Best Practices in Avoiding Pad Cratering and Capacitor Cracking

Greg Caswell, Sr. Member of the Technical Staff
August 25, 2016
AVOIDING CRACKED CAPACITORS
Due to today’s low profile surface mount components, shock failures are primarily driven by board flexure

- BGAs don’t care about in-plane shock

Specific failure modes are

- Pad cratering (A,G)
- Intermetallic fracture (B, F)
- Component cracking

Shock tends to be an overstress event (though, not for car doors)

- Failure distribution is ‘random’
What Can Cause Cracked Capacitors and Pad Cratering?

Mechanical Shock Events

- Tend to be overly focused on drop, but excessive flexure can occur at multiple points post-assembly
What Can Cause Cracked Capacitors or Pad Cratering?

- The most common method for PCB Panel Singulation is to use V-grooved boards and a system as shown below to slice though the boards at the grooves.
- If the PCBs in the panel are not properly supported, then mechanical stress cracks can occur in MLCC capacitors.
Minimum Bend Radius

- Minimum bend radius has a very small allowable deflection and is dependent of the segment length being impacted.
- An approach to calculate:

Ref: Cracks: The Hidden Defect by John Maxwell AVX Corporation.
ICT Strain: Fixture & Process Analysis

- Review/perform ICT strain evaluation at fixture mfg and in process: 500 us, IPC 9701 and 9704 specs, critical for QFN, CSP, and BGA

To reduce the pressures exerted on a PCB, the first and simplest solution is to reduce the probes forces, when this is possible.

Secondly, the positioning of the fingers/stoppers must be optimized to control the probe forces. But this is often very difficult to achieve. Mechanically, the stoppers must be located exactly under the pressure fingers to avoid the creation of shear points.
Flex Cracking of Ceramic Caps

- Due to excessive flexure of the board
- Occurrence
  - Depaneling
  - Handling (i.e., placement into a test jig)
  - Insertion (i.e., mounting insertion-mount connectors or daughter cards)
  - Attachment of board to other structures (plates, covers, heatsinks, etc.)
Flex Cracking (Case Studies)

Board Depaneling

Screw Attachment

Connector Insertion

Heatsink Attachment
Flex Cracking (cont.)
Flex Cracking of Ceramic Capacitors

- Excessive flexure of PCB under ceramic chip capacitor can induce cracking at the terminations.
Flex Cracking of Ceramic Capacitors (cont.)

- Excessive flexure of PCB under ceramic chip capacitor can induce cracking at the terminations
- Pb-free more resistant to flex cracking
  - Correlates with Kemet results (CARTS 2005)
- Rationale
  - Smaller solder joints
  - Residual compressive stresses
  - Influence of bond pad
- Action Items
  - None
Flex Cracking (cont.)

- **Drivers**
  - Distance from flex point
  - Orientation
  - Length (most common at 1206 and above; observed in 0603)

- **Solutions**
  - Avoid case sizes greater than 1206
  - Maintain 30-60 mil spacing from flex point
  - Reorient parallel to flex point
  - Replace with Flexicap (Syfer) or Soft Termination (AVX)
  - Reduce bond pad width to 80 to 100% of capacitor width
  - Measure board-level strain (maintain below 750 microstrain, below 500 microstrain preferred for Pb-free)
Ceramic Capacitors (Thermal Shock Cracks)

- Due to excessive change in temperature
  - Reflow, cleaning, wave solder, rework
  - Inability of capacitor to relieve stresses during transient conditions.

- Maximum tensile stress occurs near end of termination
  - Determined through transient thermal analyses
  - Model results validated through sectioning of ceramic capacitors exposed to thermal shock conditions

- Three manifestations
  - Visually detectable (rare)
  - Electrically detectable
  - Microcrack (worst-case)
Thermal Shock Crack: Visually Detectable

Figure 5. Extreme Thermal Shock Cracks in MLCs

Figure 6. Severe Thermal Shock Cracks in Large MLCs
Thermal Shock Crack: Micro Crack

- Variations in voltage or temperature will drive crack propagation
- Induces a different failure mode
  - Increase in electrical resistance or decrease capacitance
Corrective Actions: Manufacturing

- **Solder reflow**
  - Room temperature to preheat (max 2-3°C/sec)
  - Preheat to at least 150°C
  - Preheat to maximum temperature (max 4-5°C/sec)
  - Cooling (max 2-3°C/sec)
    - In conflict with profile from J-STD-020C (6°C/sec)
  - Make sure assembly is less than 60°C before cleaning

- **Wave soldering**
  - Maintain belt speeds to a maximum of 1.2 to 1.5 meters/minute

- **Touch up**
  - Eliminate
Corrective Actions: Design

- Orient terminations parallel to wave solder
- Avoid certain dimensions and materials (wave soldering)
  - Maximum case size for SnPb: 1210
  - Maximum case size for SAC305: 0805
  - Maximum thickness: 1.2 mm
  - C0G, X7R preferred
- Adequate spacing from hand soldering operations
- Use manufacturer’s recommended bond pad dimensions or smaller (wave soldering)
  - Smaller bond pads reduce rate of thermal transfer
- Design using flexible terminations for the capacitors
Is This a Thermal Shock Crack? No!

