The Application of Spherical Bend Testing to Predict Safe Working Manufacturing Process Strains

John McMahon P.Eng, Brian Gray P.Eng,
Celestica
Toronto, Ontario, Canada

Abstract
The increased temperatures associated with lead free processes have produced significant challenges for PWB laminates. Newly developed laminates have different curing processes, are commonly filled with ceramic particles or micro-clays and can have higher Tg values. These changes designed to reduce Z-axis expansion and improve the materials resistance to thermal excursions through primary attach and rework operations have also produced harder resin systems with reduced fracture toughness.

Celestica has undertaken an extensive "Spherical Bend Test" program to assess lead (Pb) free compatible materials and area array packages. This work has confirmed "Pad crater / Pad Lift" as the dominant failure mode in Pb-free materials in agreement with observations from multiple streams of field returned product. This work discusses the multiple phases of testing and the implications for mechanical reliability of Pb-free product. The initial phase was designed to confirm or refute the established relationship between strain rate and safe working strain in Pb-free materials. The second phase studied the effect of extended thermal excursions for an extensively used standard loss laminate material. The third phase was designed to directly compare standard loss laminate materials and has confirmed the impact of filled resin systems identified by other investigators

This new work seems to confirm the relationship between board thickness and safe working strain established by in IPC/JEDEC-9704: "Printed Wiring Board Strain Gage Test Publication". Data is only available for a limited number of package designs but these selected packages are believed to generate conservative strain limits for manufacturing process guidelines. The design of the most recent test plan was intended to generate data that would allow investigators to generalize the effect of package compliance on the safe working strain of the assembly by correlation of test data from multiple packages to an existing simplified mechanical model.

Assembly processing, test methods and results will be documented in addition to discussion on resultant data, failure analysis, distribution parameters. The effectiveness and predictive range possible from the simplified model will also be discussed.
Key words: Pad Crater, Process Strain, Spherical Bend Test, Mechanical Failures,

Introduction
The transition to lead free assembly is essentially complete for many product sectors. Low thermal mass products designed for sale directly into the consumer market such as handsets, smart phones, gaming systems, PCs and Net books, are all routinely built with lead free solder alloys and comply with widely enacted environmental legislation. The vast majority of these products are built with alloys in the Tin Silver Copper (SAC) but there have been some recent introductions of Tin Copper (SnCu) and Tin Bismuth (SnBi) alloy systems. There are a wide variety of choices available but the impact of SAC and SnCu alloys is that the minimum solder joint temperature for proper re-melting of solder spheres and powders is in the 230 to 240C range. SnBi systems reduce melting temperature significantly but are currently most commonly used in conjunction with alloys of the other two systems to replace wave solder operations. While there have been some very extensive field failure issues related to material selection, in general the materials required for robust assemblies in these low warranty time, high replacement rate product categories are now readily available. Proper analysis, material qualification and product design will result in "wear out" failure mechanisms and in-warranty repair rates that are in line with those experienced with eutectic tin lead (SnPb) assembly processes.

Two principle factors are now driving other higher reliability and higher thermal mass product sectors to Pb-free assembly processes. First, there is the resolution of the European Union discussions on the "lead in solder" exemption has produced reasonably clear timelines for the Enterprise Computing and Telecommunication (EC&T) sector. There is a wave of these server room and backbone type products that will transition over the next few years. These products are typically designed to the maximum area that can be processed through standard SMT, wave solder and test equipment. Current products typically have 20 to 30 Cu layers and thicknesses of 0.100 to 0.130 inches (2.5 to 3.5 mm) but certainly higher layer counts and thicknesses of 0.25 inches (6 mm) are predicted for these products. These high layer counts are combined with board dimensions which can exceed 16 x 20 inches (40 x 50 cm). The high thermal mass associated with this type of assembly can drive a 5X to 10X increase in the heat energy requirements when compared to consumer products. These increased energy requirements translate into longer thermal profiles and extended exposure times at high temperatures for all processing steps. In addition to thermal considerations these high complexity assemblies have another common feature: Multiple populations of application specific integrated circuits (ASICs) that usually exist as large BGA packages based on built up substrates with metal heat spreaders. The combination of thick laminate structure and large stiff package design almost certainly defines the maximum stress condition and therefore the lower boundary condition for mechanical integrity under flexure in high complexity assembly. Second, EC&T and other sectors with higher reliability requirements are also being forced to convert as the supply chain which is primarily driven by the consumer product sector reduces the availability of Pb bearing components. These high reliability sectors represent such a small percentage of the total component consumption that producers will over time stop production of all Pb bearing processes. Compliant lead plating and attached solder spheres will only be available in Pb free options.

Reliability of Pb free solders has been a topic of research for over 10 years and there is a plethora of studies on the thermal mechanical degradation of these materials. Less is known about the mechanical robustness of lead free systems. The work that is available for review is primarily related to drop shock improvements for handheld devices. There have been a variety of new additions to low silver alloys attempting to enhance the energy absorption of these alloys. Very little work has been documented on mechanical failures of larger assemblies, where the fracture toughness of the solder itself does not appear to be the limiting factor. Nadimpalli et al. [1],[2] have discussed the substantially lower energy required to initiate cracking in epoxy resin systems than in Pb free solders. This must be attributed at least in part to the changes that laminate suppliers have implemented over time to reduce the Z-axis expansion and raise thermal decomposition temperatures with the intention of making their materials more robust when subjected to extended solder reflow cycles. Unfortunately these implementations have had a detrimental effect on some mechanical properties of laminates, particularly toughness. Roggerman et al.[3][4] and others have published “cold ball pull” and “hot pin pull” testing results which identify that filled phenolic cured FR4 epoxy laminate systems fail at lower loads and absorb less energy to failure than unfilled resins from the same group. These micro particle fillers have been introduced to reduce Z-axis expansion and are widely implemented. We believe that this category of resin system represents the limiting case for mechanical integrity.

Mechanical failures in BGA solder joint systems have been categorized into ten modes to simplify industry discussion and acceptance of standardized testing. There is wide industry agreement that Mode 3, failure at the package NiP/SnNi IMC layer was the limiting case when current procedures were designed. There has been some movement in the industry to convert to Cu-Sn based interfaces at the package side and this has reduced the number of maverick lot incidents considerably. This change combined with conversion to lead free processing has produced a new dominant failure mode. Anecdotally mechanical failures in lead free systems are almost always reported as Mode 10, pad lift/pad crater unless some significant process defect is present in the solder.

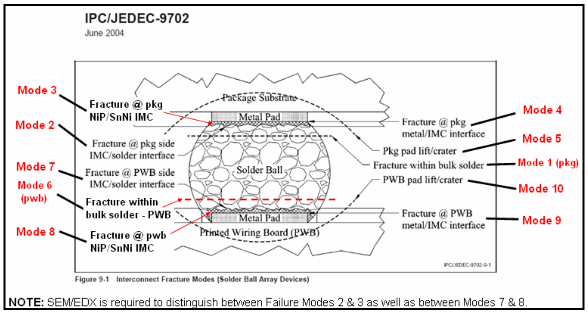


Figure 1: Failure modes in BGA solder joint systems [5]

This work outlines our efforts to generate working strain guidelines for manufacturing processes that produce equivalent safety factors for Pb-free compatible materials [6] when compared to materials that have been in use for Eutectic tin lead systems. This work will be conducted on test vehicles constructed and processed to be consistent with high complexity assembly.

Spherical Bend Testing

Various flexural test bending modes have been employed in the electronics industry. IPC-9702 [4] is based on four-point bend geometry with the package aligned parallel to the bending direction. This mode reduces scatter in the results primarily because individual solder joints are reinforced by near neighbors. IPC-9702 was intended to reduce repetitive package qualification testing by standardizing methods.

The results are easily compared between packages, but they do not represent the limiting condition and therefore are difficult to translate into safe working limits for tool qualifications and process characterizations. Orienting the package at 45 degrees to the bending direction increases the stress in the corner solder joints and provides a more conservative estimate of flexural limit. Hsieh & McAllister [7] have published an excellent comparative study of the various flexural options and identify spherical bend testing as the method that generates the highest tensile stress in the corner solder joint for a given displacement from the as built condition. Celestica has selected the spherical bend test setup which is depicted in Figure 2 for this work for three primary reasons out lined in previous work by the authors [8][9][10]. First, it represents the most conservative estimate of deflection limit. Second, it matches the conditions imposed by In-circuit test (ICT) equipment which is a standard process step for many products and is a known source for board deflection. Third, it generates data at all four corners of the package because they are loaded equally.

