MEG-Array® Connector, The First Ball Grid Array Connector

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Abstract

Improvements in chip technology drove the need for an easily applied, surface mountable connector set that had high density, high pin count, excellent electrical properties, and a low mating profile. FCI's solution was the industry's first Ball Grid Array (BGA) connector, the MEG-Array® connector. The key challenges faced during development included both design and manufacturing issues. High density and low profile required new design concepts and extremely tight tolerances. Ball attach technology complicated the reliability aspects of the connector because there were now three interfaces (ball-to-tab, ball-to-pad, and the separable contact itself) to develop. Finally, the resulting design not only severely taxed the capabilities of the traditional manufacturing processes but also added new challenges dealing with the ball attach process itself.

To deal with all these challenges FCI used a structured methodogy for both design and process development. "Virtual Engineering", which included mechanical, electrical, and process simulations, was used for the initial design. Extensive use of Failure Mode & Effects Analysis (FMEA) and Design of Experiments (DOE) facilitated the concurrent design and process development phase. The manufacturing process scale-up phase was characterized by a commitment to total statistical process control and 100% automatic inspection as required to meet the stringent quality requirements. The end result was a very reliable connector developed in record time that met all customer requirements. This paper details the significant challenges outlined above and the extensive analytical effort to verify reliability and all performance goals. Application of the product to a board is also discussed.

Connector Design and Material Sets

The resulting connector set was initially designed in two sizes, 240 positions and 400 positions, on a 1.27mm x 1.27mm grid. The need to accommodate multiple mating heights was achieved using a common plug mated to separate receptacles of varying height to provide the appropriate board separation distance. The 240 has 3.4mm and 4.0mm mating heights. The 400 has 4mm, 6mm, and 8mm heights. Other sizes and mating heights are being tooled. A 94V-0 flame retardant Liquid Crystal Polymer (LCP) resin was selected for the housing after evaluating six candidates. The primary selection criteria included moldability, flatness, internal stress, knit line strength, dimensional stability thru multiple reflow operations and Coefficient of Thermal Expansion (CTE) compatibility with the Printed Circuit Board (PCB). The vacuum pick-up caps were also molded of the same material. The plug terminal alloy, CuNiSn, was selected for it's mechanical stiffness. The receptacle terminal alloy, BeCu, was selected for it's mechanical strength. The unique dual beam design provided a minimum 30 grams normal force and 0.8mm contact wipe. The finish on both terminals was 0.4 micrometers of gold over 0.8 micrometers of nickel. The solder balls were eutectic tin lead. Finished connectors are provided in bar coded tape and reel packaging. Illustrations of the connectors are shown in Figures 1-3 below.

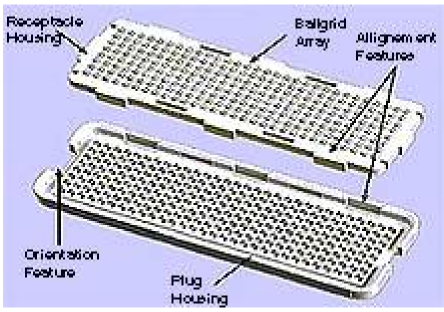

Figure 1. MEG-Array® Connector features.

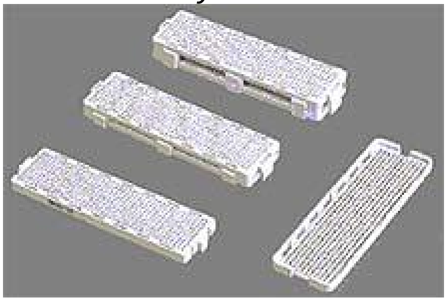

Figure 2. MEG-Array® connector 400 position parts showing distinct mating heights. The plug is common. The receptacles are distinct for each height.

