National Aeronautics
and Space Administration

Capacitor Test, Evaluation, and Modeling within NEPP.

"Why Ceramic Capacitors Fracture during Manual Soldering and How to Avoid Failures".

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**work performed for NASA Goddard Space Flight Center,
Parts, Packaging, and Assembly Technologies Office,
Code 562**

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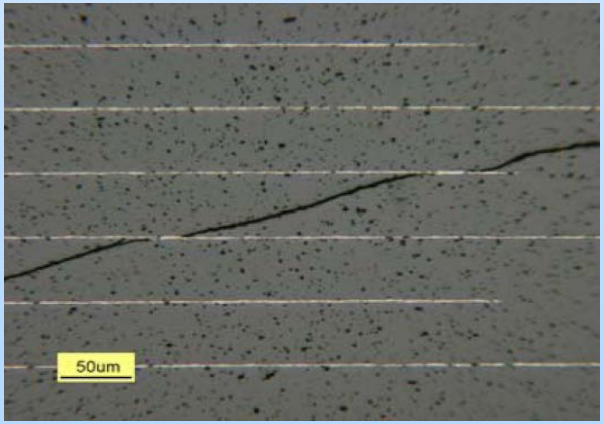
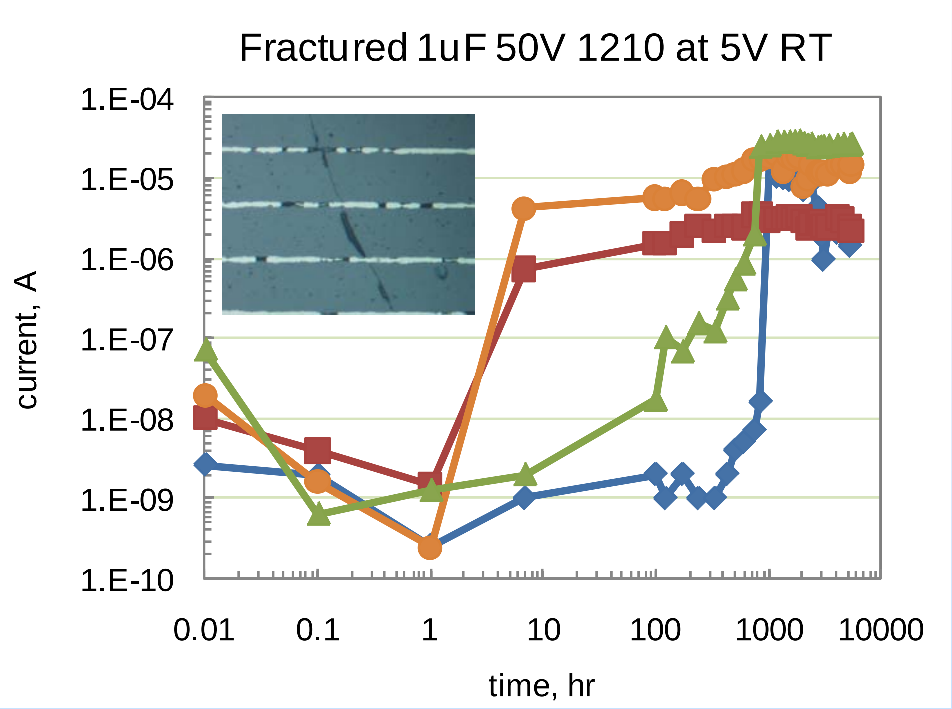
Outline

- Why MLCCs crack during manual soldering? Workmanship and parts issues.
- Do existing qualification requirements assure crack-free soldering?
  - MIL-spec Thermal Shock (TS) testing.
  - MIL-spec Resistance to Soldering Heat (RSH) test.
- What test can assure reliable soldering?
  - Mechanical characteristics of ceramics.
  - Comparison of three TS techniques: LND, TSD, and IWT.
- Simulation of TS conditions.
- Conclusion/recommendations.
- NEPP plans for FY11/12.



Background and Purpose

- ❑ Cracking in MLCCs is an old problem, goes back to 1970s.
- ❑ Crack as a time bomb.
- ❑ Derating does not help.
- ❑ "Brittle ceramic" + "soldering-induced thermo-mechanical stress" = crack?
- ❑ The problem will stay with us, but it can be mitigated.