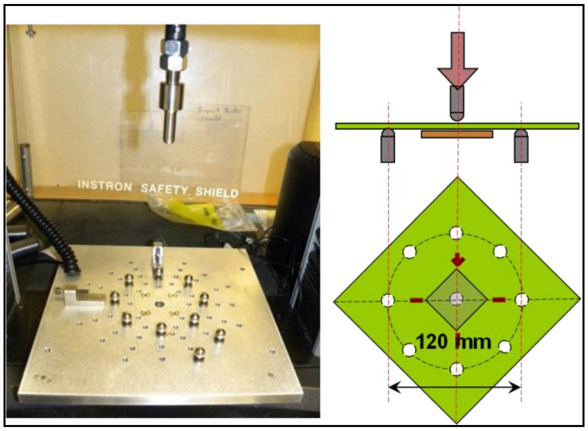


Figure 2: Spherical Bend Test Geometry [11]

The spherical bend test fixture is based on a support plate with eight spherically ground pins evenly spaced on a circle with a diameter roughly 3 times the diagonal dimension of the part. The sample under test is centered on the circle and the load is applied from the back side in the center of the package footprint by another spherically ground pin. The effect is to force the flat assembly into an area segment of a sphere whose radius is inversely related to the displacement of the loading pin. The attached package acts as a stiffener in the center of the slab and stress is imposed in a manner directly related to the diagonal distance from the center of the package. The effect is to load the corner solder joints to failure. In fracture mechanics engineering terms the loading is mixed mode I & II as depicted in Figure 3.

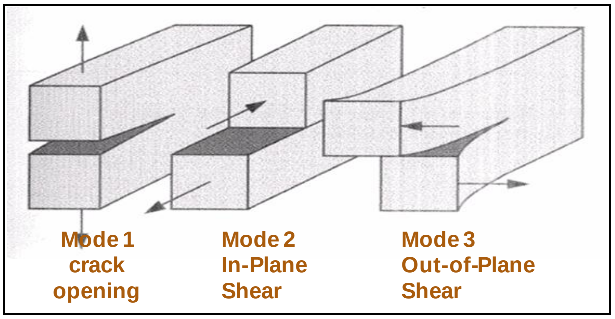


Figure 3: Crack Stress Modes [11]

- Mode I: A tensile component of the load as the stiffener (package) resists being deformed by flexure imposed on the board. This is a crack opening mode when describing a horizontal crack in the solder joint.
- Mode II: An in-plane shear stress component as the package resists being stretched as curvature is imposed on the system.

The principal strain on the board surface may not be coincident with the diagonal of the package but the maximum bending or minimum bend radius for the board is coincident, therefore the strain gauges are located on the board at the corners of the package in the diagonal orientation. If the assembled test unit is relatively compliant, gauges attached to the package corner in the same orientation also provide information. However the heavy metal heat spreader and its attachment to the package substrate make that information undecipherable for this sample set. Data collection is setup to simultaneously record resistance in the daisy chain, strain in the six gauges attached to the sample, displacement of the test head and the load induced by that displacement. Diagonal strain is recorded in the four aligned gauges and strain rate is calculated fomr the recorded data. The additional two gauges at a single corner allow calculation of the principal strain and principal strain rate.

Experimental Design: DOE1

The initial experiment was designed to assess the mechanical strain limits for lead free high complexity assembly and characterize the effect of lead free alloys and extended thermal requirements on safe working limits for board flexure in terms of peak strain and rising strain rate.

Surface strain analysis in PCBAs is the method by which we normalize a whole group of sub-parameters. Surface strain in uniform slabs is a function of deflection or curvature and board thickness (distance from the neutral axis of the slab). In electronic assembly it is complicated by non uniform reinforcement of the system by soldered components. Our interest is actually in the stress/strain concentrations that are inherent in the soldered connections. Specifically, the stresses that are imposed on the solder, the interfaces of the solder joint and the resin systems that are directly in contact with the solder pads. In this work we have introduced two factors which are "designed" to generate variation in the results. These are board thickness and strain rate. The other three factors: sphere alloy, laminate and pad plating are under study. The expectation is that each combination of strain rate and board thickness will generate a separate distribution of failures. The experimental design is actually to produce an evaluation of the reduced factor list outlined in Table 1 at each of these six combinations.

Table 1 – DOE1 Design Variables

Factor	Levels
Sphere alloy	SnPb / SAC105 SAC305 / SAC405
Laminate	Standard Filled Phenolic / Toughened Filled Phenolic
Pad Plating	OSP / ENIG

The strain rate dependence of fracture in epoxy resin systems is well documented in basic materials research, and has been widely incorporated into existing industry specifications and guidelines, such as IPC/JEDEC-9702 - Monotonic Bend Characterization of Board-Level Interconnects[2] and IPC/JEDEC-9704 - Printed Wiring Board Strain Gage Test Publication [3]. A proper treatment of this topic is beyond the scope of the current paper, but testing for this experiment was targeted at three specific Principal Strain rates intended to cover the acceptable ranges of all major assembly processes. Those three targeted Principal strain rates are 1000, 3500, 7000 micro strain per second (μe/s).

Eight sub-lot variations of a mechanical test vehicle were procured. Solderable surfaces were plated in both OSP and ENIG to generate interfaces based on both Cu_6Sn_5 IMC and Ni_4Sn_3 IMC systems. The PWBs were obtained in two laminates provided by Isola. A standard filled phenolic cured FR4 and a non-commercial variant of the first which had been modified to reduce room temperature Young's modulus by approximately 40% in an attempt to toughen the resin system.

Two versions of physical design were generated, each with identical footprints and outlines but with two distinct laminate stacks to represent incremental levels of assembly complexity. The first version was made up of 20 copper layers and had a nominal thickness of 0.100 inches (2.54 mm), the second contained 26 copper layers and had a nominal thickness of 0.130 inches (3.3 mm). The 185 x 185 mm test vehicles have a single BGA footprint for a 40 x 40 mm – 1.0 mm pitch device. A sectional view of the 0.100 inch version of the test vehicle is presented n Figure 4.

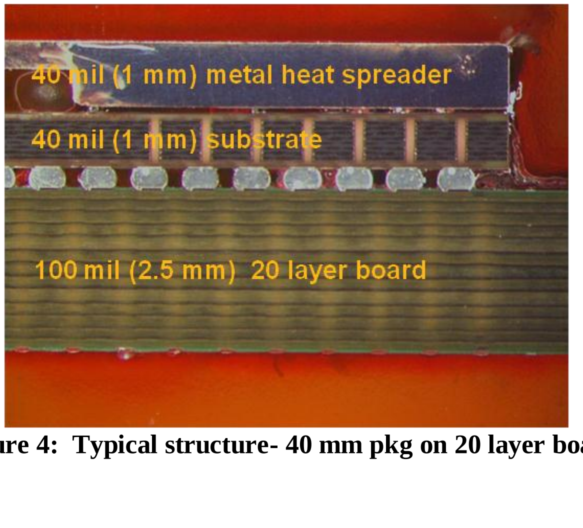


Figure 4: Typical structure- 40 mm pkg on 20 layer board

The 40 mm 1517 I/O built up flip chip packages were daisy chain devices provided by LSI. The package substrates were all plated with SAC305 over copper before spheres of the various alloys were attached. The BGA spheres were provided in Sn37Pb, SAC105, SAC305 and SAC405. Assemblies were preconditioned by one pass through the SMT oven prior to BGA attachment to account for the fact that these large devices usually exist on the top side of double sided assemblies. Where forced rework was required assemblies were processed through two further hot gas cycles to simulate removal and replacement of the BGA device. Solder joints from these processes were properly formed with acceptable voiding and typical microstructure.

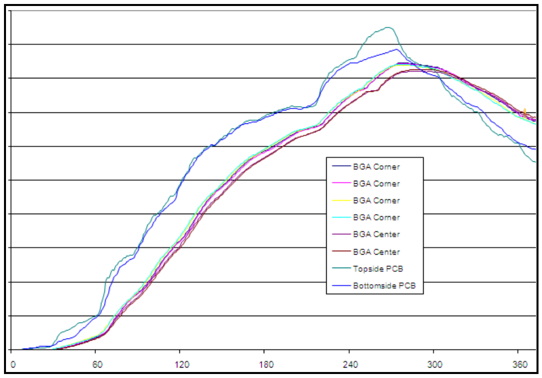


Figure 5: SMT Reflow Profile: Primary Attach

Two thermal profiles were prepared for the testing program. The SnPb devices were attached with SnPb paste while all of the Pb-free devices were processed with SAC387 paste. The characteristic Pb-free profile is presented in Figure 5. This induces minor modifications to all of the SAC alloys in the final solder joints but it is typical of results generate throughout the industry. Time zero cross sections for all process lots were inspected by optical microscopy. There were no remarkable results from primary attach. Solder conformation was normal, very little voiding was evident and the all of the standard phase compositions were measured. Packages are pre-plated with SAC305 directly over Cu so OSP boards produce Cu_6Sn_5 interfaces at both top and bottom interfaces. ENIG boards produce Cu_6Sn_5 at the top interface and a much more complicated Ni_3Sn / Ni_4Sn_3 / $(Cu\text{-}Ni)_4Sn_3$ interface at the board side pad.

