Cracking Problems and Mechanical Characteristics of PME and BME Ceramic Capacitors

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List of Acronyms

BME	base metal electrode	IFT	Indentation Fracture Test
C-SAM	C-mode scanning acoustic microscopy	IR	insulation resistance
DCL	direct current leakage	IWT	ice water test
DF	dissipation factor	MLCC	multilayer ceramic capacitor
ECM	electrochemical migration	MOR	modulus of rupture
EDS	energy dispersive spectroscopy	PME	precious metal electrode
EM	electrical measurements	RH	relative humidity
ESR	Equivalent series resistance	TSD	terminal solder dip
FA	failure analysis	VH	Vickers hardness

Abstract

Most failures in MLCCs are caused by cracking that create shorts between opposite electrodes of the parts. A use of manual soldering makes this problem especially serious for space industry. Experience shows that different lots of ceramic capacitors might have different susceptibility to cracking under manual soldering conditions. This simulates a search of techniques that would allow revealing capacitors that are most robust to soldering-induced stresses. Currently, base metal electrode (BME) capacitors are introduced to high-reliability applications as a replacement of precious metal electrode (PME) parts. Understanding the difference in the susceptibility to cracking between PME and BME capacitors would facilitate this process.

This presentation gives a review of mechanical characteristics measured in-situ on MLCCs that includes flexural strength, Vickers hardness, indentation fracture toughness, and the board flex testing and compare characteristics of BME and PME capacitors. A history case related to cracking in PME capacitors that caused flight system malfunctions and mechanisms of failure are considered. Possible qualification tests that would allow evaluation of the resistance of MLCCs to manual soldering are suggested and perspectives related to introduction of BME capacitors discussed.

Outline

- Problems with cracking of MLCCs.
- In-situ mechanical testing.
  - Flexural strength.
  - Vickers hardness.
  - Indentation fracture toughness.
  - Board flex testing.
- Failure history case.
- What can be done to mitigate manual soldering cracking.
- Conclusion.

Cracking-Related Problems

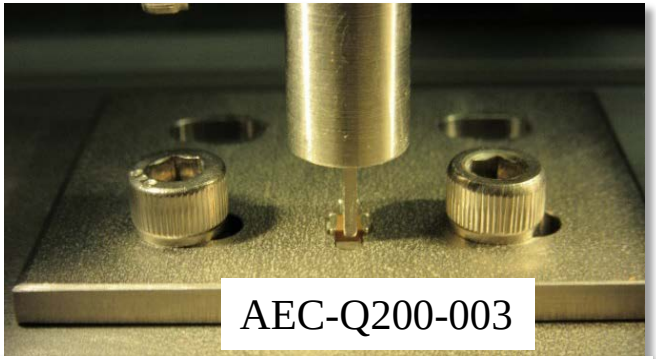
- Mechanism of cracking during manual soldering.
- Revealing cracks in capacitors (loose and soldered).
  - Electrical measurements (C, DF, IR, VBR)
  - Electromechanical effects
  - Visual, radiography, ultrasonic analysis
- Effects of cracking on reliability in humid and HT environments.
- Robustness of MLCCs towards thermo-mechanical stresses.
  - IWT (ice water testing)
  - TSD (terminal solder dip testing)
- In-situ mechanical testing.
  - Flexural strength
  - Vickers hardness
  - Indentation Fracture Test
  - Board flex testing
- Susceptibility to cracking of PME and BME capacitors.

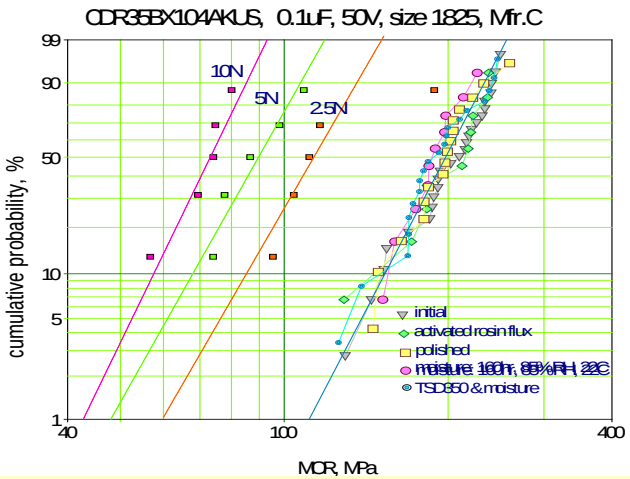
Degradation of MLCCs with cracks and the effectiveness of different techniques is described in various publications and reports posted at the NEPP web site.

✓Do different types of MLCCs have different susceptibility to cracking under manual soldering conditions and how it can be revealed?

Flexural Strength

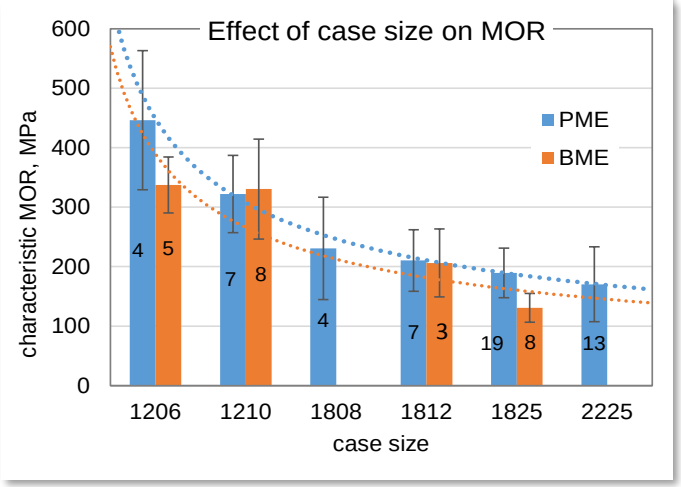
- The test is described in AEC-Q200, but acceptance criteria are up to the users.