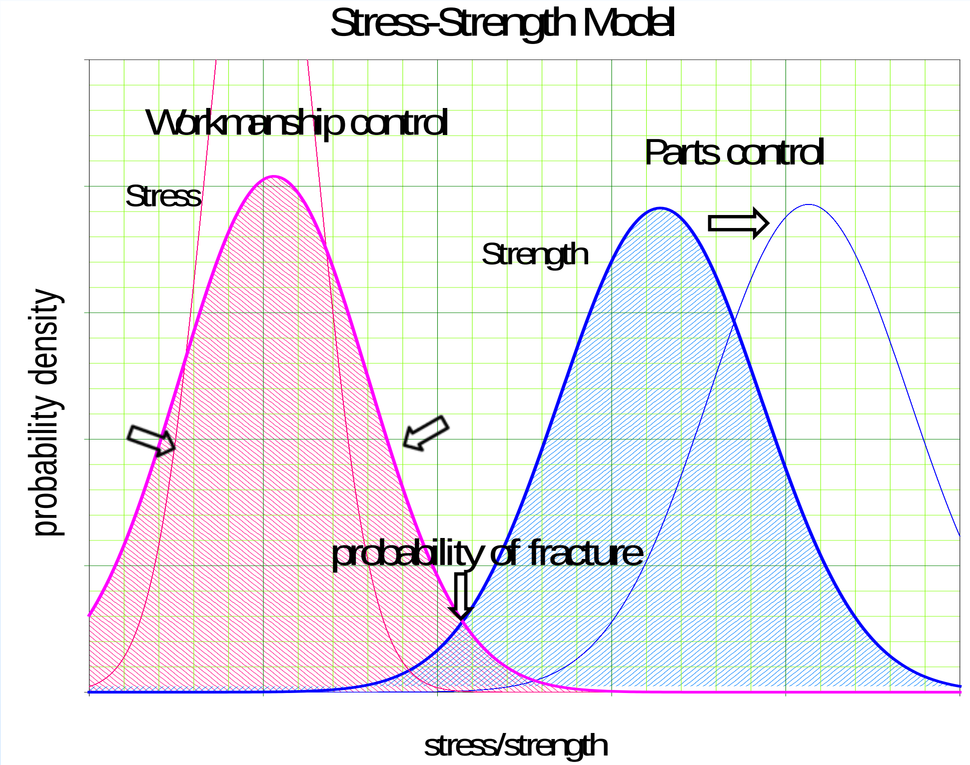


Purpose:

- ❑ Better understand the reasons of fracturing of large MLCCs under manual-soldering-induced thermal shock conditions;
- ❑ Suggest mitigating measures.

Probability of MLCCs Cracking

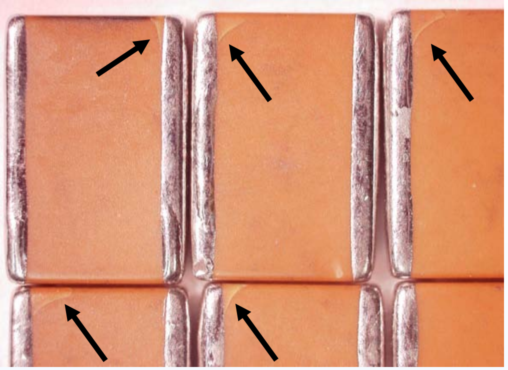
Failure criteria: $\sigma > S$



Probability of failure:

$$P = \int_{-\infty}^{+\infty} f(\sigma) \times \left[\int_{-\infty}^{\sigma} f(S) dS \right] d\sigma$$

- Assuring that the level of soldering stresses is at the acceptable level is a workmanship issue and should be achieved by reinforcing compliance with the guidelines.
- Assuring robustness to soldering stresses is a part issue and should be achieved by adequate qualification tests.

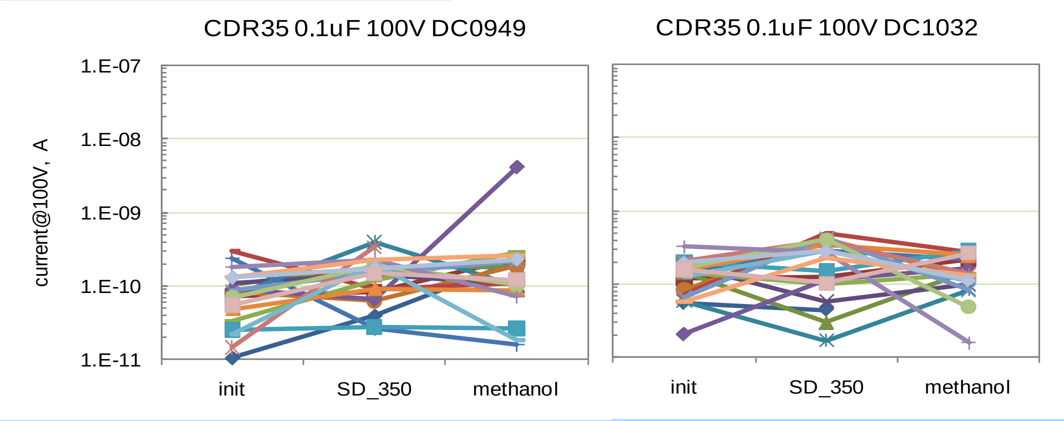


Can Parts and Workmanship Issues be Discriminated?