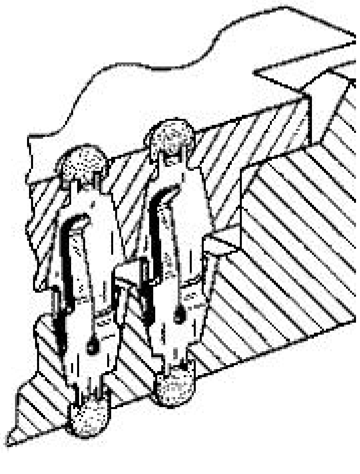

Figure 3. Cut-away view of the mated MEG-Array® connectors showing mated terminals and solder balls.

Connector Application Development

The connectors are typically applied to PCB's via convective oven reflow. It was determined through extensive reliability testing that the design and construction of the BGA pad was just as important as the design of the connector itself.

Figure 4 below details the recommended pad layout. The key to reliability was to have copper defined solder pads of the correct size with the solder mask sufficiently distant from the pad so it didn't interfere with the ball-to-pad joint. Solder mask that overlaps a pad may initiate cracks between the ball and the pad by inducing abnormal stresses. The recommended volume of pad paste was critical to insure proper ball collapse and correct mating height.

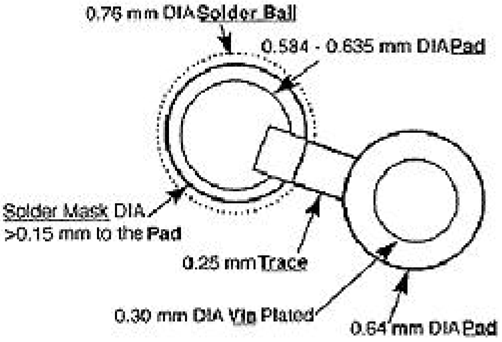

Figure 4. Recommeded PCB pad layout for MEG-Array® connectors.

Proper connector mating after board attach was accomplished by a combination of rough alignment and the built-in guidance and locating features on the housing.

Rough alignment was necessary when the possibility for mismatch was more than 0.8mm.

Technical Challenges

As mentioned previously, there were a significant number of technical challenges, both for design and process. The fact that there were three interfaces added to the challenge. The performance requirements for MEG-Array® connectors were typical for a reliable interconnect system. The mechanical mating requirement was 50 cycles with typical specifications for mate and unmate force. For example, the mating force was 14 kilograms maximum for a 400 position connector. Electrical requirements included standard tests such as IR, DWV, current rating, capacitance, impedence, crosstalk, and rise time degradation. Environmental requirements included temperature cycling, humidity, high temperature life, and corrosive atmosphere (H_2S and SO_2). Two additional tests, z-axis tensile and 3 point bend, were developed and added to the specification to evaluate the "goodness" of the ball-to-tab joints. The dual beam receptacle mated with the spade plug performed extraordinarily well in environmental testing. The maximum allowable change in Low Level Contact Resistance (LLCR) after environmental testing was 10 milliohms. This design also provided for a very short signal path and low inductance.

The need for a high density/high pin count array design with low profile caused numerous challenges. A number of patentable features ensued as part of the design solution. The low profile forced the plug gold contact region to be in close proximity to the solderball attach area of the terminal. Solder stop features were designed into the plug terminal and proprietary processing developed to eliminate chances for solder wicking. A unique dual beam receptacle design provides adequate normal force and contact pressure without overstressing the material despite a short (1mm) beam length. Figure 5 below illustrates the design and Finite Element Analysis (FEA) model.

Figure 5. FEA model employed to develop the receptacle dual beam terminal.

The design optimization of the terminal tab-solder ball joint required considerable FEA analysis and experimentation as well. The goal was to design the joint to withstand the rigors of temperature cycle testing and accommodate any differences in CTE between the board and the connector. Figure 6 below illustrates the FEA analysis. Also, the strength of the joint had to be defined and measurable to insure that joints meeting a mechanical specification also met the reliability specification. Work to achieve this is discussed in detail later in this paper. Optimization of the solder ball-to-pad was accomplished in a parallel effort. The pad requirements stated above in the Application Section are also a result of extensive experimentation.