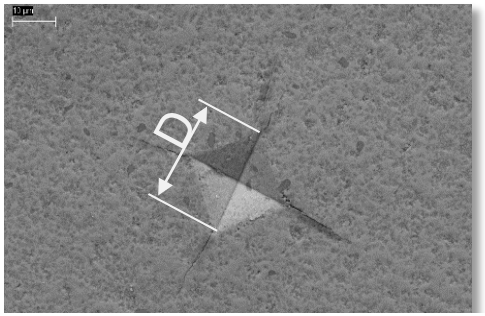
Modulus of rupture

$$MOR = \frac{3FL}{2bd^2}$$

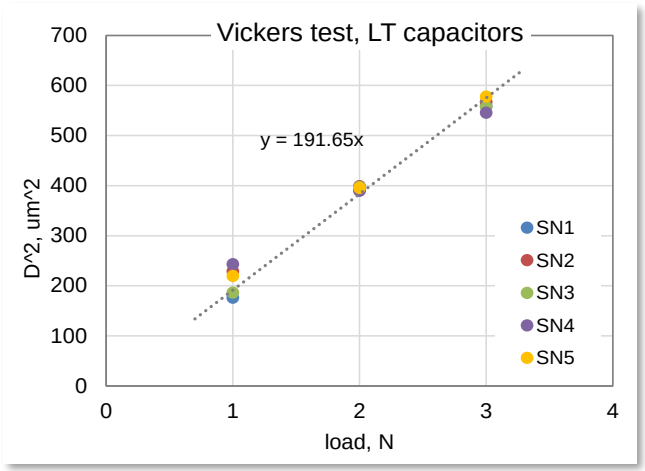


- ✓ No effect of possible flaws but surface cracks reduce MOR.
- ✓ Smaller size MLCCs have greater strength – Benefits of BMEs.
- ✓ No substantial difference between BME and PME capacitors.
- ✓ Variations of MOR values from lot to lot might exceed 50%.
- ✓ The test can be used for relatively large (≥1206) parts.
- ✓ Same size capacitors can be used for comparative analysis.

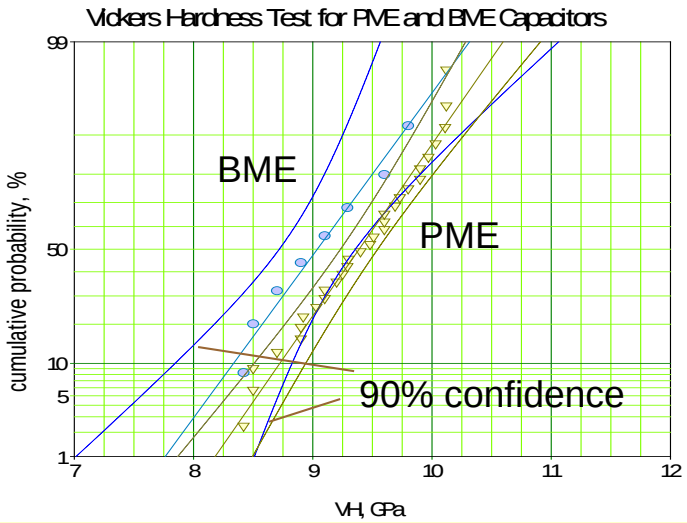
Vickers Hardness



- Hardness is a resistance to indentation.
- Testing is specified in ASTM C1327-15 (2015)