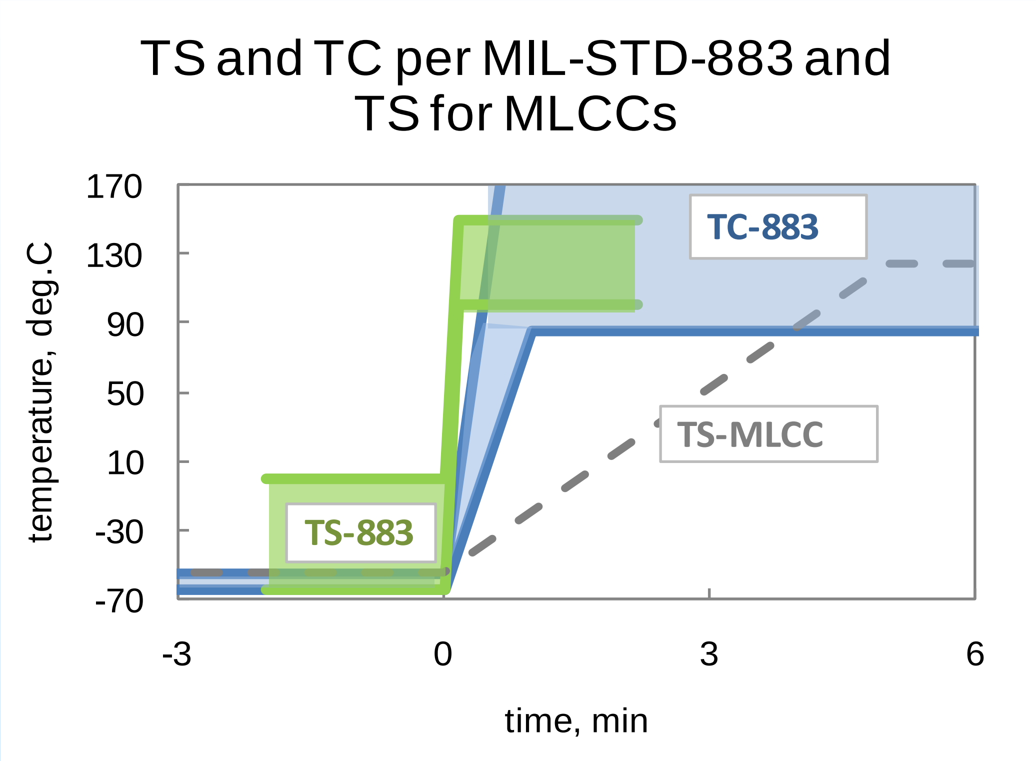
- A lot of 1825 X7R capacitors had multiple fractures after manual soldering. The board was reworked using another lot of capacitors, and no fracturing was observed.
- Was a technician more careful with the replacement lot, or two lots had different susceptibility to cracking?

LDC	VH, GPa	STD VH	K1C, $MPa*m^{0.5}$	STD K1C
DC0949	12.7	1.98	1.16	0.23
DC1032	10.4	1.42	1.10	0.09

- Mechanical and electrical characteristics of two lots were similar.
- TSD test showed 55% fracturing for DC0949 and 0% for DC1032.
- One part in DC0942 failed post_TSD methanol test.
- This is a part issue.



Thermal Shock Testing That Does not Create TS Conditions



MIL-883

TC, TM1010: air to air;

TS, TM1011: liquid to liquid

MIL-PRF-55681 ***(chip)***

TS : air to air

- Difference between TC and TS:
  - results of TC depend on $\Delta T = T_{max} - T_{min}$ and CTE mismatch;
  - results of TS depend on temperature gradient across the part.
- TS conditions for MLCCs are less stressful than TC per MIL-883.
- Were any failures of MLCCs due TS testing ever observed?

Thermal Shock Testing

Spec.	Part type	TS testing	Comments
MIL-PRF-55681	ER and non-ER chip capacitors.	Qual. inspection (TS and immersion): 18(1). Test cond. A (M202) but at 125C.	No TS during Gr. A insp. Qual: only 5c from -55C to +125C and 2 cycles of immersions from tap water at 65C into salty water at RT.
MIL-PRF-123	Capacitors for space and other high rel. applications.	Gr. A inspection: 20c. Qual. Inspection: 186 samples, 100 c. Gr.B insp.: 100c. cond. A but at 125C.	Qual: 100 cycles from -55C to +125C.

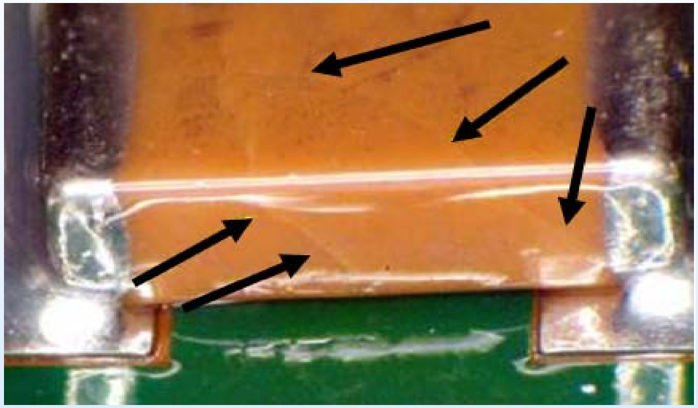
- Existing TS testing do not cause any significant thermo-mechanical stresses and does not simulate soldering conditions.
- MIL MLCCs cannot be used in hybrid microcircuits that require 100 TC between -65 ^{o}C and +150 ^{o}C without additional testing.

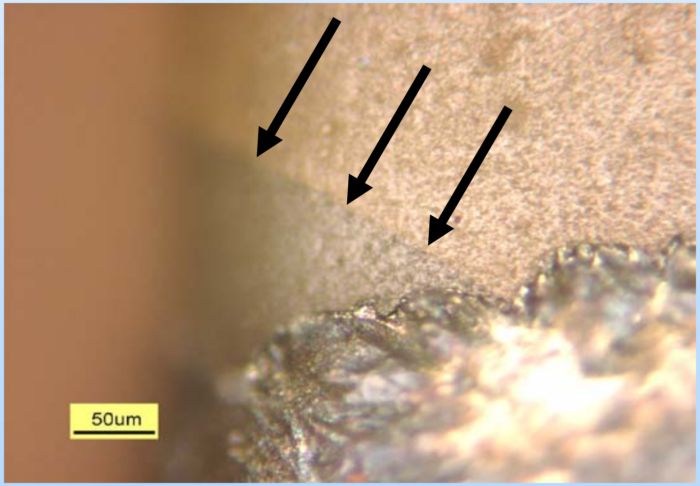
Resistance to Soldering Heat

Spec.	Part type	RSH test	Comments
MIL-PRF-55681	ER and non-ER chip capacitors.	QCI: 9(1) Test cond. J (M202) (convection reflow), except with only one heat cycle.	Precaution for mounting: "… will not be the cause of, nor contribute to, failure of any test for which it may be used". One cycle to 235°C.
MIL-PRF-123	Capacitors for space and other high rel. applications.	QCI: 12(1) Test cond. B: 2 times. Solder T=230°C, 5 sec.	Manufacturers are using this test at 260°C and higher