Experimental Design: DOE2

The intent of this experiment was to identify and quantify differences in pad crater resistance and therefore survivable strain on a typical filled, phenolic cured laminate after forced BGA rework. Boards supplied in a single laminate from a single source were assembled with the 40 mm BGA devices using the standard high thermal mass conditioning and attach reflow excursions using the profile displayed in Figure 5. The lot for comparison was then subjected to two further thermal excursions on standard semi automated hot gas rework equipment. The initially attached component was removed the site was dressed using standard methods and then another component was attached using SAC305 solder. The assembly lots were then spherical bend tested at a target primary strain rate of 3000 micro strain per second. Microstructures were examined and failure distribution parameters were established for each lot. Board and component design and construction were identical to those tested in DOE1.

Experimental Design: DOE3

The premise for this experiment was that by holding all other factors including board design constant the inherent susceptibility of the resin / glass system would be comparable. Test Vehicle assemblies built from a single set of design data and specifications were built with OSP solder surface by a variety of qualified suppliers in a variety of laminate resin systems. The PWB suppliers provided sample lots that complied to the design criteria which were then all assembled with the same 32 mm monolithic ceramic device using a single thermal recipe for SMT reflow. This process did allow for some variation in the material beyond the resin system. Thickness specifications are normally +/10% which allowed the PWB facilities to utilize their qualified pressing processes which must be optimized for both resin cure and finished stack height. The resin and glass systems themselves were worthy of inspection. There is a notable difference in the bundles of glass reinforcement fibers. In some lots they were very well defined elliptical shapes while in others the glass was far more dispersed and difficult to identify in the filled resin system. This dispersed glass is implemented by some suppliers to improve the consistency of laser ablation drilling techniques. The variation in glass reinforcement is displayed in Figure 6.

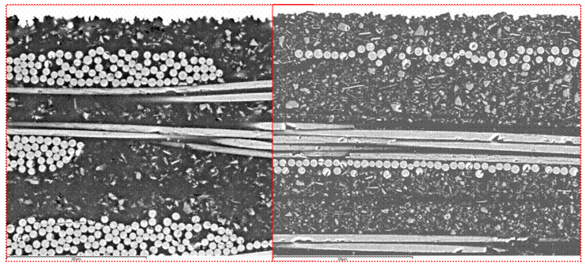


Figure 6, Variation in Glass Reinforcement

Results: DOE1

Previous work with more compliant systems has allowed us to record either the change in resistance that signifies failure at one of the solder interfaces or a localized minimum in the strain profile that indicates a laminate failure in either the board or the package substrate. These very stiff "high complexity typical" systems do not store enough energy in the package to create these events in the strain gauge signal at low strain levels. Strain events only occur at higher levels of displacement where they are related to catastrophic failures and do not represent the first damage to the system. Alternatively events may occur at low strain levels but the systems produce enough signal noise from vibration effects to make the events undetectable. In this experiment Mode 10, "Pad crater" was not only the dominant failure mode under this test method, it was the only failure mode detected in assemblies from standard "Primary Attach" processes. Destructive evaluation of samples subjected to increasing levels of displacement (flexure) determined that for this material and test setup there are three distinct displacement zones where the material response can be defined. These zones are depicted in Figure 7 and are described as:

- Zone 1: A safe zone where no damage occurs
- Zone 2: A mixed zone where package corners both fail and survive.
- Zone 3: A zone where all package corners fail.

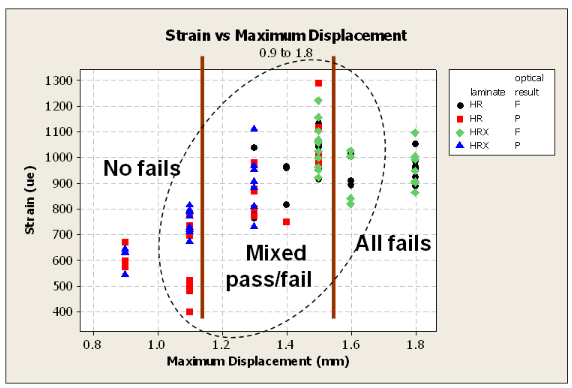


Figure 7: Mixed Response Zone

The intent of further testing was to define the boundary conditions for Zone 2 and generate distributions that would allow extrapolation to safe working limits. We defined a "step stress" procedure to test groups of samples to progressively higher peak strains at fixed displacement rates. For each data point peak strain, rising strain rate and outcome were recorded. The distributions of these estimates of survivable strain were used to generate working limits.

This work also required that we redefine our criteria for failure. In most compliant systems where "strain events" are recorded, failed samples inspected after penetrating dye has been applied exhibit complete separation of the BGA structure from the board. The crack path is very consistent; it involves a cone shaped failure in the "butter coat" of the laminate and follows the top surface of the glass bundles in the first reinforcing layer. We have yet to see any work in the literature that investigates the crack path. We normally assume that cracks initiate at the surface but it has been postulated and subsequently demonstrated that there could be internal separation and coalescence of micro cracks below the surface before this catastrophic failure occurs. As result of our analysis we have defined two distinct portions of the pad crater crack, which represent two different levels of failure categorized as cohesive and adhesive separation.

- Cohesive Separation: The crack initiates at the surface of the laminate in close proximity to the solder pad and travels at approximately 45 degrees to the first level of reinforcement. Testing identified that this portion of the damage can be generated without any progression under test conditions to the next phase.
- Adhesive Separation: The crack subsequently follows the top surface of the first reinforcement layer until it finds a short path back to the surface inboard of the solder pad.

We understand now that in these stiffer systems the cohesive portion of the crack occurs without generating any discernable disturbance in the strain profile, but we believe that it represents a significant risk to product shipping into service environments. To summarize, any damage to the laminate resin system discernable by dye penetration and optical microscopy is considered to be a failure.

Failure distributions were best modeled using Weibull distributions for two reasons. First: The failure rate is expected to be constantly increasing as the stressing factor is increased. In fact, there is a point at which no further survivors will be detected. This is the boundary between Zone 2 and Zone 3. The data includes both failures and survivors. In statistical terms the data is right censored. As expected the scatter in the results increases as the testing strain rate is increased. In general the distributions of all data at the various strain rates are consistent with the behavior currently accepted by the industry. The survivable peak strain decreases as rising strain rate increases.

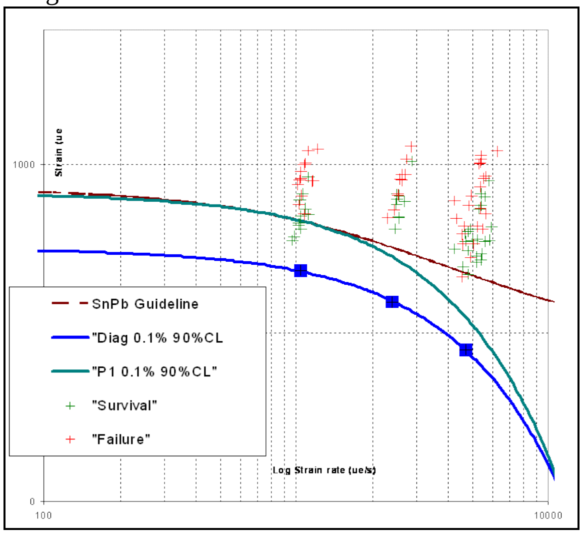


Figure 8: Typical Strain / strain rate behavior in FCBGA devices

Distributions are combined for individual board thicknesses. Data and calculations of safe limits were plotted in the common strain / strain rate format on log linear graphs. Basic regression techniques were used to generate safe working limits over the range strain rates associated with manufacturing processes. Figure 8 is a typical output from this process and displays individual data points, and the two limit curves based on diagonal and principal strains for a single board thickness. This process was repeated for all board thicknesses under study. This data was compared against the current estimate of the board thickness relationship and seems to correlate well. There is some evidence that the strain rate dependency for this fracture mode is different than the relationship currently accepted by the industry for SnPb assembly

Results: DOE2

The two process streams provided very different thermal histories for the lots. The “Primary Attach” lot was exposed to approximately 6000 degree seconds above Tg for the laminate whereas the “Forced Rework” lot was exposed to approximately 14000 degree seconds above the Tg point.

The Weibull distributions shown in Figure 9 are well formed. When reviewed together with the 95% confidence contours (CC)s displayed in Figure 10 they clearly define a statistical difference between the sample lots. Based on these distributions there is a 13% reduction in survivable strain associated with the forced rework of this laminate material. Apparently, the substantial additional thermal excursions related to hot gas rework of BGA devices do affect the resistance of the material to damage. This might be attributed to higher levels of cross-linking in the polymer, which reduce the compliance of the material.