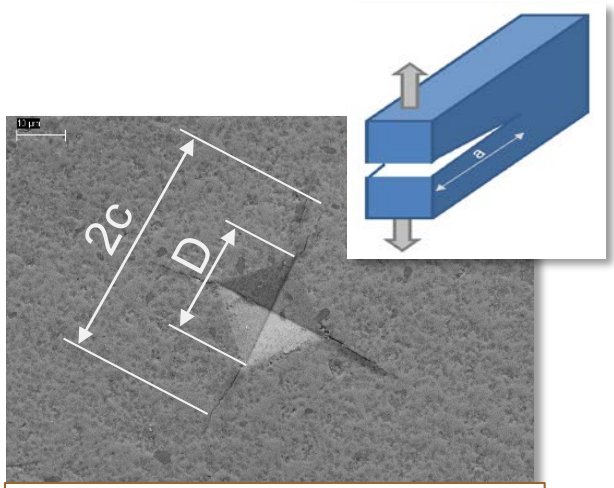
$$VH = \frac{1.854 \times P}{D^2}$$

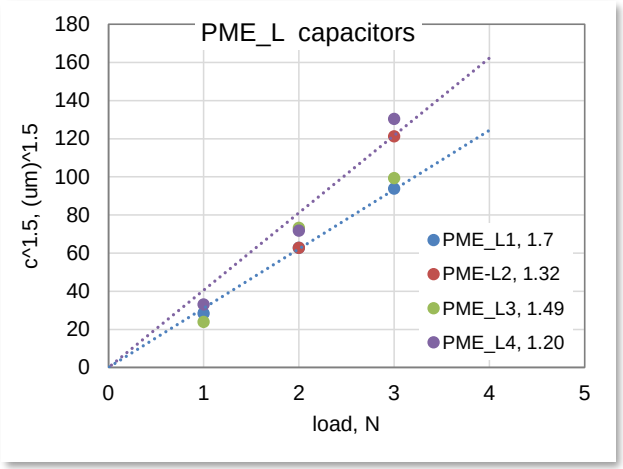


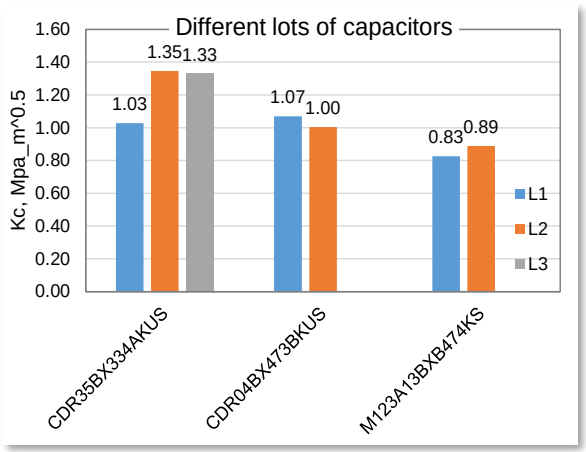
- ✓ In-situ VH measurements are possible using MLCCs with relatively thick cover plates. *P* should be low so the depth of the indentation is < 2x the thickness of the cover plate.
- ✓ No correlation between strength and VH for ceramic materials.
- ✓ No significant difference between PME and BME capacitors.
- ✓ Reduction of errors might allow for revealing differences in lots.

Indentation Fracture Test

- Fracture Toughness: the ability of a material to withstand stresses in the presence of cracks.
- IFT technique is the most controversial.







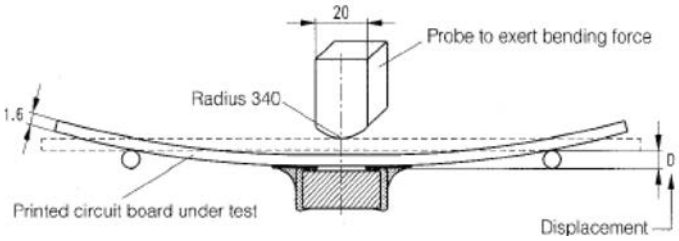
$$IFT = \xi_{R\_M}\left(\frac{E}{VH}\right)^{0.5}\left(\frac{P}{c^{1.5}}\right)$$

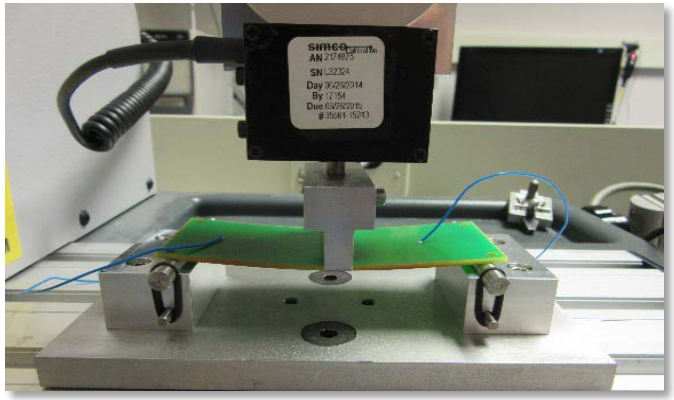
	PME BX	PME BP	BME X7R
IFT_{avr}	1.08	1.46	0.95
STD	0.20	0.19	0.23
N	12	2	6

- ✓ Test results depend on environments and time of exposure.
- ✓ IFT might be useful for selecting parts for manual soldering, but more work is necessary to reduce errors and select criteria.
- ✓ No significant difference between PME and BME capacitors.

Board Flex Testing

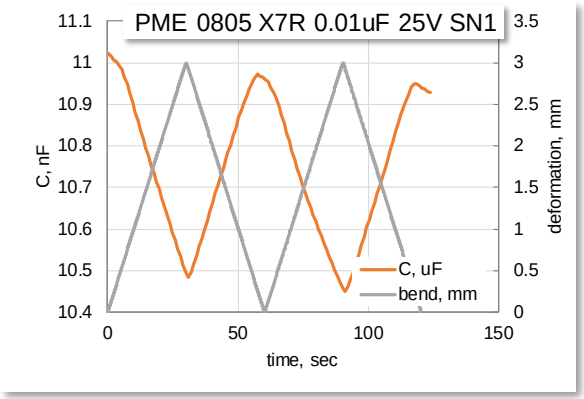
- AEC-Q200-005 specifies conditions and the size of the test board. "A failure is when a part cracks or causes a change in the parametric being monitored."
- M32535 allows for multi-chip boards.
  Failure criteria: *C* >+/-10% at δ = 2 mm.
- Factors affecting test results:
  - Orientation of the component;
  - Attachment with Ag-epoxy absorbs stress;
  - Solder fillet height, and thickness under the chip;
  - Solder type (less cracking for Pb-free alloys)
  - MLCC material (X7R weaker than COG)
  - Larger chips experience greater stress and have greater susceptibility to cracking.