- Cracking parallel to the electrodes is due to stack-up or sintering processes during capacitor manufacturing
- These defects can not be detected using in-circuit (ICT) or functional test
  - Requires scanning acoustic microscopy (SAM)
- With poor adhesion, maximum stress shifts away from the termination to the defect site
  - No correlation between failure rate and cooling rates (0.5 to 15°C/sec)
The root cause of this type of crack is due to rapid cooling during capacitor manufacturing.

The propagation path is perpendicular to the electrodes.

Ref: Design and Process Guidelines for Use of Ceramic Chip Capacitors – CALCE – University of Maryland
A Method to Test for Capacitor Viability

- This approach from Harold Snyder of Physical Solutions is a type of HALT test for capacitors to ascertain their viability prior to utilization in a product.

- The selection process is a multistep process which includes:
  - measure capacitance and dissipation
  - a six (6) hour accelerated aging sort at 150C at 400 Volts,
  - a methanol leakage test, at 10 volts DC then measuring leakage
    - Then raise MLCC to 85C and immerse in methanol bath for 15 minutes, blow dry the parts at 25C and re-measure leakage current
  - a visual examination at ten (10X) power
  - and final capacitance and dissipation characterization.

- The results of the sorting procedure provide the inputs needed to calculate the expected failure rates.

- Ref: RELIABILITY CALCULATIONS AND SCREENING PROCEDURES FOR EXTREME HIGH RELIABILITY MULTILAYER CERAMIC CAPACITORS UTILIZED IN HIGH TEMPERATURE APPLICATIONS
AVOIDING PAD CRATERING
Pad cratering is defined as cracking which initiates within the laminate during a dynamic mechanical event such as In Circuit Testing (ICT), board depanelization, connector insertion, and other shock and vibration inducing activities.

I’ll show the key drivers, measurement and detection protocols, and preventive tactics for this serious but prevalent failure. Pad cratering was first recognized in BGA packages but newer leadless, bottom termination components are also vulnerable.
Pad Cratering: Strain and Flexure

- Cracking initiating within the PCB laminate during a dynamic mechanical event
  - In circuit testing (ICT), board depanelization, connector insertion, shock and vibration, etc.
Laminate Cracking Leads to Trace Fracture

Trace routed externally

Functional failure will occur

Bending Force
Pad Cratering

- **Drivers**
  - Finer pitch components
  - More brittle laminates
  - Stiffer solders (SAC vs. SnPb)
  - Presence of a large heat sink

- **Difficult to detect using standard procedures**
  - X-ray, dye-n-pry, ball shear, and ball pull
SAC Solder is More Vulnerable to Flexure & Strain

Sources of strain can be ICT, stuffing through-hole components, shipping/handling, mounting to a chassis, or shock events.

NEMI study showed SAC is more Sensitive to bend stress.

Means and Std Deviations

<table>
<thead>
<tr>
<th>Level</th>
<th>Number</th>
<th>Mean</th>
<th>Std Dev</th>
<th>Std Err Mean</th>
<th>Lower 95%</th>
<th>Upper 95%</th>
</tr>
</thead>
<tbody>
<tr>
<td>SAC</td>
<td>18</td>
<td>0.230859</td>
<td>0.056591</td>
<td>0.01334</td>
<td>0.20272</td>
<td>0.25900</td>
</tr>
<tr>
<td>Sn-Pb</td>
<td>18</td>
<td>0.416101</td>
<td>0.040408</td>
<td>0.00952</td>
<td>0.39601</td>
<td>0.43620</td>
</tr>
</tbody>
</table>

Oneway Analysis of Load (kN) By Solder Alloy

Each Pair Student's t

Means and Std Deviations

0.1
0.15
0.2
0.25
0.3
0.35
0.4
0.45
0.5

SAC Sn-Pb
Solder Alloy

NEMI study showed SAC is more Sensitive to bend stress.
Pad cratering has been around for a while......