- Existing requirements mostly follow the guidelines for safe soldering conditions and are relaxed compared to MIL-STD-202.
- The test does not simulate possible worst case soldering conditions and is not sufficient to reveal potentially weak lots of capacitors.
- None of the MIL specs for capacitors uses soldering iron test per MIL-STD-202, TM210 (350C, soldering pad, 5 sec).

Parts Control to Assure Reliable Soldering of MLCCs



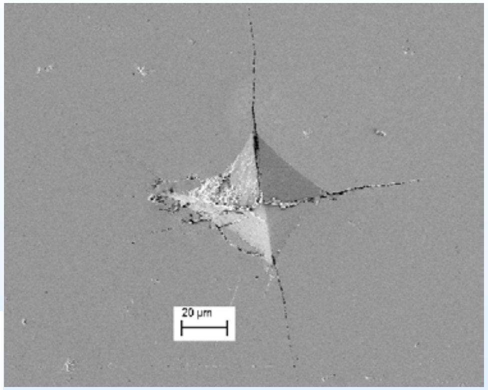


- MIL specifications for ceramic capacitors do not assure crack-free soldering.
- Likely for this reason manufacturers warn against hand soldering of large capacitors:
  "Never use soldering irons for parts with a case size of more than 1210"
  J. Maxwell
- Are there mechanical characteristics and/or test methods that might assure robust manual soldering of MLCCs?

Mechanical Characteristics of Ceramics

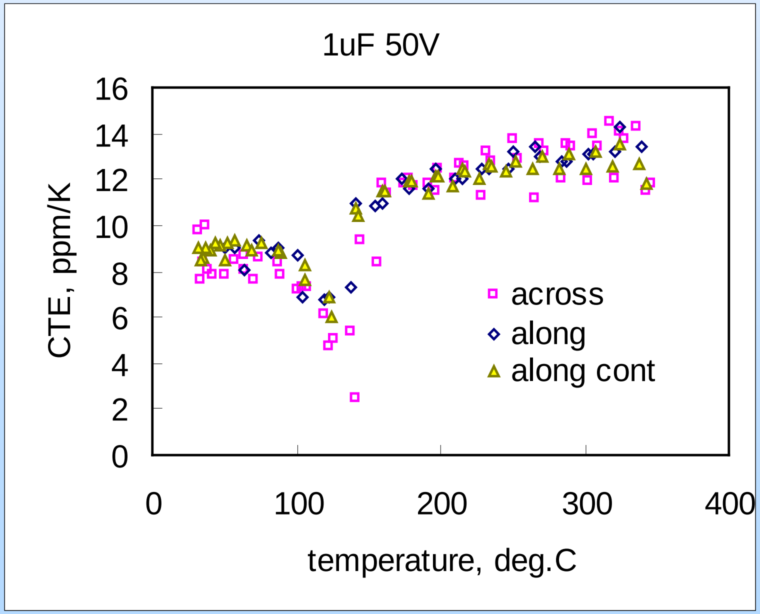
- Mechanical behavior of the parts was characterized by measurements of Vickers hardness, VH, fracture indention toughness, K1C, and CTE.

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



$$K_{1c} = \varsigma \left[\frac{E}{H} \right]^{0.5} \left[\frac{P}{c^{1.5}} \right]$$

- CTE values in X7R capacitors measured perpendicular to the plates were ~10% greater than along the plates.
- The anisotropy is likely due to built-in compressive stresses.
- Average CTE_{X1}= 9.6 at STD=1.2 and CTE_{X2}= 12.4 at STD=0.3