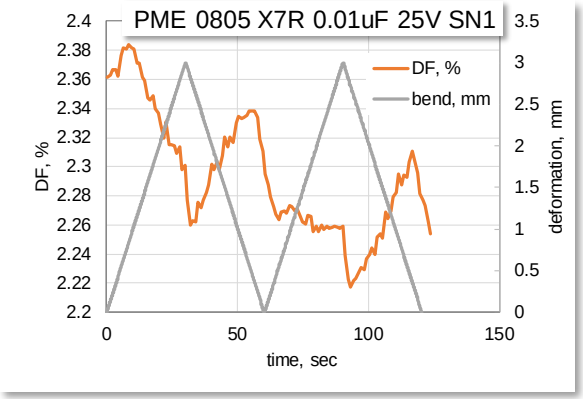


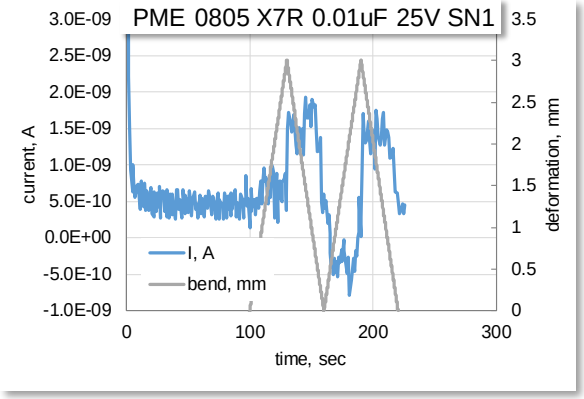


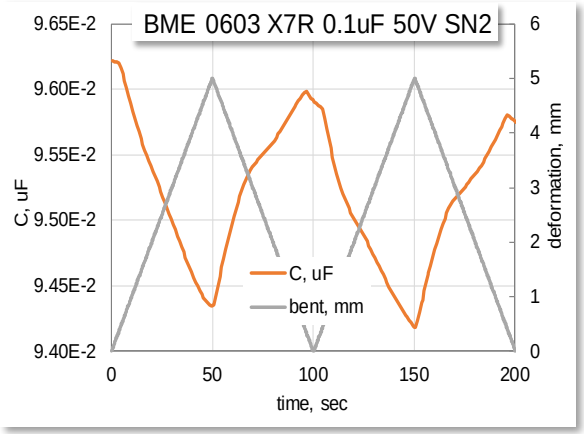
- ✓ This test is widely used to address cracking during de-panelization.
- ✓ Results are affected by variety of factors.
- ✓ Conditions for using multi-chip boards need additional analysis.

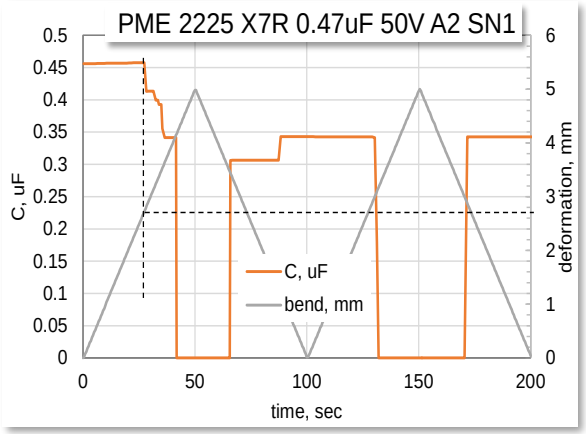
Board Flex Testing, Cont'd

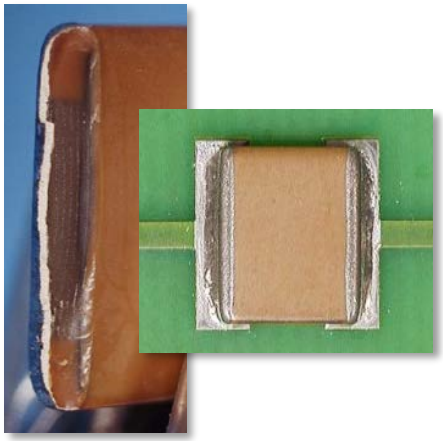






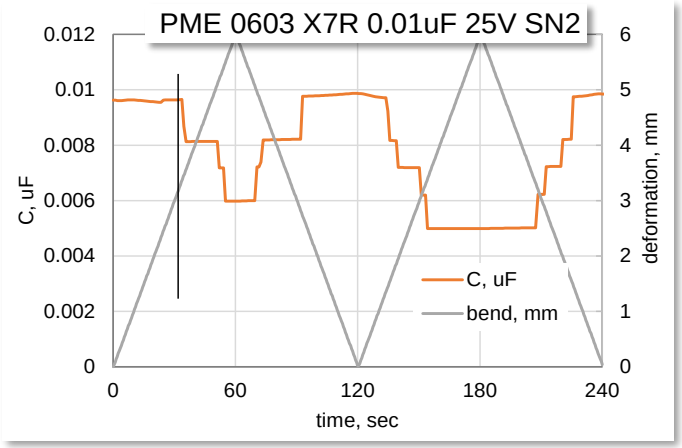


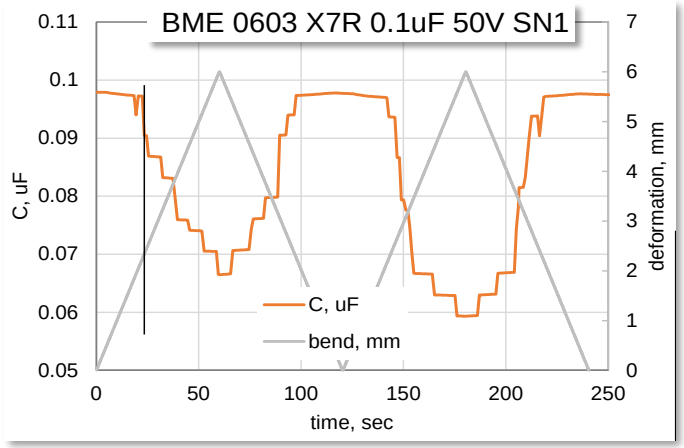


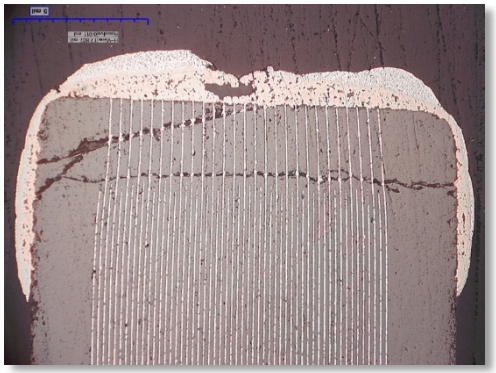


- ✓ Mechanical stresses affect characteristics of class II capacitors.
- ✓ Deviations of ε can change C during flex testing up to a few %.
- ✓ Variations of C might be reversible even in the presence of cracks.

