ball diameter than was actually true. One possible cause could bc duc to the skewness of the ceramic solder balls observed visually and by S1 ;M.

PROGRAM STATUS

A large number of variables inside the design, manufacturing and lest of the lest vehicles (TVS) were statistically toggled using a Design of Experiment (DoE) technique to determine the influence and criticality of these variables. Each test vehicle has four BGA packages that are in the 300 and 600 I/O categories. Two silts were used for assembling of TVs:

- Celestica, IBM/Canada, a commercial contract facility with extensive experience, and,
- 1<1'1', a university with no experience in assembling BGAs.

University laboratories are participating in assembling advanced electronic parts for usc in NASA's missions.

After process optimization and assembling of 20 trial TVs, a total of 200 additional TVs were assembled (about 170 by Celestica and 30 by RIT) and were subjected to various types of inspections including, X-ray and scanning, electron microscopy (S1 ;M) prior to environmental exposure.

- Type 1, ceramic and plastic BGA packages with nearly 300 I/Os, and,
- Type 2, ceramic and plastic BGA packages with nearly 600 I/Os. Also utilized was a 256 leaded and a 256 plastic BGA package for evaluating and direct comparing manufacturing robustness and reliability.

The TVs are currently being thermally cycled at three sites, under three environmental conditions. They are being monitored continuously through daisy chains to electrical failure of all daisy chains. Ninety (90) TVs arc being thermally cycled at JPL and the remaining sixty TVs will bc subjected to cycling, power cycling, and dynamic exposure. Boeing is cycling 19 and EMPF 33 'I'Vs. JPL's cycle is between -30 °C and 100 °C with about a minimum of 10 minute dwells. Boeing and EMPF thermal cycle.s arc much harsher than the JPL's and are between -55 °C and 125 °C. Dwell and ramping rates are also different for the two sites.

Extensive monitoring is being performed to understand and record cycling damage progress. Five TVs from Boeing and EMPF will bc removed and sent to JPL for inspect ion, Boeing and EMPF are performing visual inspections at specified intervals. Boeing is also performing limited S1 ;M evaluation. At JPL, there arc sets of TVs allocated for inspection at cycle intervals, and a fcw individually cut specimens for scanning electron microscopy evaluation. Inspection TVs and cut specimens are being removed periodically for visual inspection, SEM evaluation, and cross-sectioning for clack propagation mapping.

Data gathered will bc analyzed and fitted to distributions using the Weibull distribution, and the Coffin-Manson relationships for the cycles to failure distribution and failure projection. Manufacturing defects and occurrence frequencies for different surface finishes and package types and configurations will bc correlated to cycles to failure data. Finite element modeling techniques to bc developed at the Goddard Space Flight Center (GSFC) will bc used to correlate theory and the experimental results.

THERMAL CYCLING RESULTS

in addition to the above environmental cycles, a set of ceramic assemblies were subjected to a NASA cycle that with 45 minutes dwells at extreme temperatures has been widely used for qualification testing and in our previous studies. A large data base is available for SMT solder joints subjected to this cycle (Reference 4 -5). For cost effectiveness and engineering efficiency considerations, it is desirable (o have the shortest possible test period. However, adequate high temperature dwells are necessary for solder creep and relaxation occurrence.

This long duration cycle start at 25°C with a decrease rate of 2°C per minute. to -55°C with an oven dwell setting of 45 minutes. The temperature increase to 100°C at a rate of change of 2°C per minute with an oven dwell setting, of 45 minutes, followed by a decrease of temperature to 25°C completes the cycling. The duration of one cycle is '246 minutes.

Figure 4 compares cycles to failure for CBGA 625 I/Os and 68-, 28-, and 20-pin ceramic Lead Less (LCC) assemblies subjected to this cycle. Only for this set of CBGA assemblies, failure detected manually by checking daisy chain resistance for opens. Other BGA test vehicles are being continuously monitored through a LabView system designed for this purpose. For LCCs Failures were detected by Anatech® and verified by visual inspection. The failure distribution percentiles were approximated using a median plotting position, Fi = (i-0.3)/((n+ 0.4).