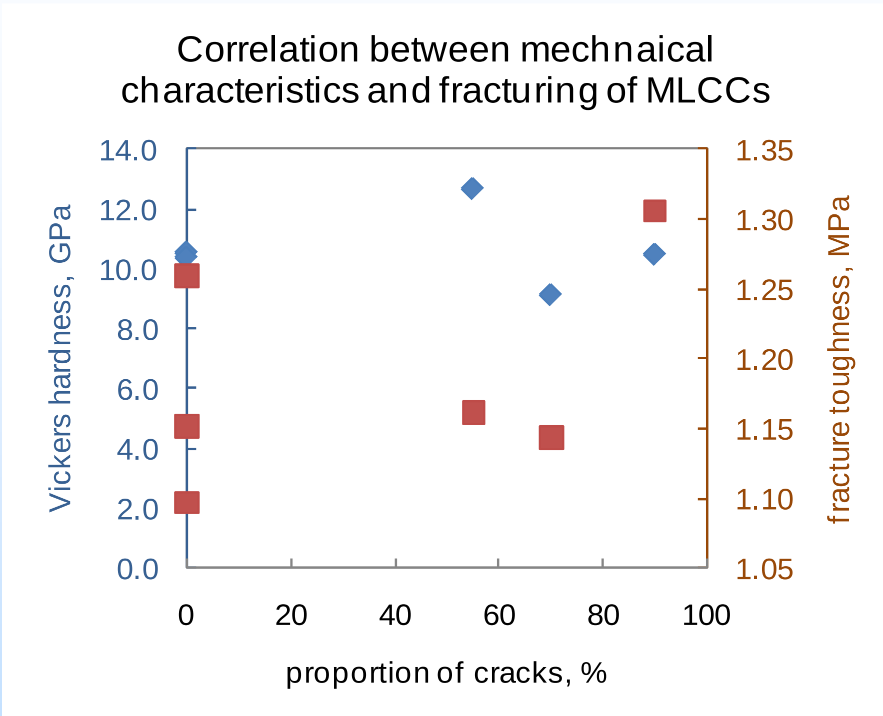


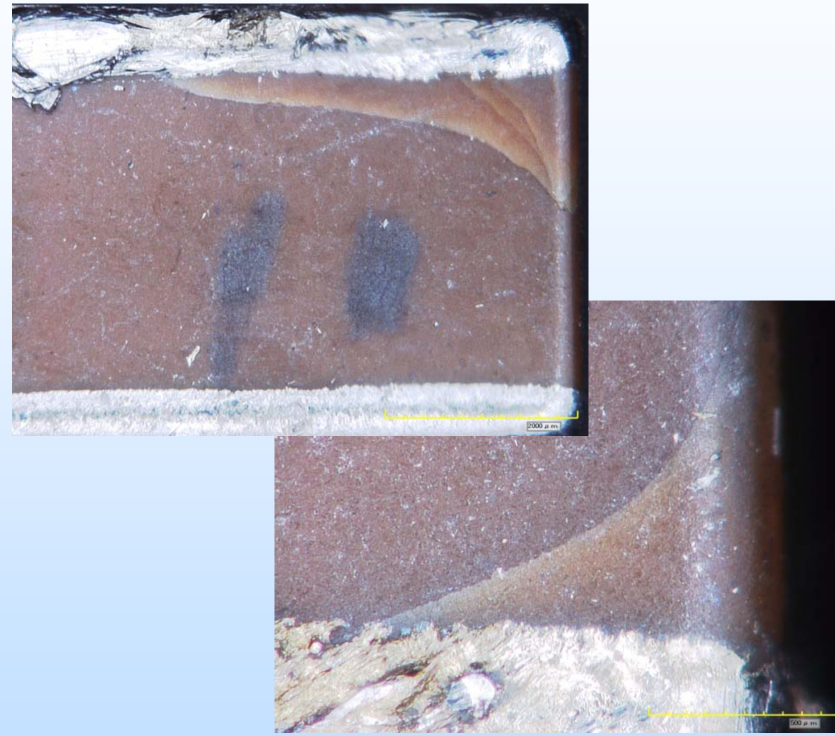
Mechanical Characteristics of MLCCs

Capacitor	HV, GPa	STD	K1C, MPa-m$^{0.5}$	STD
1.0μF, 50 V L1	9.5	1.7	0.91	0.07
100μF, 6.3V	10.6	1.6	1.55	0.09
2.2μF, 50 V	6.5	0.3	1.52	0.14
10μF, 50 V	10.4	1	1.06	0.13
47μF, 16 V	6.6	1.2	1.37	0.08
22nF, 50 V	8.8	0.2	2.81	0.32
22μF, 25 V	8.2	1	1.47	0.07
1.0μF, 50 V L2	9.2	0.9	1.14	0.18
1.0μF, 50 V L3	10.5	0.6	1.15	0.05
0.1μF, 100 V L1	10.5	2.2	1.26	0.27
0.1μF, 100 V L2	10.5	0.3	1.31	0.11
0.1μF, 100 V L3	12.7	2.0	1.16	0.23
0.1μF, 100 V L4	10.4	1.4	1.10	0.09

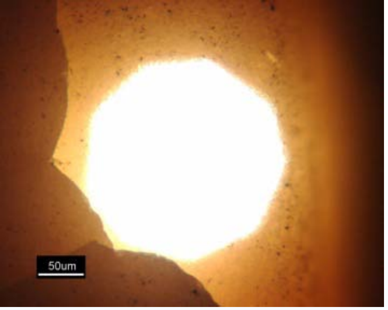
- Hardness of different types of capacitors varied from 6.5 GPa to 12.7 GPa and did not depend significantly on the type of materials used.
- Estimations of the fracture toughness showed that X7R dielectrics had K1C values in the range from 0.9 to 1.55 MPa-m$^{0.5}$, whereas capacitors with COG dielectric had a much larger value, 2.8 MPa-m$^{0.5}$.
- TS robustness of the parts was expected to increase in the sequence 1μF 50V ≈ 10μF 50V < 47μF 16V < 22μF 25V ≈ 2.2μF 50V ≈ 100μF 6V << 22nF 50V.

Correlation between Mechanical Characteristics and TS Testing





- Different lots had statistically different proportion of cracks after thermal shock testing (TSD-350).
- No correlation between the probability of fracturing and hardness or fracture toughness.