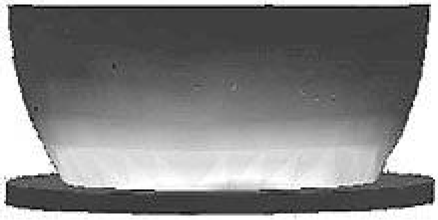

Figure 6. Example of the extensive FEA analysis to develop reliable joints between the solderball and PCB pad.

Design tolerances had to be very tight (typically +/-0.02mm). Tight product tolerances also meant even tighter tool tolerances. Our tool suppliers didn't have the capability (metrology) to measure their manufactured parts to these tight requirements. Partnerships were developed between FCI and several suppliers to implement the required metrology.

Manufacturing Methodology

An assertive decision was made by FCI management at the start of the program to institute a new methodology for the development and commercialization of the MEG-Array® connector system. All development, decisions, and actions would be data driven. The magnitude of the effort mandated the creation of a new and unique division within FCI to implement the methodology. The initial customer for the product worked in close partnership with FCI and provided much guidance. Vendor partnerships were established for new processes where FCI lacked experience.

The key objective was to create a complete manufacturing process based on statistical process control. The resulting methodology guaranteed that every terminal in every conector met product requirements. An organization was established consisting of a CCB (Change Control Board) and a MRB (Material Review Board) which provided the necessary discipline to meet the objectives. The CCB controlled and approved all product and process changes. The board insured all effort and decisions were driven by data and facts. Extensive training at all levels was conducted in statistics, statistical process control (SPC), change control, problem solving, design of experimentation, and project management. The MRB was used to control and approve routine lesser changes to the product and process and to disposition product or materials as necessary.

The resultant design was not only extremely challenging to manufacture, but required a very aggressive manufacturing ramp-up. Compounding these issues was a customer requirement for rigid change control. Each time a change was made to the process or design, an extensive testing, verification, and approval process resulted. As an example, starting up a multiple cavity mold tool required that tool to be as capable statistically as the single cavity tool it replaced.

Overall, molding was the most challenging discipline. The array design possessed wall thicknesses as thin as 0.1mm. The intricate terminal retention features caused many problems with fill and flatness. These characterisitcs demanded critical process control. Each molding press was integrated into the plant's overall software control system. Consequently, every critical process parameter was measured each cycle and parts passed or rejected automatically. To insure functionality, special vision system programs were developed to inspect critical features. An example of this application was used to control housing flatness, which was affected by subsequent insertion and reflow operations. A rapid feedback system after inspection was implemented to help develop a reliable process.

Another manufacturing challenge was the selective gold plating process. The plug terminal is only 1.75mm in length. The plating process was required to selectively gold plate the contact area to within +/-0.05mm. The region between the contact and the tab where the solder ball was attached was designated a "no gold" area to avoid solder wicking during the subsequent ball attach process. It was necessary to quantify the "no gold" area and then develop a process to meet the definition. All critical parameters had to meet the 1.3 Cpk criteria. Once the process was mastered, a multi-out configuration was required in order to meet forecast.

Assembly engineers were challenged to insert terminals at rates far in excess of what was commercially available. Thus, a new automated insertion technology was developed internally by a global team of FCI engineers. A companion inspection technology included a combination of 100% automatic on-line product inspection and selected off-line audits to insure capability of critical parameters. For example, incoming terminals were 100% inspected for presence, true position, and malformation. Incoming housings were inspected for orientation and correct part number.

Process engineers were faced with the new challenge of establishing a BGA reflow profile which provided a reliable solderball-to-tab joint. Compounding this task was the requirement for a single reflow profile for all product variations and their respective thermal masses. Several DOE's were conducted in conjunction with reliability testing to develop the profile.

System engineers were chartered with integrating the terminal insertion, ball attach, reflow, cleaning, inspection, laser marking, and packaging processess for all product sizes into an automatically controlled process. Complete process and material traceability was provided through bar coded assembly routings and laser marking of finished parts.