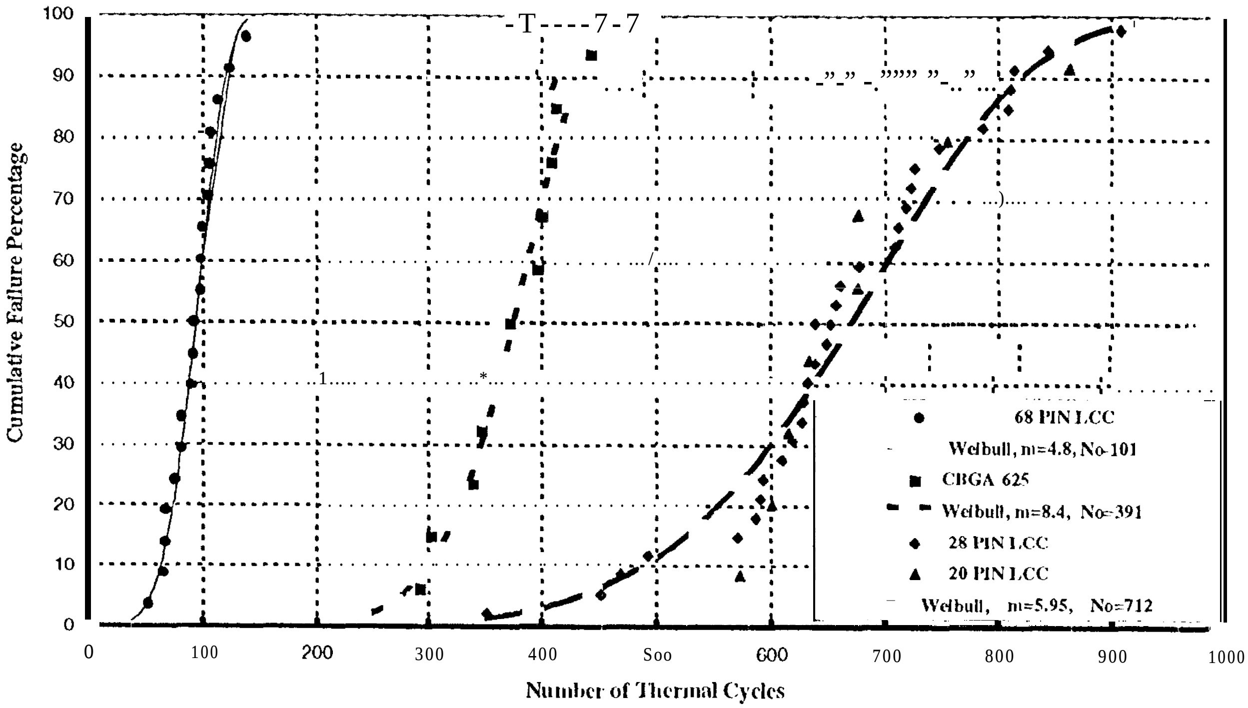


Figure 4 Cumulative Failure Distribution Plots for CBGA 62.5 1/0 aud LCC Assemblies

As cxpcc.ted, the.re was a large spread in cycles to failure because of variance in board materials (FR-4 and Polyimide for CBGAs, FR-4 for LCCs), solder joint volume, quality and location, The first failure for CBGA was detected at 312 cycles and occurred between 292 and 312 cyles. The last failure detected between 450 and occurred between 439 and 450 cycles.

The first failure for the 68-pin LCCs was detected at 53 cycles while the last sample failed after 139 with 93 average cycle.s. 28-pin LCCs failed at much higher cycles in the range of 352 to 908 with 660 average cycles. The 20-pin cycles to failure were in the same range as for those of 28-piss and failed within 573 to 863 averaging 674 cycles. The difference in part size for 20- and 28-pin LCCs could have been offset by difference in solder fillet resulting in an about the same CTE mismatch shear strain.

often, two-parameter Weibull distributions have been used to characterize failure distribution and provide modeling for prediction in the areas of interest, The Weibull cumulative failure distribution was used to fit cycles to fail urc data, The Weibull scale and shape parameters for CBGA were 391 cyles aud 8.4 respectively. 1@ 68-pin LCCs, the scale and shape parameters were 101 cycles and 4.8, respectively. These were 712 cycles and 5.95 for the 28-pin LCCs.