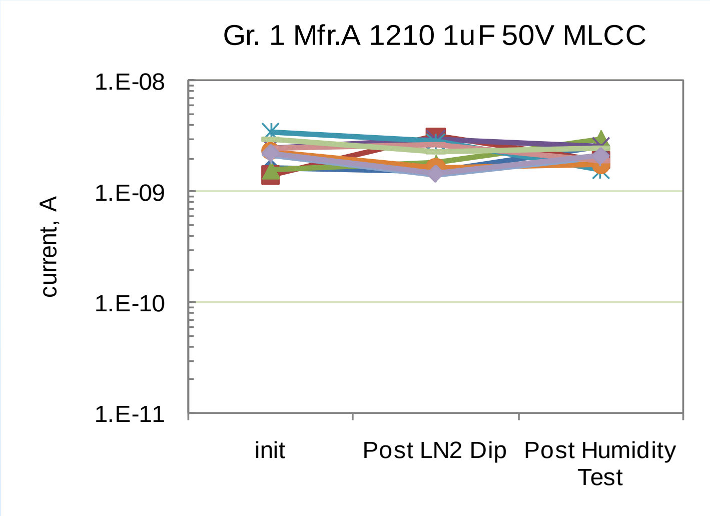
Thermal Shock Methods that Create TS Conditions

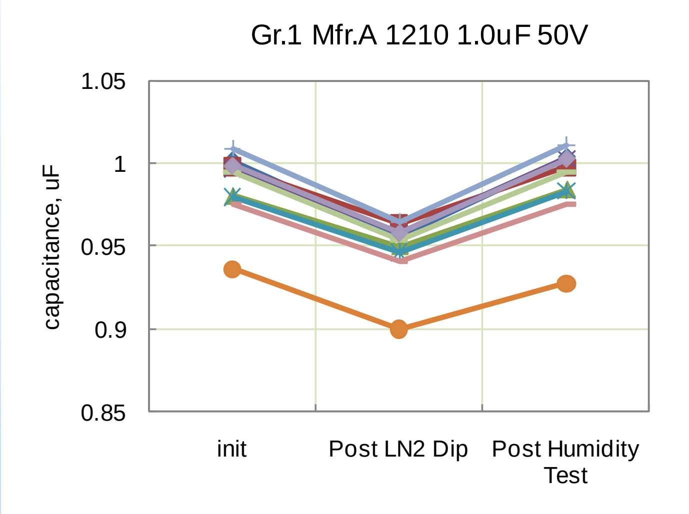
Technique	Conditions	Parts	ΔT
Terminal Solder Dip (TSD)	•Solder pot temperature 300 ºC, 325 ºC, 350 ºC. •Cooling in air for 3m. •Repeat 10 times	•13 lots from 3 Mfr •1uF 50V, X7R •Size from 1825 to 2225	275 ºC to 325 ºC
Ice Water Test (IWT)	•Preheat parts at 150 ºC to 225 ºC •Drop in water at 0 ºC	•14 part types from 4 Mfr •1uF 50V, 10uF 50V, and 0.1 uF 100V, X7R •Size from 0805 to 2225	150 ºC to 225 ºC
Liquid Nitrogen (LN) drop test	•Drop into a Dewar with LN	•4 lots of 1uF 50V, X7R •Size from 1210 to 2225	220 ºC

If ΔT is the most important parameter of TS testing, one can expect most failures during TSD test and least during IWT.

Liquid Nitrogen Drop Test

- 4 types of 1uF 50V capacitors: 1206, 1210, 2220, and 2225.
- AC and DC characteristics were measured at RT after LN drop and after 10 days at 85°C and 85% RH.