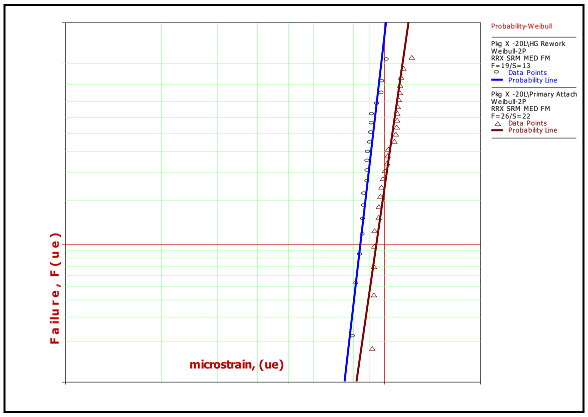


Figure 9: Weibull Distributions for Thermal Excursion Lots

The additional thermal exposure of laminates and solder pads caused by forced rework of large BGA devices also produces changes in the board side solder interfaces and where ENIG pad plating is present. A second failure mode, Mode 8 – Fracture at the NiP / NiSn IMC layer at the board side was identified as a second failure mechanism but Mode 10 remains dominant. The occurrence of two failure modes did not significantly affect the distribution of the data or the calculated limits.

Figure 10: 95%CC for Themal Excursion Distributions

Results: DOE3

The six lots processed for this experiment were selected from a larger group of tested laminates with the intention of covering the range of responses that have been encountered. We have endeavored to select a laminate from the worst and best performers as well as one from the middle of the pack. All lots meet the experimental expectations for Beta values based on testing from that significant number of laminate lots. The selected lots exhibit the well formed distributions that are expected for single failure modes and meet our condition for a well defined mixed response zone.

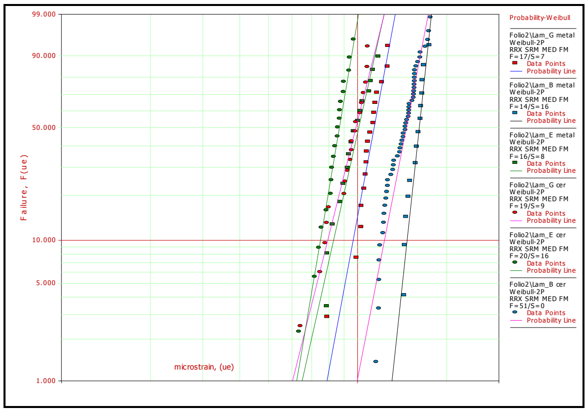


Figure 11: Weibull Distributions - DOE3

The Weibull distributions are plotted in Figure 11. As expected there is a benefit to characteristic life by moving to a more compliant package construction. It is also notable that the rank order of laminates in terms of survivable strain has not changed under the more compliant system.

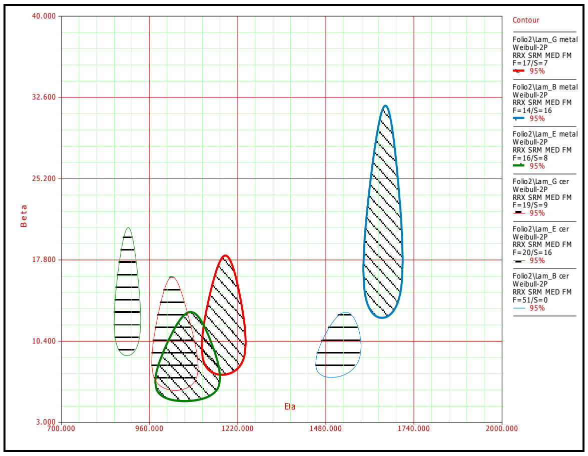


Figure 12: 95% CC for DOE3 Distributions

The plot of 95% CC for the Weibull distribution parameters displayed in Figure 12, clearly demonstrates the increase in characteristic life for each individual laminate which are defined by color. There is some variation in Beta value driven by the proximity of the boundary condition for laminate B. The top ends of both of these distributions are very close to or at the strain level where mixed failure modes would be expected to occur.

Summary

The Spherical bend test methodology has been shown to provide informative comparisons between sample lots created by varying laminate material, process thermal history and package construction. The nature of the test produces comparisons at extreme or boundary case conditions but the information provides insight into more standard conditions as well and may be widely applicable. The expansion of the test program to begin to establish the relationship to package stiffness may enable a first level model of susceptibility to this type of mechanical damage around BGA devices. The fact that the rank order of laminate materials did not change with alternate package construction leads us to believe that a more comprehensive model than the current is possible. We would with increased amounts of data be able to expand on the current, board thickness and strain rate model to include laminate material and package stiffness.

Observations

- The dominant failure mode for Pb-free compliant materials under flexure is Pad crater.
- The process strain limit model developed for IPC 9704 when interfacial fracture was the dominant failure mode can be modified to produce more realistic results for Pb-free compliant materials.
- Under the spherical bend test geometry Pb-free compliant materials have been shown to have a different strain rate dependency for mechanical failure under load.
- Significant differences in laminate material performance are evident under this test method.
- Laminate material susceptibility to this defect increases with thermal exposure.

Acknowledgements

The authors would like to thank LSI and IBM for their contributions of material.

References

1. Nadimpalli, S., Spelt, J., A Geometry and Size Independent Failure Criterion for Fracture Prediction in Lead-Free Solder Joints, International Conference on Solderability, SMTA, Toronto 2010
2. Nadimpalli, S., Spelt, J., Characterization and Prediction of Pad-Crater Fracture in Lead-Free Compatible PCBs, International Conference on Soldering Reliability, SMTA, Toronto, May, 2011
3. Roggeman B, Borgesen P, Li J, Godbole G, Tumne P, Srihari K, Levo T, Pitarresi J. Assessment of PCB Pad Cratering Resistance by Joint Level Testing, Electronics Components and Technology Conference, 2008.
4. Godbole, G., Roggeman, B., Borgeson, P., Srihari, K., “On the nature of pad cratering.”, Proc. 59th Electronic Components and Technology Conference, SanDiego, California, May 2009
5. IPC/JEDEC-9702 Monotonic Bend Characterization of Board-Level Interconnects
6. IPC/JEDEC-9704: Printed Wiring Board Strain Gage Test Publication
7. Hsieh G, McAllister A, Flip Chip Ball Grid Array Component Testing Under Board Flexure, EC&TC 2005
8. McMahon, J., Gray, B., Mechanical Failures in Pb-Free Processing: Evaluating the Effect of Pad Crater Defects on Process Strain Limits for BGA Devices. Pan Pacific Microelectronics Symposium, 2010

9. Gray, B., McMahon, J., Mechanical Failure in Pb-free Processing: Selected Mitigation Techniques for Pad Crater Defects, SMTA International, 2010
10. McMahon, J., Gray, B., Laminate Resistance to Pad Crater Defects: Comparative Spherical Bend Testing, Pan Pacific Microelectronics Symposium, 2011
11. IPC/JEDEC-9707 Spherical Bend Test Method for Characterization of Board Level Interconnects
12. He MY, Hutchinson JW. Asymmetric four-point crack specimen. J Appl Mech 2000;67:207–9.

APEX EXPO 2012 IPC

The Application Of Spherical Bend Testing To Predict Safe Working Manufacturing Process Strains.

John McMahon P.Eng. & Brian Gray P.Eng

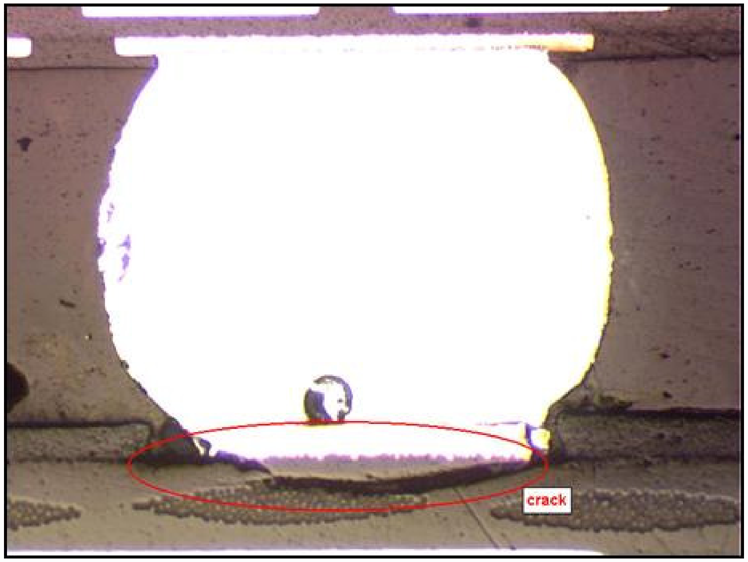
Celestica™
Solid partners. Flexible solutions.