Transient Bend Board Flexure Initiative

Presented by
Frank W Joyce
frank.w.joyce@intel.com
Sr. Mechanical Engineer
Test Technology Development

Test Development Engineering (TDE)
Intel Corporation

15 June 2005

Other names and brands may be claimed as the property of others
Documents 3 test methods
- Pin Pull
- Ball pull
- Ball shear

Each test has pros and cons

No pass or fail criteria
- User must define what is acceptable
- Base on design and reliability requirements
BGA Mechanical Loading Failure Modes

- Weakest link in the system fails first

**Different Failure Modes**

**Legend**

- A. Package Pad Lift/Crater
- B. Pkg Metal/IMC Interface Fracture
- C. Pkg IMC/Solder Interface Fracture
- D. Bulk Solder Fracture
- E. PWB IMC/Solder Interface Fracture
- F. PWB Metal/IMC Interface Fracture
- G. PWB Pad Lift/Cratering
Choice of pad geometry affects BGA failure rate and failure location.
IPC 9708 Pin Pull Test

- Good for any pad geometry – no balls required
- Most sensitive to board material and design variables

- Requires pins to be soldered to pads
IPC 9708 Ball Pull Test

- Quick test after BGA ball attach
- No expensive pins required
- Almost as sensitive as pin pull
  - BGAs only
  - Highly dependent on solder ball so process control is critical
IPC 9708 Ball Shear Test

- Quick test after BGA ball attach
- Less control needed than ball pull test

- BGAs only
- Least sensitive to design and material variables
Universal Instruments Test Method Comparison Results

- **HBP/HPP**
  - Longer to run: 2-3 minutes
  - Can run as cyclic test
  - Paste deposit or solder ball does not affect test result
  - Suited to universal test: pad geometries & angles
  - Loading mode correlates to warpage/bending
Universal Instruments Test Method Comparison Results

- **Cold Bump Pull**
  - Easy & fast: 15-30 seconds per test
  - Limited to vertical pull
  - Loading correlates to warpage/bending
  - Choice of sphere solder alloy doesn’t affect strength
  - Speed dependence noted on filled phenolics
Universal Instruments Test Method Comparison Results

- Easiest & quickest to run
- Universal test
- Lower strength than pull
- Correlates to CTE mismatch & shear modes
- Different mode on phenolic resins
Testing Recommendations

- **Coupon-based testing**
  - Allows direct comparison between design, materials and process changes
- **Pin pull & ball pull** characterize tensile loading
- **Ball shear** characterizes shear loading
- Use at least 2 of the 3 tests so that both tensile & shear loads are covered
Details test & equipment required

- Measurement & reporting for both strain & strain rate
- SMT devices covered, no discretes
- Measure all BGAs with a package body size =/> 27 mm x 27 mm
- Measure 3 largest otherwise

Strain induced failures include ball cracking, trace damage, pad lifting and substrate damage
Rosette Strain Gages

- Measures strain on several axes at the same time
- Pre-wired with either two 3-ft. (1 m) leads or three 9-ft. (3 m) leads
- Determine the magnitude and angle of stress
- Strain Gages for both static and dynamic applications
  - Broad Temperature Range
Grid strains e1 and e3 should be oriented parallel to the edges of the package.

Grid strain e2 should be oriented diagonally away from package with respect to the edges of the package.

Consistent and precise placement of gages is critical to correlation of data between test location and samples.
IPC 9702

**4 Point Bent Test**

- Used to characterize fracture strength of board level interconnects
- Failure modes from this test are not easily differentiated
  - High speed test
  - Short duration
  - Failures in quick succession
Detection Methods

- Limited visual inspection options
- Electrical Characterization
  - Critical for both detection & failure analysis
- Functional and in circuit testing (ICT)
- Acoustic Microscopy
- Highly Accelerated Life Testing (HALT)
 ICT Strain: Fixture & Process Analysis

- Review/perform ICT strain evaluation at fixture mfg and in process: 500 μs, IPC 9701 and 9704 specs, critical for QFN, CSP, and BGA

To reduce the pressures exerted on a PCB, the first and simplest solution is to reduce the probes forces, when this is possible.

Secondly, the positioning of the fingers/stoppers must be optimized to control the probe forces. But this is often very difficult to achieve. Mechanically, the stoppers must be located exactly under the pressure fingers to avoid the creation of shear points.
Sherlock Software

- Eliminate potential bed of nails damage by:
  - Identifying components on the circuit card that could experience cracking or failure during bed of nails testing.
  - Prior to the ICT, the designer can optimize the process:
    - Change test points
    - Change pogo pin pressure, or
    - Add / move board supports
  - Sherlock analysis is component-specific, allowing for more precise identification of at-risk areas
Designers can identify potential bed of nails damage early in the layout process, before a bed of nails tester is ever designed.