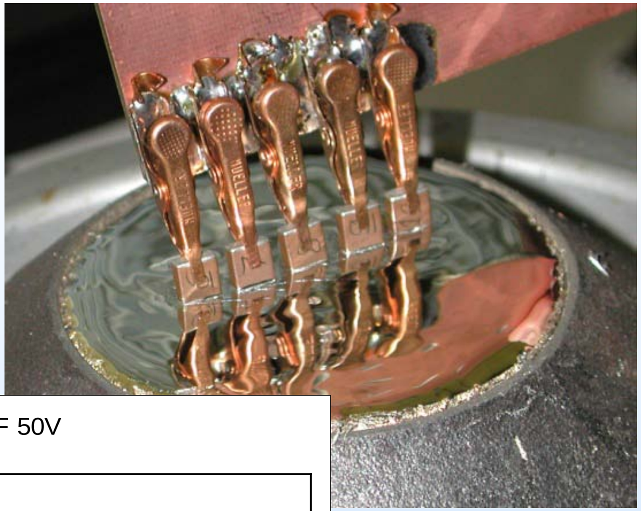


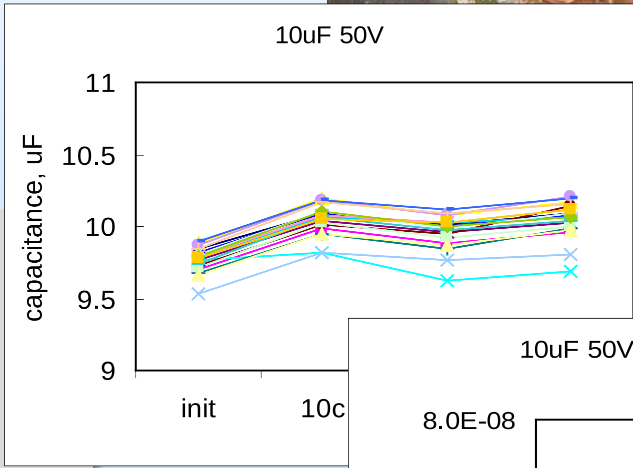


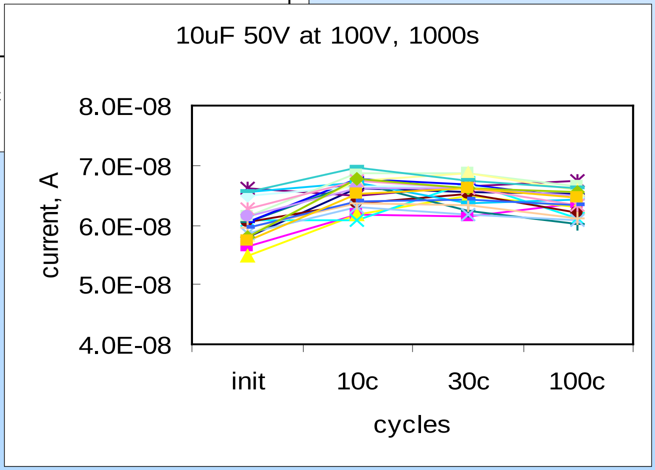
- No electrical failures or evidence of degradation.
- A few parts had shallow cracks that were limited to the margin area.
- Variations in capacitance indicate the effect of mechanical stresses.

Terminal Solder Dip Test, TSD_300

- Seven lots of 2220 MLCCs with thickness from 1 mm to 3.2 mm, 20 samples each, were subjected to the molten solder (300 ^{o}C) terminal dip test.
- AC and DC characteristics were measured after 10, 30, and 100 solder pot cycles.



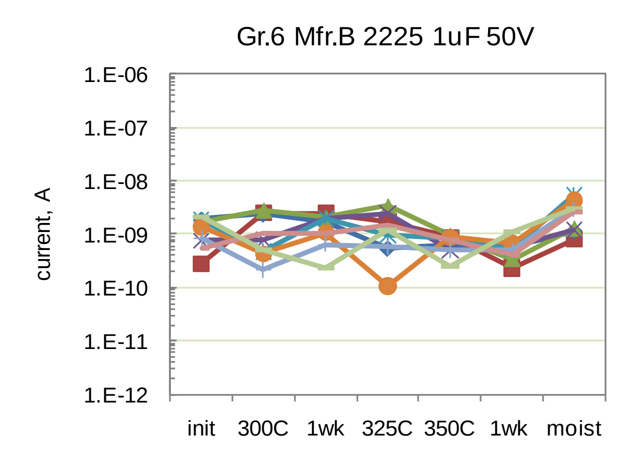


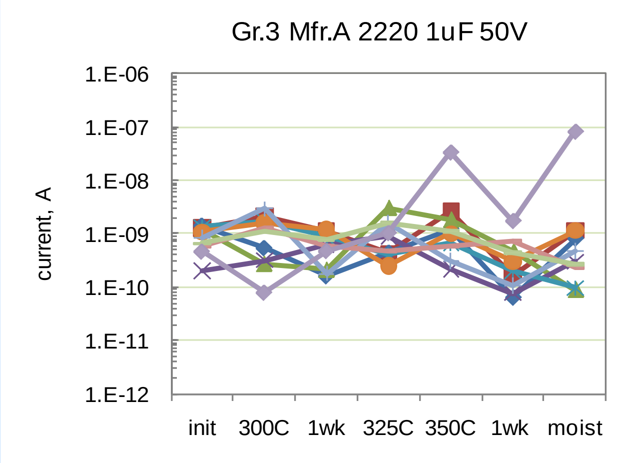


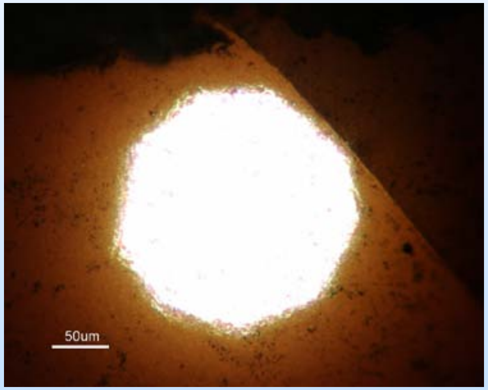
- No failures or significant parametric variations.
- Vicinal illumination microscopy revealed no cracking.
- Normal-quality lots can withstand TSD_300 without fracturing.

Terminal Solder Dip Test, TSD_350

- Six types of 2220 and 1825 capacitors were stressed by TSD at temperatures from 300 ^{o}C to 350 ^{o}C in 25 ^{o}C increments.
- Measurements of AC and DC characteristics, and vicinal illumination microscopy were used to reveal cracks.