Board Flex Testing, Cont'd



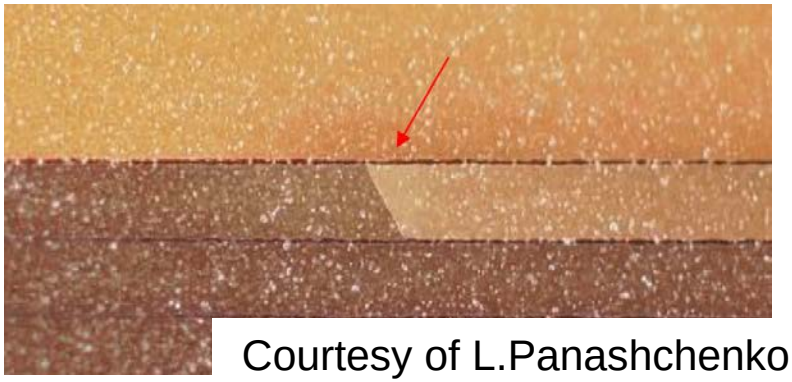


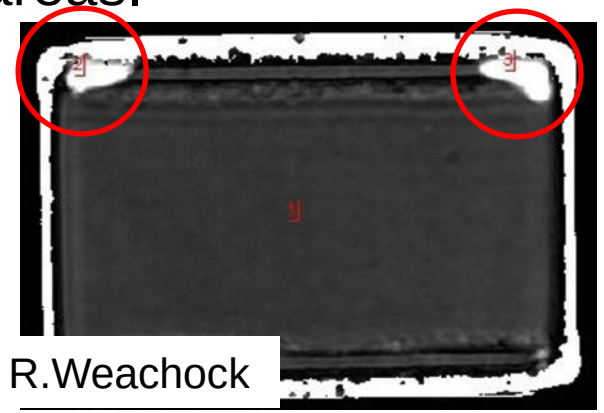


- ✓Variations of capacitance having cracks with load are reversible.
- ✓Degradation of *C* by steps indicates partial separation of electrodes.
- ✓Distributions of δ_{cr} ($0.9C_{init}$) might be more effective for assessment of the vulnerability to cracking compared to 2 mm pass-fail criteria.
- ✓No substantial difference in the flex cracking between PME and BME capacitors.
- ✓A smaller size of BME compared to similar value PME capacitors makes BME less vulnerable to flex cracking.

A History Case

- On-orbit anomalies after months of operation were attributed to excessive leakage currents in CDR35 capacitors.
- The parts were soldered manually and suspected of having cracks.
- Testing of a spare unit on the ground also showed increasing leakage currents after several weeks of operation.
- FA: the failure was due to delaminations and cracking in the part.
- No external cracks on the failed lot were observed.
- Acoustic microscopy showed that a substantial proportion of parts had delaminations at the termination areas.



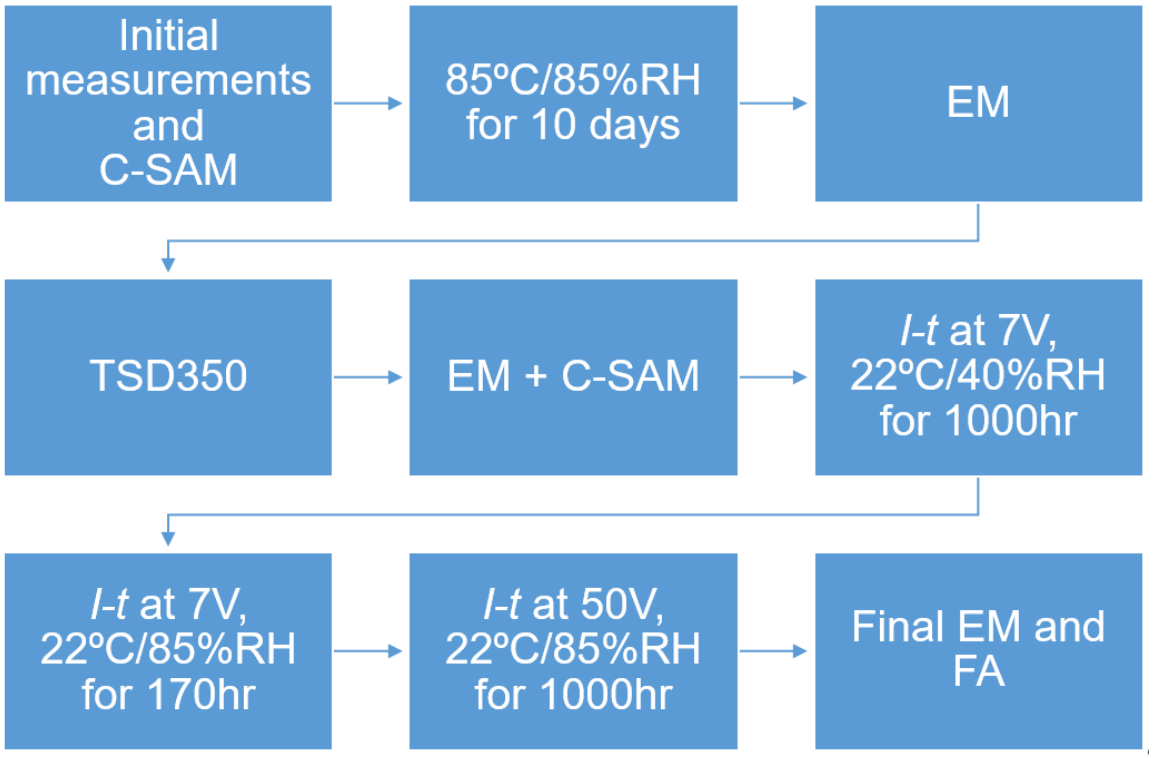


Courtesy of L.Panashchenko and R.Weachock

A History Case. Test Plan.