Pad Crater Defects

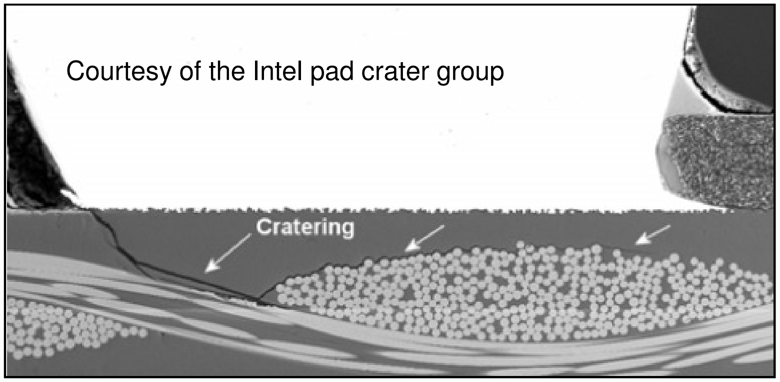
Crack initiation in the PWB resin system between the top surface and the first layer of glass reinforcement

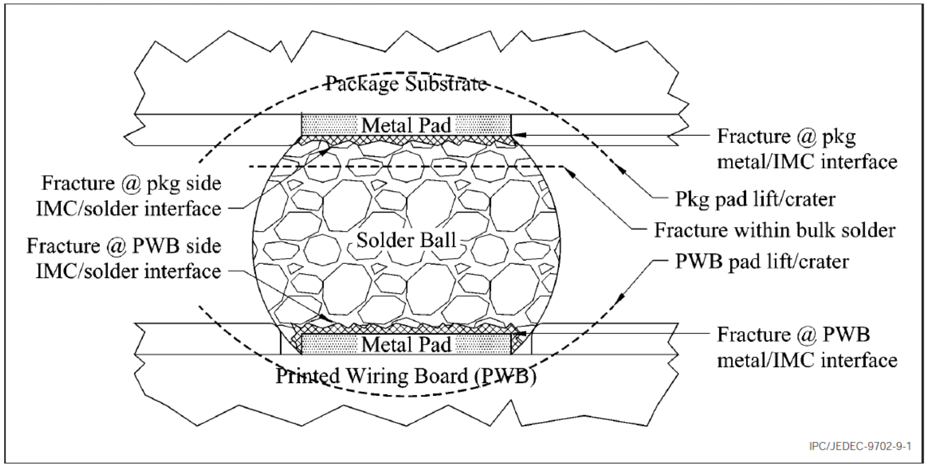
- •Pb-free solders are less compliant
- •IMC interfaces are now more resistant to fracture
    - –Packaging houses have converted to direct solder on Copper processes

- •"Phenolic" cured resins systems replace "Dicy" cured resins
- •Micro clays and ceramic particles are added to resin systems to reduce Z-axis expansion.



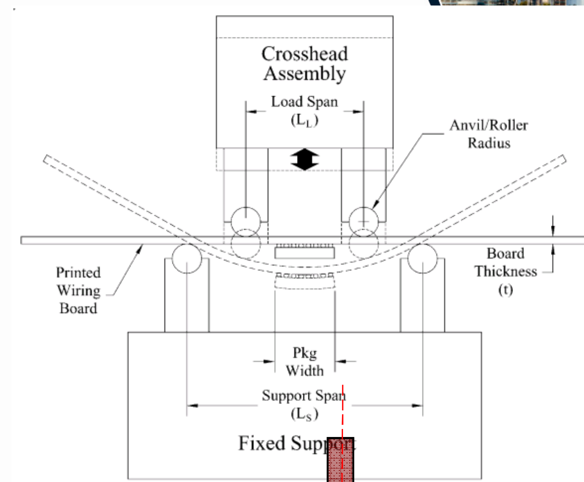
Pad Crater is now reported as the dominant mechanically induced defect in PCBA assembly

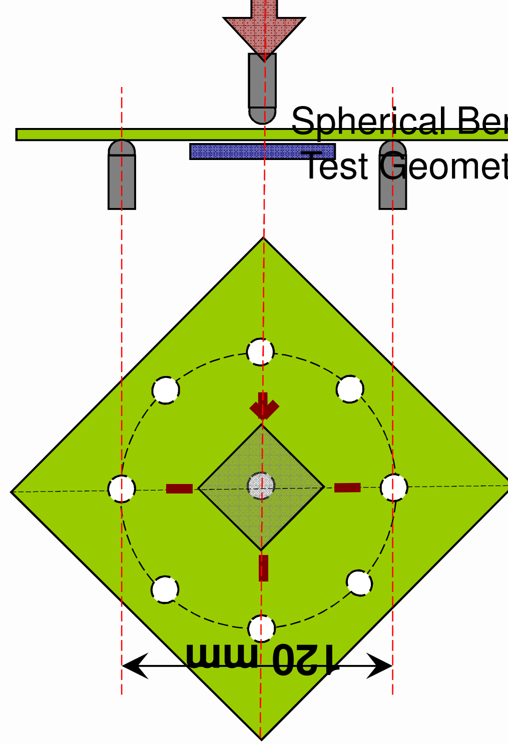


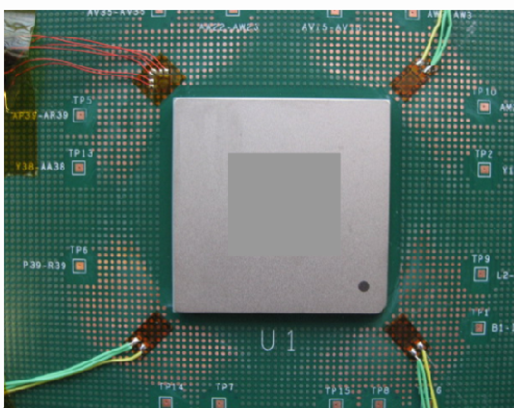


Bend Test Comparison

- 4 point Bend
  - Unidirectional strain and constant bending moment between anvils
- Spherical bend
  - Based on ring on ring stress test.
  - Drives biaxial strain
- Proposed specification 9707 for spherical bend