Reliability Testing and Qualification

Solderball-To-Contact Interface

Although BGA technology was certainly not a new technology, it was new to board-to-board connector applications and to FCI. This "inexperience" prompted key customers to influence their reliability and qualification requirements during FCI's product development rather than after. This influence did not alter the product development approach but rather emphasized the reliability of the solder ball interconnections.

A major concern expressed by customers was the ability to reliably attach the solderball to the terminal tab region of both plug and receptacle contacts. Consequently FCI's development activity began with assessing the intermetallic bond between the solderball and contact. This assessment consisted of metallographic cross-sections (x-sections), Scanning Electron Microscope (SEM) photographs, and Energy Dispersive X-ray Analysis (EDXA) digital line scans.

Metallographic x-sections were prepared to visually verify the presence and condition of the intermetallic bonds. Figures 7 & 8 illustrate solder joint and intermetallic condition at the edges and plated interfaces of a plug contact. This specimen was prepared by grinding through the sheared edge of the contact fork. Figure 8 indicates a continuous and relatively uniform intermetallic exists at both the sheared edge (base metal) and plated surfaces of the terminal tab.

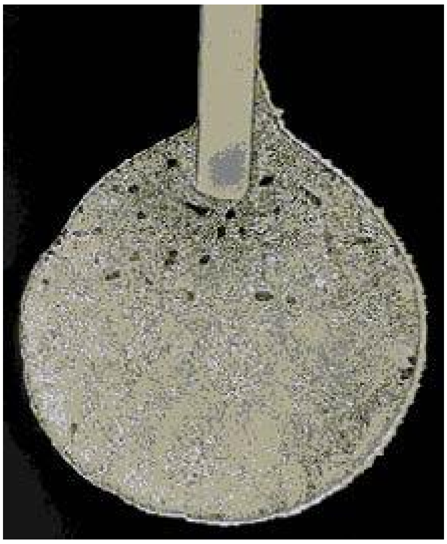

Figure 7. 80x view of solder joint and intermetallic examination area.

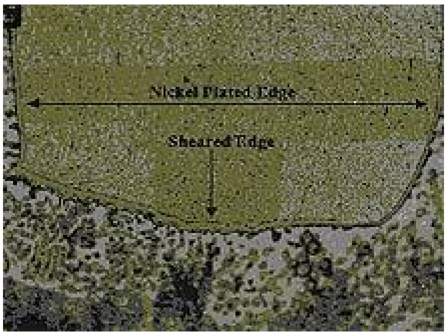

Figure 8. 1000x edge view of contact showing intermetallic formation at both unplated contact tip and plated contact sides.

SEM photography was used to qualitatively assess the initial condition of the solderball/contact interface relative to solder coverage uniformity and base metal/plating exposure. Examined specimens were prepared by applying a tensile force to the contact and removing it from the solderball. Figure 9 illustrates the typical solder coverage of both the sheared (base metal) edges and plated sides of plug contacts.

While solder voiding was present, none of the voids exposed platings or base metal. This SEM photograph further illustrates that the failure mode due to specimen preparation was cohesive failure of the bulk solder rather than fracture and/or failure of the intermetallics.

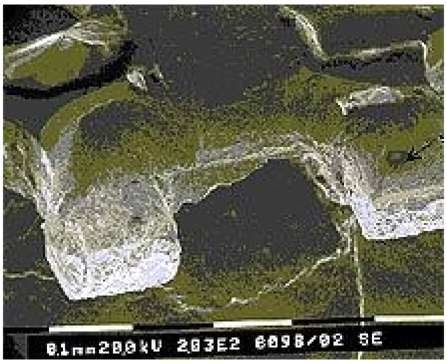

Figure 9. 203x SEM photo showing contact condition following contact

separation from solderball.