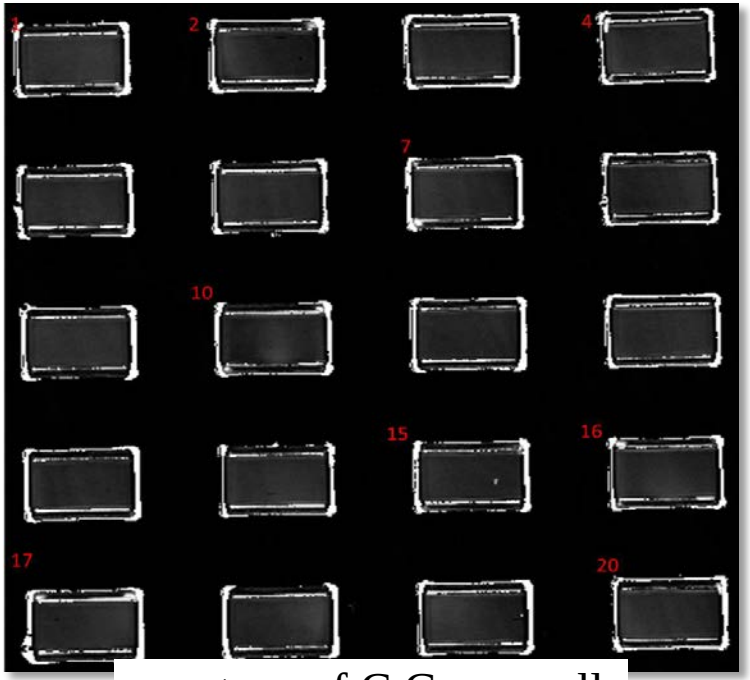
- To check whether the flight lot has high susceptibility to cracking and to identify techniques for assessment of the robustness of parts to manual soldering, 20 capacitors from the flight lot (lot A) and a reference lot (lot C) were tested in parallel.

  - Before stress testing the parts were characterized by mechanical, electrical and acoustic (C-SAM) tests.
  - Terminal solder dip testing (TSD350) was used to simulate manual soldering stresses.
  - Leakage currents were monitored with time at different voltages and environmental conditions.

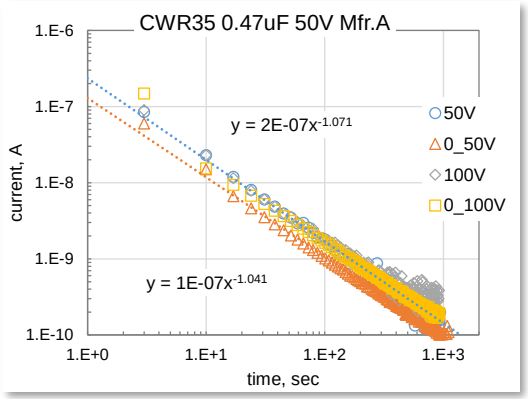


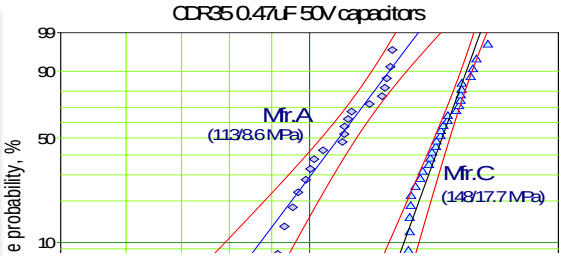
A History Case. Initial Characteristics.

- Optical examination: no anomalies.
- EDS: similar composition of ceramics.
- C_SAM: no defects in the lot C and corner delaminations in lot A.
- No substantial difference in distributions of C, DF and IR between the lots.
- Both lots had DCL at 2VR <10^{-10} A.
- VH and IFT did not reveal significant difference. However, the flexural strength was greater for lot C.



courtesy of C.Greenwell



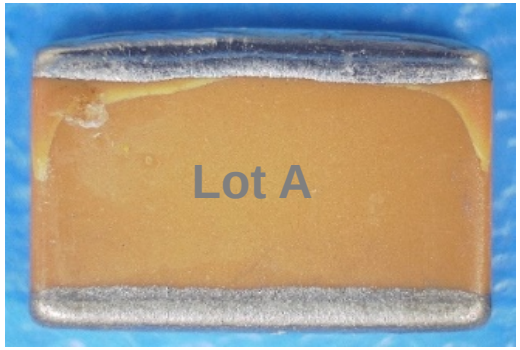


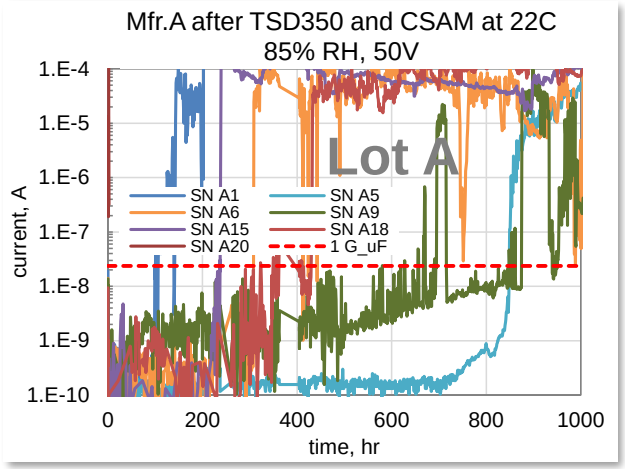
✓Some difference between lots was revealed by acoustic microscopy and flexural strength testing.