LESSONS LEARNED

- Parameters toggled in the DoE test matrix were well thought out and discussed in details at JPL's Workshop and weekly telecones.
- Face-to-face meetings were very valuable and demonstrated a concurrent engineering approach. Several follow up face-to-face meeting for a more thorough review was necessary, but was limited to telecons. This cause some flaws in the PWB daisy chain design
- A model that can simulate TVs' daisy chains and correct the inconsistancies is highly desirable.
- The test vehicle design had numerous valuable features; one was the ability to remove each individual package as discrete independent. These

features should bc included in other future test vehicle design.

- The comer balls of CBGA 361 were excluded from the daisy chain pattern by IBM design so that reliability could bc increased. We were unable to include these balls in our study even though comer lands on PWBs were daisy chained. This must be considered when reliability data from this package will be compared to other ceramic packages that include the corner balls in daisy chain design.
- Ceramic packages showed lower warpage and were more coplanar than their PBGA counterparts.
- Numerous ceramic packages bad tilted solder balls. These packages should be inspected for skewness of ball attachment.
- Planarity and warpages were unexpectedly higher for the few PBGA packages. These packages must be inspected particularly careful l y to assure conformance to the requirements.
- Being in an early production at the time of evaluation, a number Super BGA packages showed missing balls duc to handling.
- Many ceramic. balls showed signs of skewness when visually were inspected.
- QFPs were extremely susceptible to handling damages, many of them were damaged prior to assembling.
- Polyimide yield was lower than epoxy due to some delamination. Polyimide showed more edge and tooling hole fractures from pinning and handling operations, as reported by Akron, inc.
- In solder mask defined (SMD) pads, some of the via boles bad mask in the bole. Some mask degradation was observed by Altron duc to the Ni/Au process temperature.
- The SMD technique for pad coverage was selected based on Motorola's past experience with PBGA's. Motorola's recent investigation (A. Mawer, Surface Mount Iternational Proceedings, Sept. 1996) indicated a possible three fold increase in reliability when NSMD for both package and PWBs arc used.
- Selection of the right amount of solder paste volumes and 50% stencil step down al 10 wed successfu i i y assembling of test vehicles with mixed technology packages. Ceramic and plastics packages as well as fine pitch QFPs were successfull y assembled in one reflow process step.
- As expected, BGAs were robust in assembling compared to the 256 QFPs. The void levels were the same as those generally observed by Celestica on other assemblies. All of the QFPs, however, showed bridging and bad to bc reworked.
- Robustness of BGAs was also apparent at 1{1'1'. RIT dealing with very limited resources was successful in assembling the majority of BGAs whereas had many problems with QFP placement and were unable to eliminate solder bridging.
- It is very important to understand the reasons for solder process reflow time and temperature in order to be able to assemble packages with different thermal dissipation properties. This knowledge allowed successful assembling of TVs in an IR oven at RIT.
- RMA and water soluble reflow profiles arc different and are. not interchangeable and they should be optimized separately for the applications. When the watt] soluble rcftow profile was used for an RMA paste, solder joint showed excessive voids. This technique can be used to generate different voids levels when investigating the effects of voids on solder joint reliability.
- PWBs with different surface finishes were successfully assembled. Thermal performance prior to assembly was not established.
- Cleaning of BGA for RMA flux should be considered when commercial facilities arc used.

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BIOGRAPHY

Dr. Reza Ghaffarian has more than fifteen years of industrial and academic experience in mechanical, materials, and manufacturing processes engineering. At JPL, he supports research and development activities in SMT for infusion into NASA's missions including projects in advanced electronics packaging, interconnection, and assembly, These projects cover conventional SMT, BGAs, and Chip Scale assemblies. His responsibilities include technical coordination, Design of Experiment (DOE) statistical test vehicle implementation, manufacturing, process, inspection methodology development, failure analysis, and environmental test data collection and analysis. Dr. Ghaffarian has authored or co-authored over 25 technical papers and numerous patentable innovations. He bas also organized and chaired many technical sessions. He received his M.S. in 1979, Engineering Degree in 1980, and Ph.D. in 1982 all in engineering from University of California at Los Angeles (UCLA).