EDXA digital line scans were performed to ascertain the change in elemental composition from the base material to the solder ball. It was important to verify the presence of a good metallurgical bond by examining for intermetallics between the base metal, electrodeposits, and solder ball. Figure 10 is a SEM photo of the sheared edge of the terminal tab at 3240x magnification. Similar to the metallographic x-sections, the specimen was prepared by grinding through the sheared edge of the terminal fork. The tip of the terminal is skewed toward the left in the photograph. The plated side of the terminal is skewed toward the right. Figure 11 is the elemental line scan for the line labeled 100 in Figure 10. The regions in Figure 11 bounded by intersection of the various elemental intensity lines represent to formation of intermetallics. The scan shows the desired result, an optimum intermetallic formation and metallurgical bond.

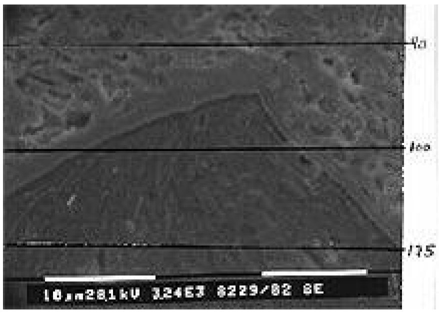

Figure 10. SEM photo showing EDXA line scan locations

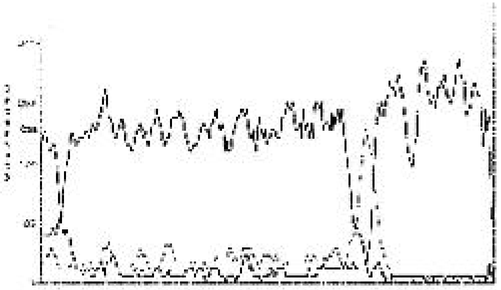

Figure 11. EDXA line scan through line #100

The EDXA digital line scans confirmed the elemental transition anticipated when migrating from base material to solder. Line scans verified the presence of the expected intermetallic on both edges and plated surfaces. Visual inspection via SEM photographs indicated proper intermetallic bonding existed. All of the aforementioned analyses confirmed that FCI's solderball to contact attach process exhibited sound solder joint mechanics.

Additional solderball-to-contact design verification tests included tensile testing and 3-point bend testing. Tensile testing, which measured solderball to contact strength, was performed using a compression/tensile tester. A design value of 1000 grams was established empirically. Although this value became an initial design specification, the test was frequently used to assess joint strength degradation following temperature cycle testing.

The 3-point bend test was advocated by a receptacle customer. This test was designed to simulate the deflection a system board encountered during manufacturing and testing operations. The MEG-Array® connector was assembled to a test board, inverted, and supported at a fixed distance not less than the length of the connector (Figure 12). Using a compression/tensile tester, the test board assembly was deflected for a distance of 0.5mm/1mm of support distance. Following deflection, a penetrating dye was applied to the periphery of the connector. A vacuum was applied and then the sample was placed in an oven to ensure the dye was dry. The connector was then separated from the sample board. The exposed interfaces were examined for the presence of dye. A failure was defined as an interface with 100% of the surface coated with dye.

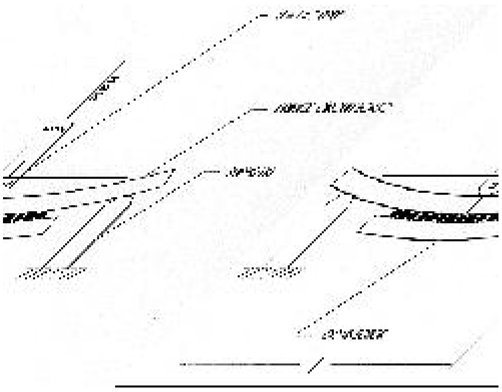

Figure 12. 3-Point Bend Test Set-up

Solderball-To-Pad Interface

Upon design verification of the solderball-to-contact attachment, MEG-Array® product development proceeded to solder joint reliability testing. The solder joint reliability testing consisted of 1000, 30 minute temperature cycles from -25o C to +100o C. Testing was performed in an air-to-air thermal shock machine since a rate of temperature change between temperatures was not specified. Sample size consisted of 30 mated connector pairs assembled to test boards. Test boards contained a daisy chain, series circuit wiring pattern through all connector positions. This circuitry enabled the resistance of the total circuit to be monitored in situ. Resistance was recorded on each of the 30 samples at 5 minute intervals throughout the entire 1000 cycles. An electrical failure was defined as no more than 100% increase in resistance from the initial value established at 100o C.