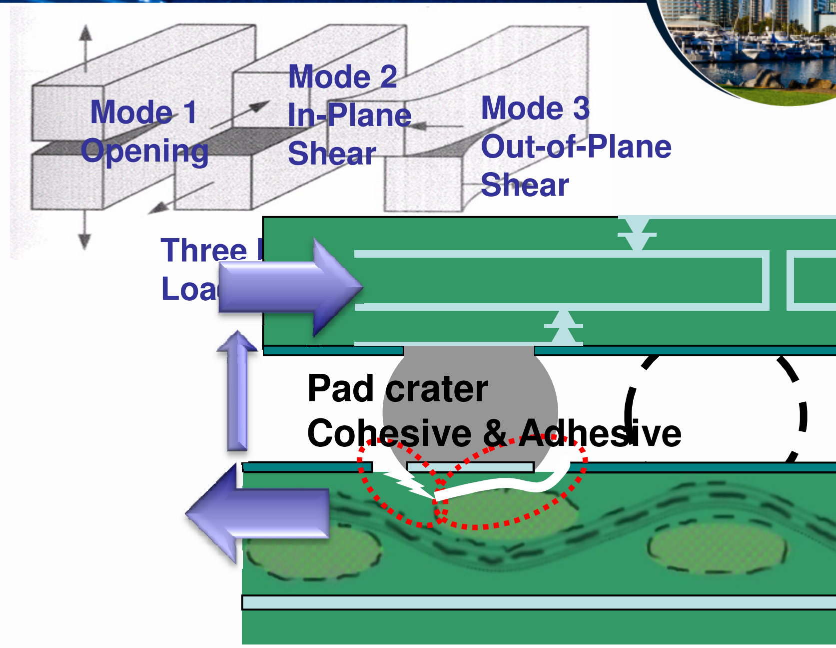


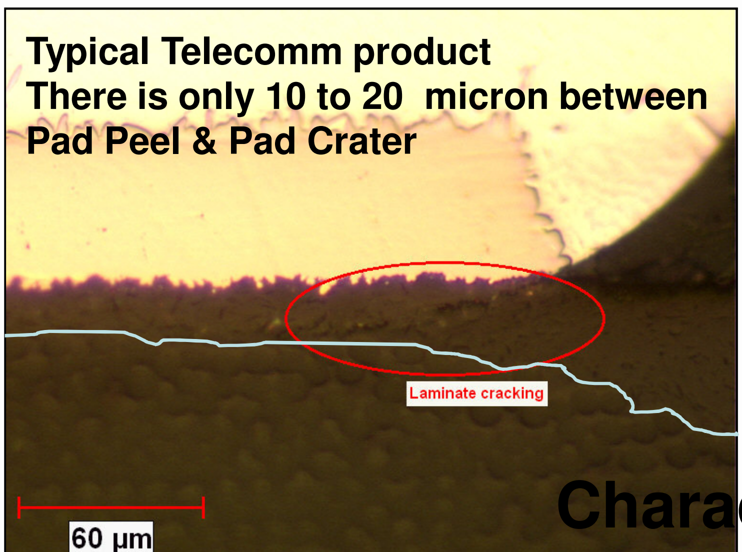


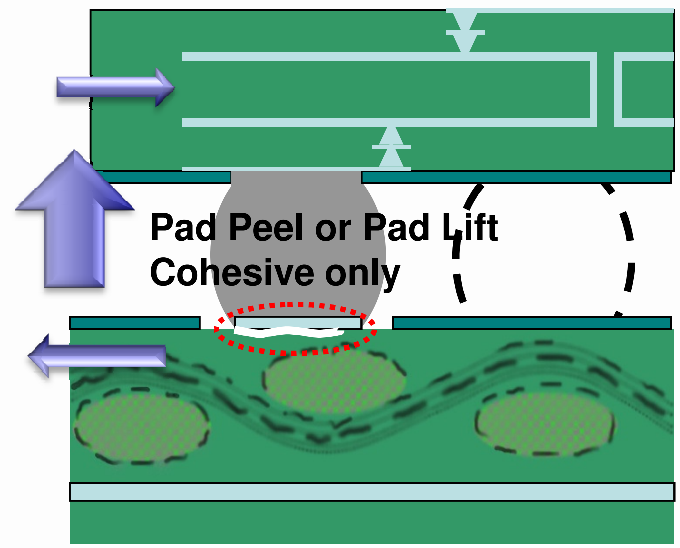


Crack Loading & Path

- Crack path is determined by two primary factors.
- Stress profile – relative proportions of mode 1 & mode 2
    - Stiffer packages generate mode 1 dominant sytems.
- Type of material – filled or unfilled
    - Filled material creates many opportunities for crack to turn



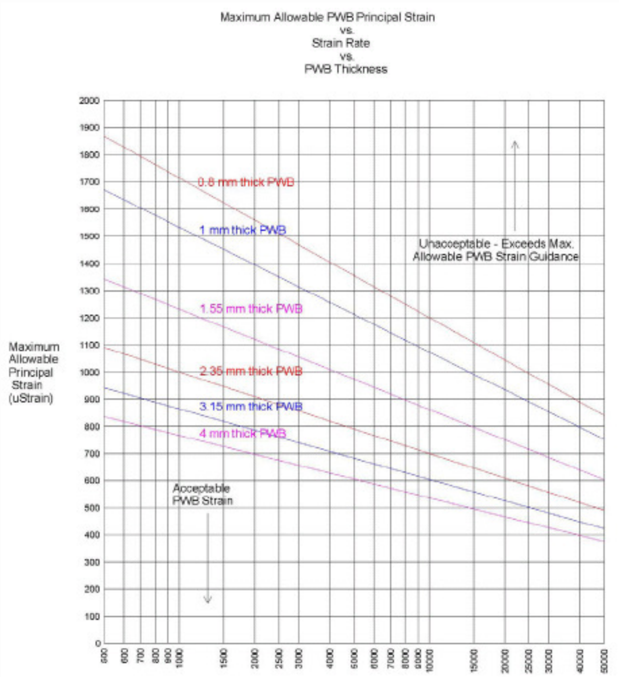




Characteristic crack paths

Strain Limit Specifications

- IPC-9704 process window for strain vs. strain rate based on failure in solder joint
- Revised guidelines published in 2005 – Courtesy of Keith Newman
- Current proposed revision of IPC 9704 moves strain vs. strain graph to white paper to make updating easier



SMTAI – Oct . 2011

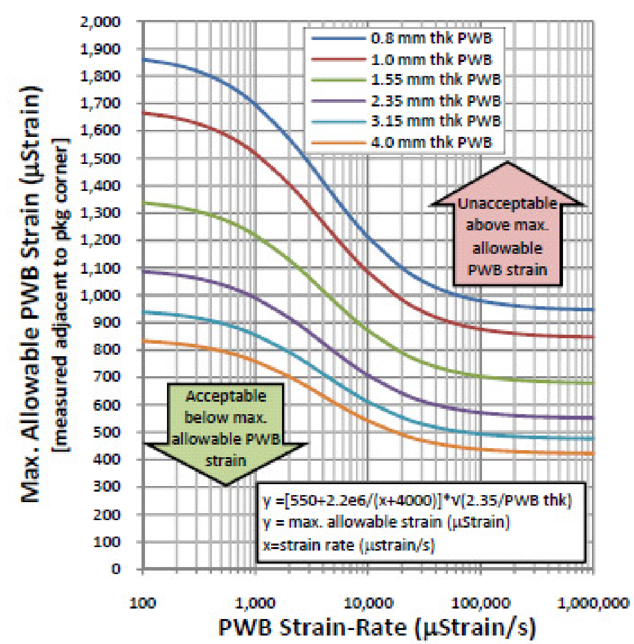
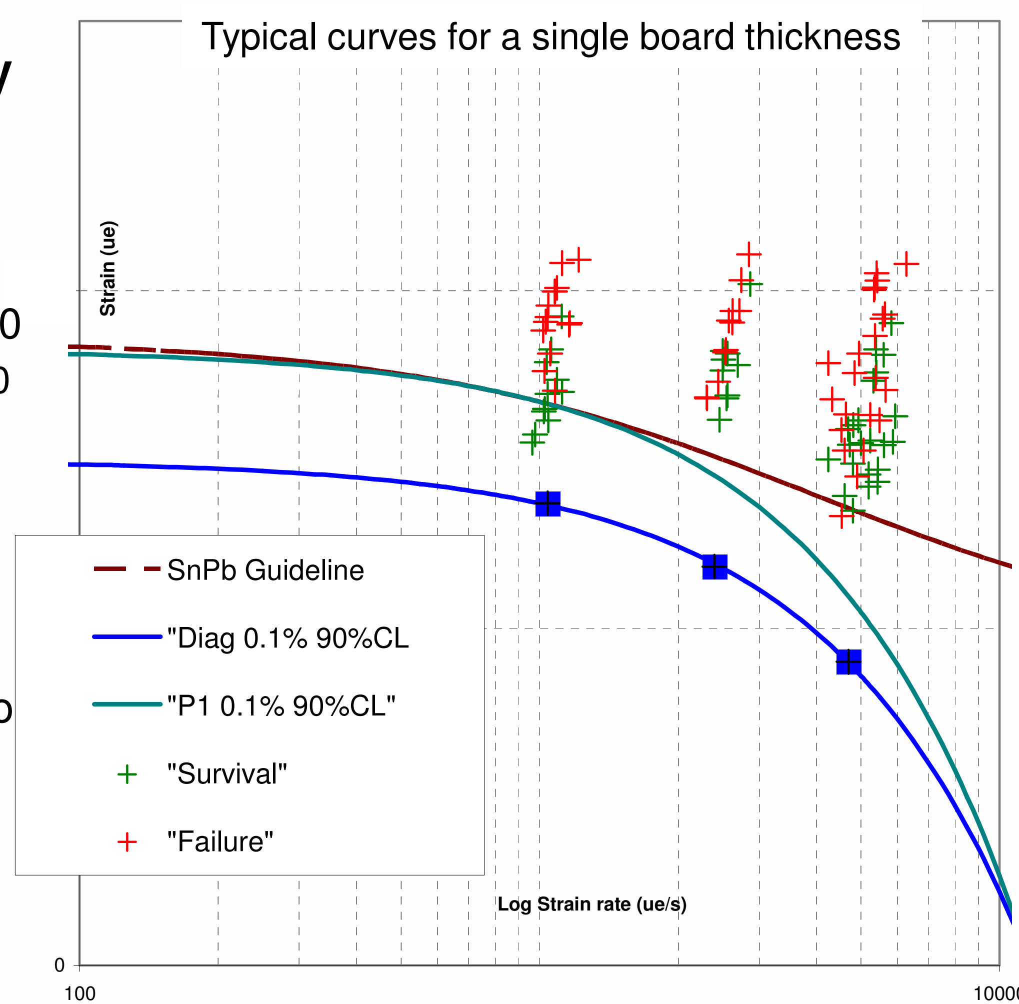


Figure 4 – Maximum allowable PWB strain (2005 guidance)

Celestica Internal Strain Limits

Test Program to Validate "Safe Working Strain" Limits for Pb-free compatible materials.