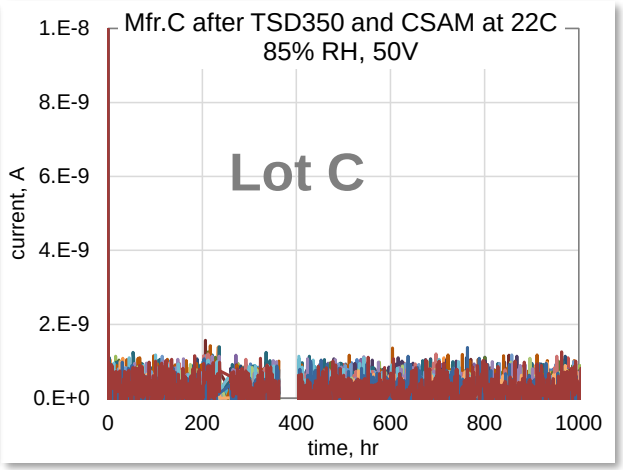
A History Case. Effect of TSD350.

- 20 samples were subjected to 3 cycles of TSD at 350 ºC

	visual	C-SAM	EM	1000hr at 50V, 22ºC/85%RH
Lot A	20/20	18/20	1/20	6/20
Lot C	1/20	0/20	0/20	0/20



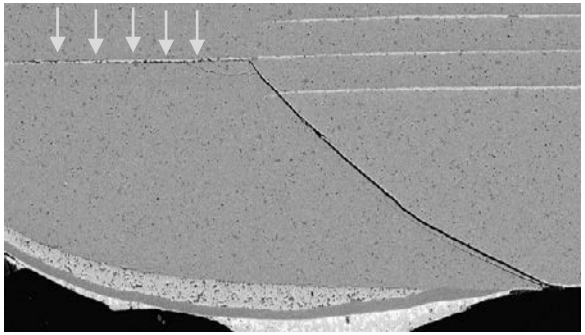




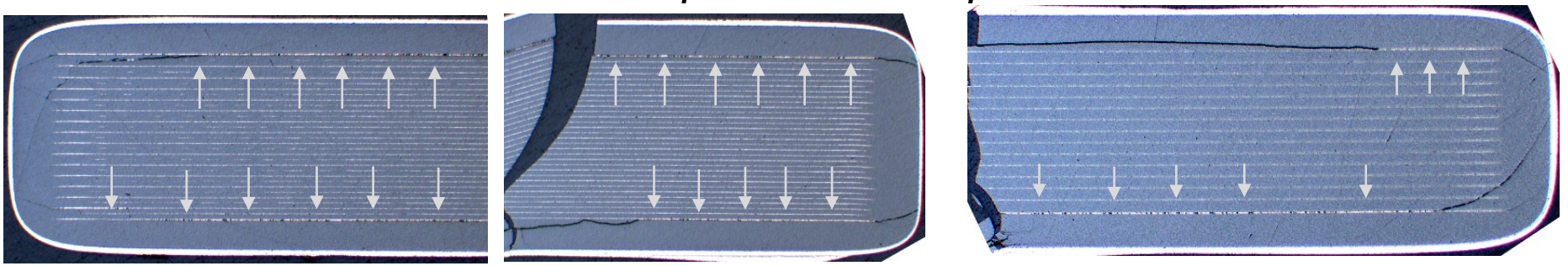
✓ Two lots had a substantially different propensity to cracking and electrical failures after manual soldering simulations.

A History Case. Failure Analysis.

- Cracks in lot A started from the surface and continued as metal/ceramic delamination.
- To evaluate interaction of cracks with delaminations, virgin and post-TSD samples were fractured in the middle.
- No delaminations on virgin samples from lot A and on both virgin and post-TSD samples from lot C.