After numerous design iterations, solder joint reliability testing proved the reliability of the solderball-to-contact interface. However, occasional solder joint cracking still occurred at the solderball-to-pad interface as shown in Figure 13. Failure analysis indicated this cracking was occurring through the solder ball and thus was a cohesive rather than adhesive failure mechanism. The initial hypothesis was too much CTE mismatch in the Y axis. However, subsequent detailed examination revealed a different failure cause.

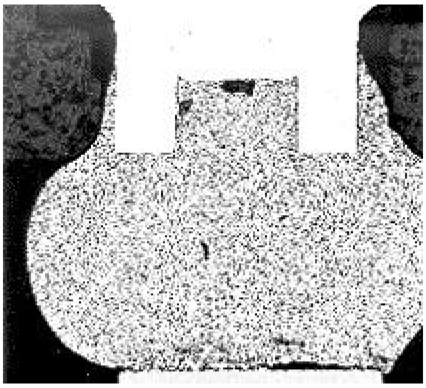

Figure 13. Cohesive solder failure at pad interface (80x)

Numerous quantitative techniques were employed to characterize the connectors and test boards during both thermal cycling and reflow. Two changes were made upon determining the cause of the problem. One change dealt with an adjustment to the housing material. Subsequent temperature cycle testing verified our findings and corrective actions. The design then successfully and routinely completed 1000 temperature cycles. Figure 14 illustrates worst case solder joint cracking at the solderball-to-pad interface. Only superficial cracks, typical of BGA technology, were observed at 1000 cycles. The remaining samples of this test successfully completed 1250 cycles without failure.

Figure 14. Worst case crack initiation (1000 temperature cycles) following material adjustment.

Contact Interface

In parallel with the solder ball joint reliability testing, contact interface reliability testing was also conducted. Qualification of the contact interface included durability cycling (50 cycles), corrosive atmosphere, humidity, and high temperature life testing. Insulation resistance and dielectric withstanding voltage testing was performed following humidity exposure to assess the electrical insulation properties of the housing.

High temperature life was a stress relaxation test of the contact materials. The test was used to determine if an adequate amount of elastic energy existed in the spring material over time. Contact resistance was measured following 240 hours high temperature life exposure at 85^{o} C. Maximum change in resistance observed was 2.38 mΩ.

Humidity testing was performed to evaluate the ability of the contact interface to withstand moisture penetration and any subsequent plating deterioration. It also evaluates the ability of the connector system and its materials to withstand any moisture absorption which may change important mechanical and insulation properties. Maximum change in contact resistance following 10 days of cyclic humidity exposure was 4.37 mΩ. Minimum insulation resistance after testing was 55 GΩ. No arc-over or leakage current greater than 1 mA was observed during dielectric withstanding voltage measurement.

The biggest challenge for the contact interface was the corrosive atmosphere test. This test was performed to evaluate the contact's ability to withstand oxide formation over time. This test was particularly noteworthy since a new 2-gas composition was imposed by one particular customer. The test required gas concentrations in the ppm rather than ppb range. The samples were pre-conditioned with 50 durability cycles then exposed mated for 96 hours. SO_2 and H_sS concentrations were 10 ppm and 3 ppm respectively. The test produced severe corrosion products away from the contact interfaces. But, the maximum observed increase in contact resistance following test exposure was only 7.17 mΩ.

Conclusions

FCI faced three challenges; develop a reliable high density, high pin count, low profile connector system, develop a capable, high volume manufacturing system, and meet critical time lines. The result was the industry's first BGA interconnect system, the MEG-Array® connector, manufactured in a totally automated assembly process. This project stretched the limits of traditional connector manufacturing and tooling technology. The resulting design, processes, and tooling provided a proven reliable interconnect system. This new technology going forward provides end users with many new packaging options.

Acknowledgements

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