- **Spherical bend Test geometry**
- **Step stress approach to testing stiff systems.**
- Test program:
  - 3 strain rates 1000, 3000, 6000
  - 2 board thicknesses 0.100 & 0.130
  - 2 surface finishes
  - 4 solder sphere alloys
    - SnPb & SAC105, 305, 405
  - Primary attach & forced rework



- Below 2000 ue/s the results seem to be in good agreement with previous guidelines.
- Above 3000 ue/s The difference becomes significant.

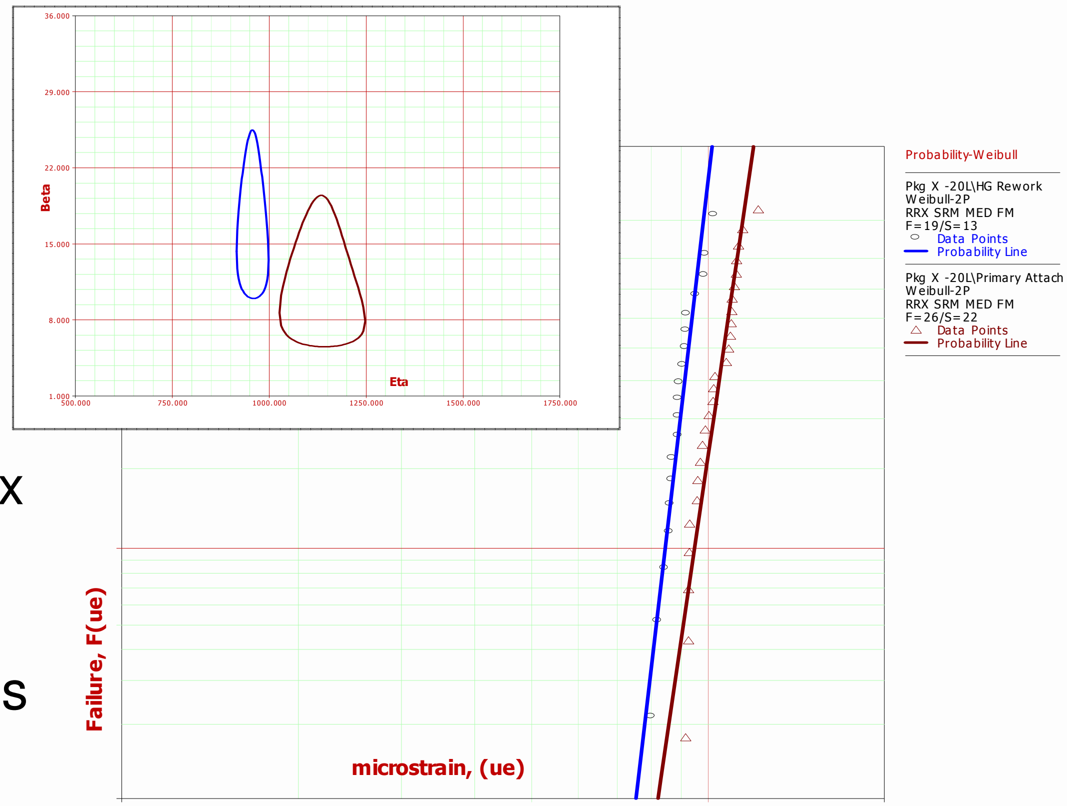
SMTAI – Oct . 2011

Forced Rework

- Added heat exposure does affect performance.
- Forced rework lot has very similar slope (Beta)
- Approx. 10% reduction in survivable strain

- PA = 2x SMT reflow
  - 6000 degree seconds above Tg
- Rework = 2x SMT plus 2x concentrated hot gas reflow
  - 14000 degree seconds above Tg

Comparisons are based on:
Nominal Principal Strain rate = 3000 µe/s
TV - 20 layer – 2.54 mm (0.100)
40 mm BGA
Single laminate testing

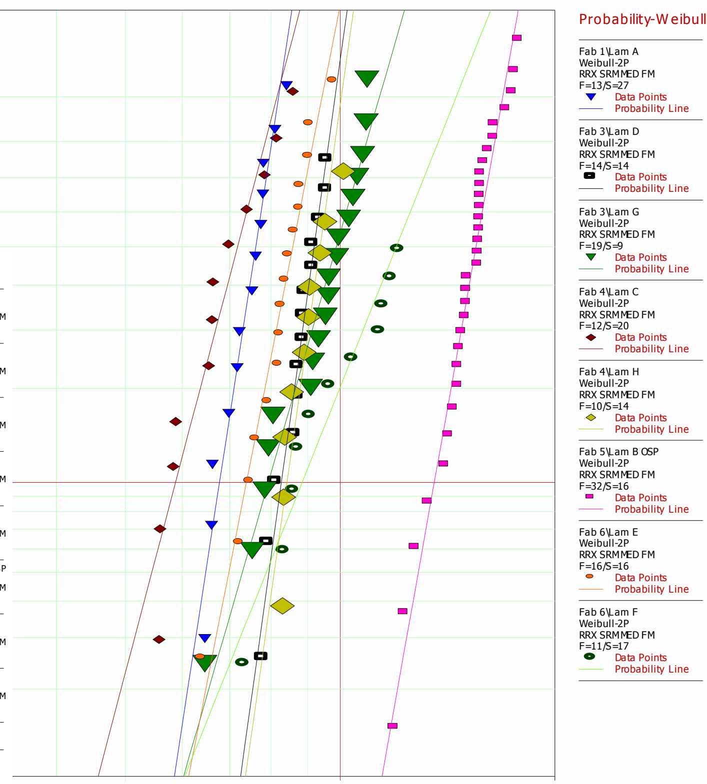


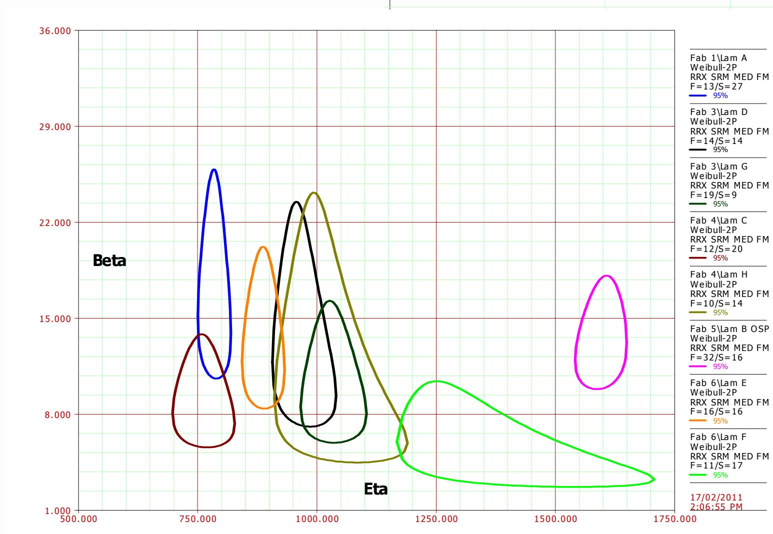
Laminate Susceptibility

- Multiple Suppliers build to a single design data package
- With minor exceptions the slopes (Beta) are very similar and we understand now what to expect from a new lot.
- The test method does define statistical differences between lots.

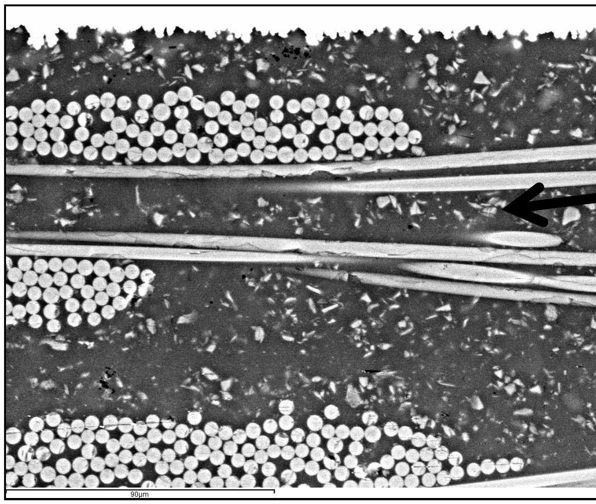
Comparisons are based on:
Nominal Principal Strain rate = 3000 µe/s
TV - 20 layer – 2.54 mm (0.100) (0.104)
32 mm CBGA