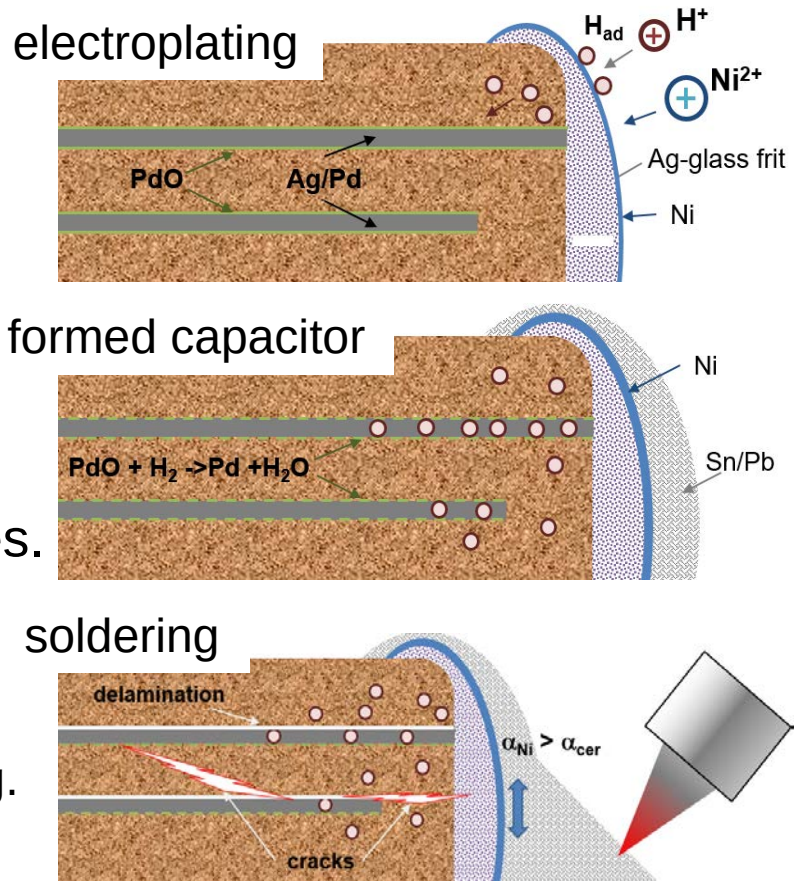
Fractured post-TSD samples



✓TSD testing and fracturing resulted in delaminations located mostly at electrodes close to the surface of capacitors.

A History Case. Failure Mechanism.

- Probability of failures after manual soldering was increased due to the presence of delaminations.
- Corner location indicates that delaminations might be due to formation of terminals.
- Reasons for corner delaminations [*]:
  - Thick Ni layers increase mechanical stresses.
  - Generation of H_2 during electroplating:
    - Decreases fracture toughness of ceramics;
    - Removes PdO barrier on Ag/Pd electrodes, weakens the interface and facilitates ECM of Ag.
    - Fast evolution of H_2 might cause pop-corning during soldering.



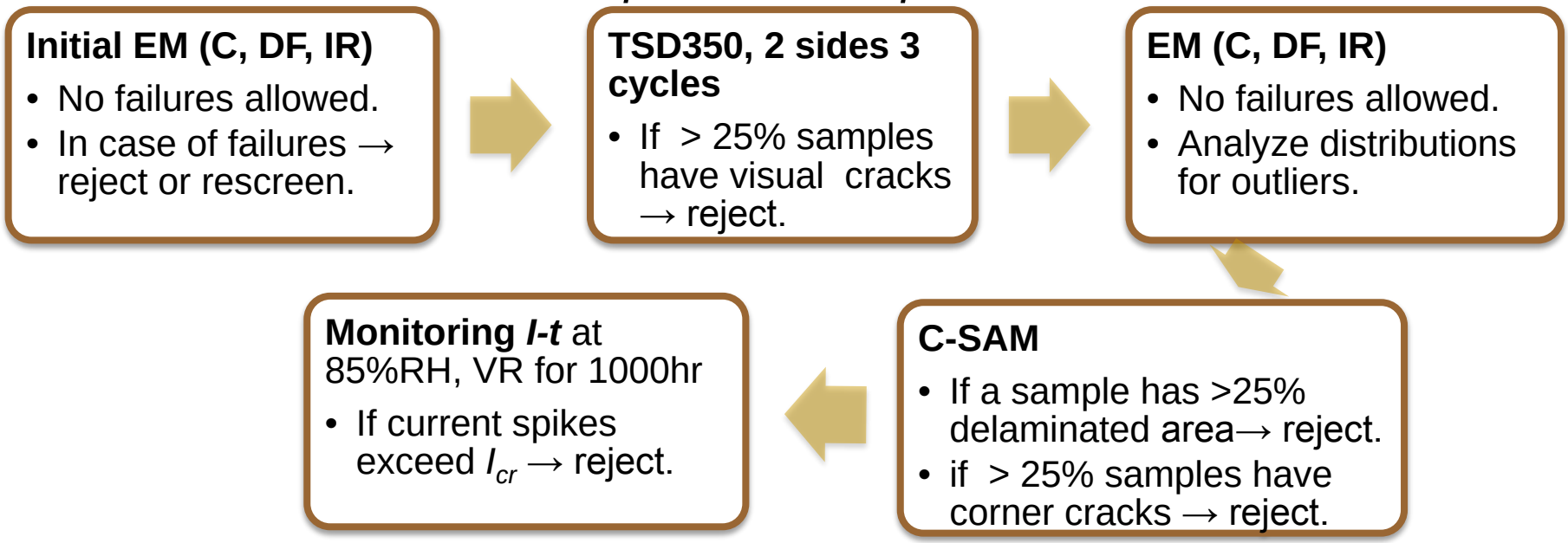
[*] "Susceptibility to Cracking of Different Lots of CDR35 Capacitors,", NEPP report2017, https://nepp.nasa.gov/files/29210/NEPP-TR-2018-Teverovsky-CDR35-Capacitors-TN52049.pdf

✓ Cracking and delaminations caused by electroplating occur more often with PME than with BME capacitors.

Resistance to Manual Soldering Test

- None of the tests provides reliable information regarding the susceptibility to cracking, but some test have better sensitivity.

Example of test sequence



- ✓ A combination of TSD350, C-SAM, EM, and humidity tests can be used to select parts more robust to manual soldering.
- ✓ Depending on criticality some tests can be skipped or replaced.

Conclusions

- In-situ mechanical testing of MLCCs, and the flexural strength in particular, can reveal lot-to-lot variations.
- Different lots of MLCCs do have different susceptibility to cracking and failures caused by manual soldering.
- No substantial difference between mechanical characteristics of PME and BME capacitors.
- Capacitors with cracks can pass ground phase testing, but fail during the mission.
- Combination of TSD350, C-SAM and electrical testing can be used to mitigate the risk of failures.
- Due to a smaller size and different degradation mechanisms, BME capacitors have a lesser probability of failures caused by manual soldering compared to PME parts. However, more problems might be expected with small (≤0603) size MLCCs.