Allows for tradeoff analyses, saving costly board damage and redesign.
Cisco Alternative Test Methodology

- Cisco has developed a detection method based on Acoustic Microscopy
  - Referred to as Acoustic Emissions (AE)
  - Appears to detect onset earlier and with greater capture rate than electrical methods
  - Modified 4 point bend test
  - Full assembly based test rather than test vehicle
  - Intent is to capture partial/small cracks which could propagate to failure
    - Some studies show 20% crack growth during thermal cycling

“A New Approach for Early Detection of PCB Pad Cratering Failures,” “COMPREHENSIVE METHODOLOGY TO CHARACTERIZE AND MITIGATE BGA PAD CRATERING IN PRINTED CIRCUIT BOARDS”,

9000 Virginia Manor Rd Ste 290, Beltsville MD 20705 | 301-474-0607 | www.dfrsolutions.com
Acoustic Microscopy

- Used when delamination or voiding is suspected
  - Electrical shorting within the package (delamination, electro-chemical migration)
  - Electrical opens (delamination, wire bond failure)
  - Insufficient thermal performance detected (i.e. die attach)

- Some value for ceramic BGAs
  - Attenuation due to multiple interfaces prevents imaging of interconnects under PBGAs
Solutions to Pad Cratering

- **Board Redesign**
  - Solder mask defined vs. non-solder mask defined

- **Limitations on board flexure**
  - 500 microstrain max, Component, location, and PCB thickness dependent

- **More compliant solder**
  - SAC305 is relatively rigid, SAC105 and SNC are possible alternatives

- **New acceptance criteria for laminate materials**
  - Intel-led industry effort
  - Attempting to characterize laminate material using high-speed ball pull and shear testing, Results inconclusive to-date
SMD versus NSMD for Pad Cratering

Solder mask defined pads can provide additional strength

- Increases tolerable strain
- But, moves failure location from pad crater to intermetallic fracture
More Compliant Solder

What do we know about SAC305?

- Does not wet/solder as well as SnPb
  - Attacked through flux reformulation, improvement in assembly equipment (10-12 zone ovens) and changes in visual inspection criteria

- Tends to outperform SnPb in temperature cycling

- Can perform poorly under bending or mechanical shock
  - Tighter restrictions on board movement during post-assembly handling
  - Limit use of nickel-based platings
  - Movement to low-silver SAC alloys for certain components in mobile applications

- Concern about performance under vibration
  - Either not implemented in high vibration environments (avionics, military) or using conservative design rules (automotive)

- Some question about predicting performance in small volumes
Pad Cratering Failure Analysis Techniques

- Always start with Non-Destructive Evaluation (NDE)
  - Obtain maximum information with minimal risk of damaging or destroying physical evidence
  - *Emphasize the use of simple tools first*
- *(Generally) non-destructive techniques:*
  - Visual Inspection
  - Electrical Characterization
  - Acoustic Microscopy
  - X-ray Microscopy
  - Thermal Imaging (Infra-red camera)
  - SQUID Microscopy
- Known good or reference component is often required.
Cross-Sectioning

- **Standard method for confirming pad cratering**
- **Method:**
  - Saw to approximate area of interest
  - Pot in epoxy resins to aid polishing
  - Polish. medium dependent upon materials: typically diamond, SiC, or alumina suspensions & embedded polishing cloths
  - Grind, Coarse to fine (600 grit to 0.05 um) to eliminate damage from previous step, repeat
  - Final etch often used for microstructural relief
  - Optical/electron microscopy techniques used for inspection
  - High precision necessary – easy to grind through!
Pad Geometry

- Pad design influences failure
  - Smaller pads result in higher stress under a given load
- Solder mask defined pads can provide additional strength
  - Increases tolerable strain
  - But, moves failure location from pad crater to intermetallic fracture
Pad Cratering Conclusions

- Pad Cratering is an increasingly common failure mode
  - Catastrophic and non-reworkable
- Easy to avoid detection and difficult to diagnose
  - Partial cracks riskiest since they escape and expand in the field
- Multiple paths for mitigation but few for true prevention
- No hard, fast rules for avoidance
  - Dependent on design, component, layout, process...
Pad Cratering Recommendations

- Maintain awareness in design & manufacturing
- Evaluate each and every design
  - No one size fits all criteria but some “rules of thumb”
  - Validate results with destructive cross-sections
- Test & Control are key
  - Use multiple testing strategies to maximize success at finding and preventing failures
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THANKS

Greg Caswell
Sr. Member of the Technical Staff
301-640-5825
gcaswell@dfrsolutions.com