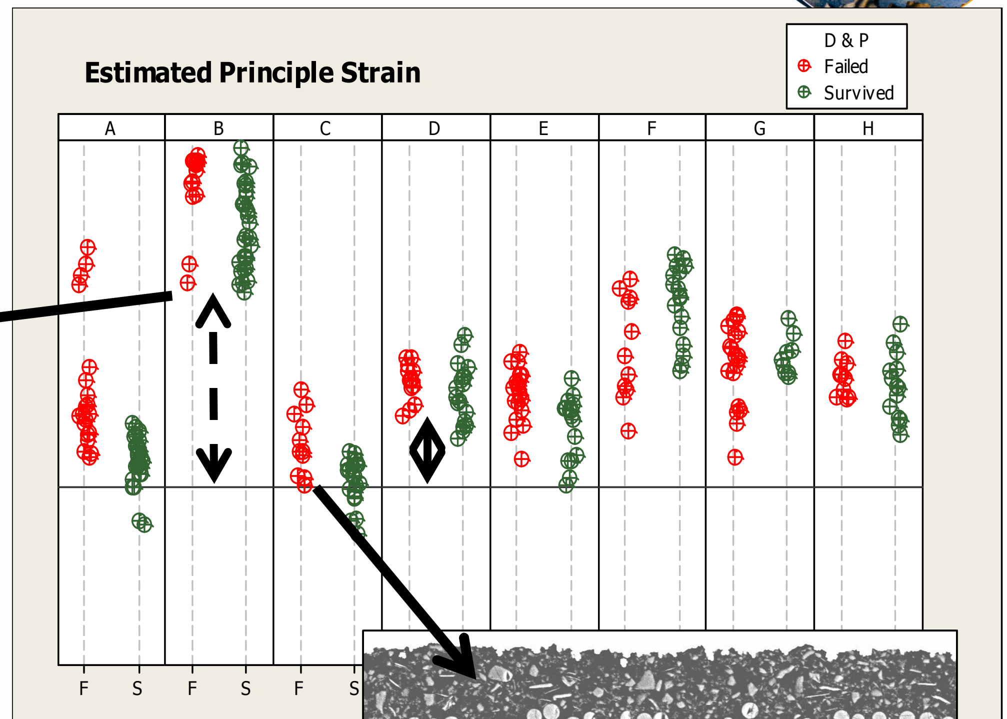
Probability – Weibull 2P

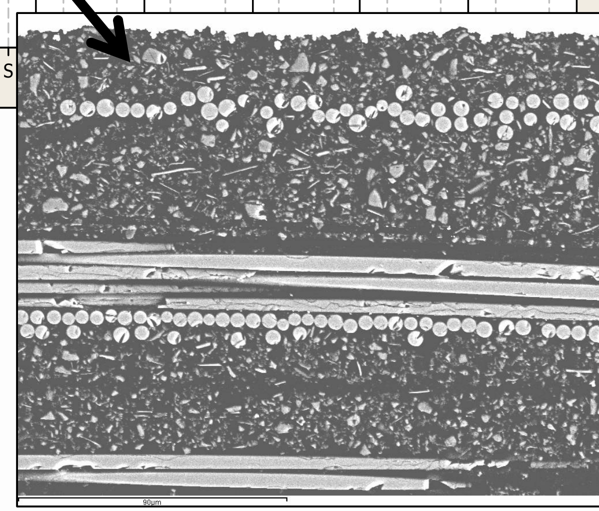




Laminate Results





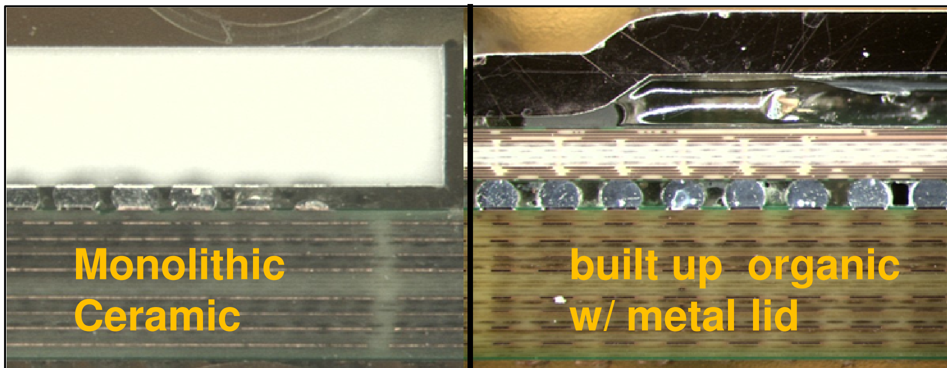


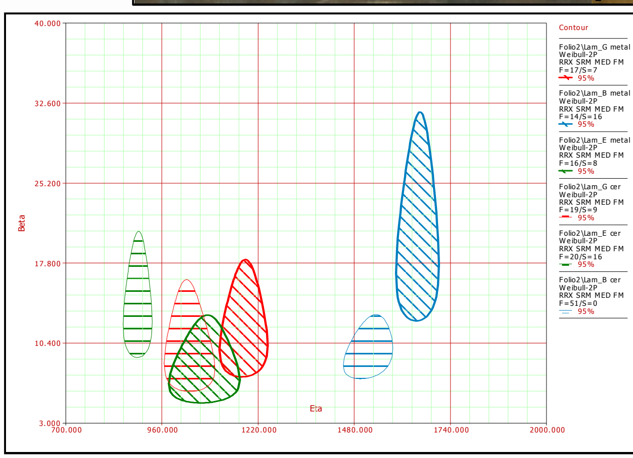
- There is no notable difference in the structures that would account for a difference of 100% between laminate B & C.
- The "hidden factor" is the resin system .

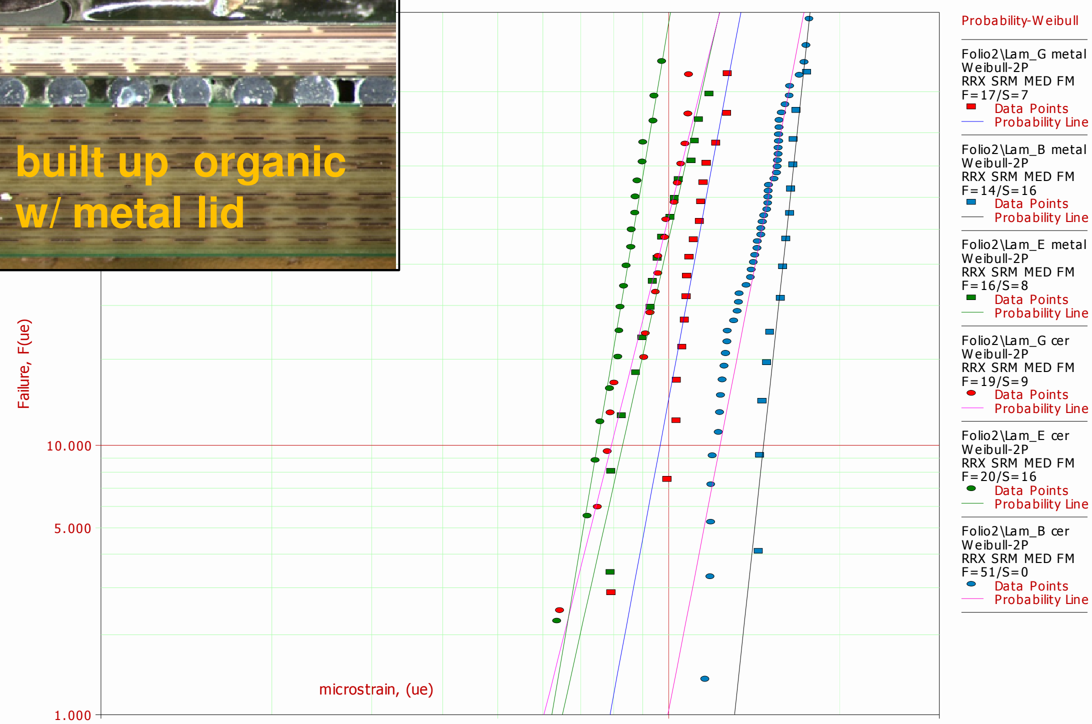
SMTAI – Oct . 2011

Package Compliance

- No change in rank order of selected laminates.
- More compliant pkg. produces an increase in survivable strain.
- In this application 14%-17% increase in Eta.
- Exception is at the high end of the range. Distributions converge as mixed failure mode is more probable







Conclusions

- The dominant mechanical failure mode in Pb-free compliant materials is Pad Crater and there are no non-destructive methods to identify crack initiation or even significant cracking.

- The strain rate dependency defined in IPC 9704 should be modified for use with Pb-free compatible materials.

- The board thickness dependency has been confirmed by independent testing at different thicknesses.

- Significant differences have been identified between resin systems in terms of susceptibility to Pad Crater initiation.

- Package stiffness is also a significant factor and could be incorporated into a model generated for a specific program.

Thank you

John McMahon P.Eng.

jmcmahon@celestica.com

Celestica™

Solid partners. Flexible solutions.