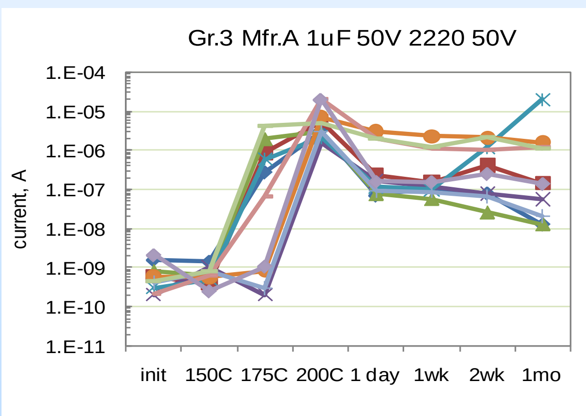


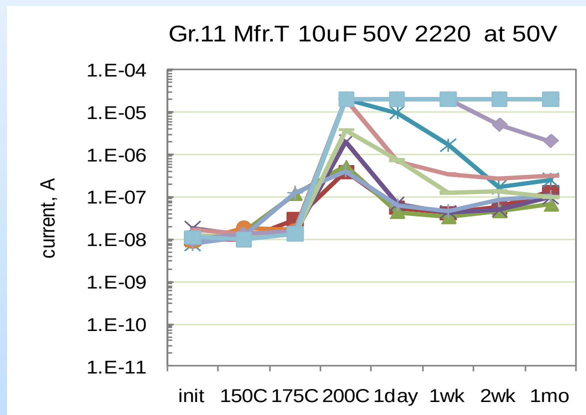


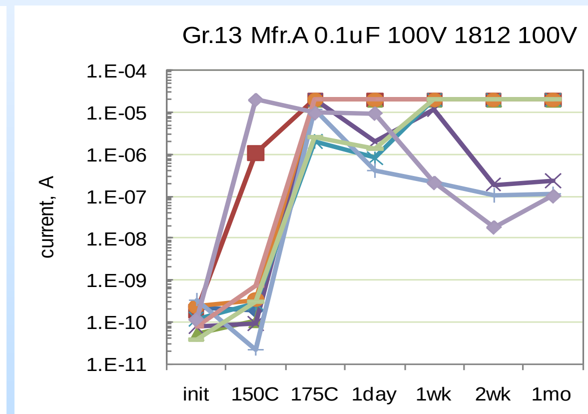
- After TSD at 350 ^{o}C one out of ten samples in in one out of 7 groups had increased DCL.
- Three out of six lots had no fractures.
- Large-size capacitors (2220 and 1825) might have high resistance against thermal stresses developed during soldering.

Ice Water Test

- Capacitors preheated to T varying from 150 to 225 ºC are rapidly quenched in a bath with ice water.
- Preheat temperature that results in substantial DCL increase is considered as critical, ΔT_c.
- Based on distribution of ΔT_c , average ΔT_c and STD were calculated to characterize TS resistance of the lot.







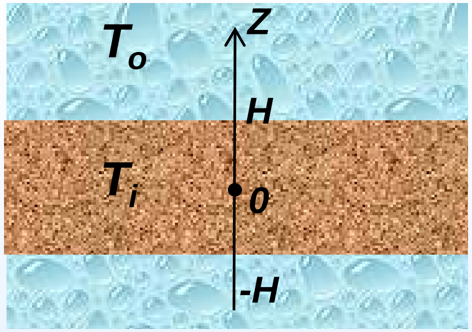
- Based on IWT of 16 lots of X7R capacitors: ΔT_{c_min} = 170 ºC and ΔT_{c_max} = 222.5 ºC at STD ~9.6 ºC.
- Calculated tensile strength is from 110 MPa to 200 MPa.
- The reproducibility of test results was good, below average STD.

Comparison of TS Test Results

Technique	ΔT	Result
Terminal Solder Dip (TSD)	275 ^oC to 325 ^oC	• None out of 200 parts from 13 lots had cracks or electrical failures at TSD_300. • Two out of 80 parts from 6 lots failed TSD_350 and samples in 3 lots had from 50% to 90% of “hot TS cracks".
Ice Water Test (IWT)	150 ^oC to 225 ^oC	• All 160 parts from 16 lots failed at ΔT below 225 ^oC. • All parts had “cold TS cracks”.
Liquid Nitrogen (LN) drop test	220 ^oC	• No electrical failures. • Samples in two out of 4 lots had from 20% to 90% of shallow cracks.

- ❑ ΔT is not the major factor affecting thermal shock test results.
- ❑ Results of TS testing are lot-related.

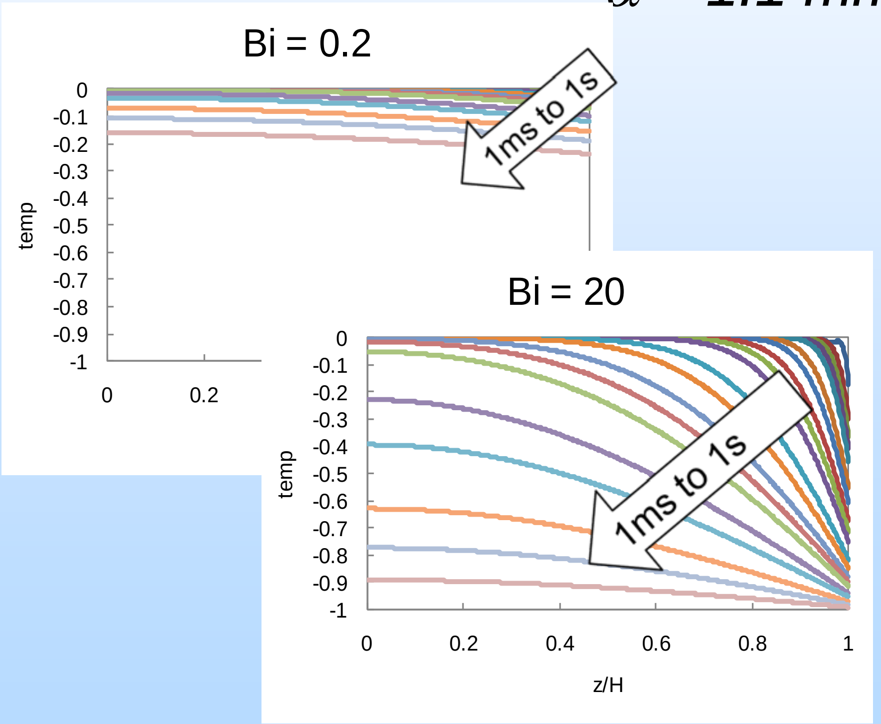
Modeling TS Conditions. T-distributions

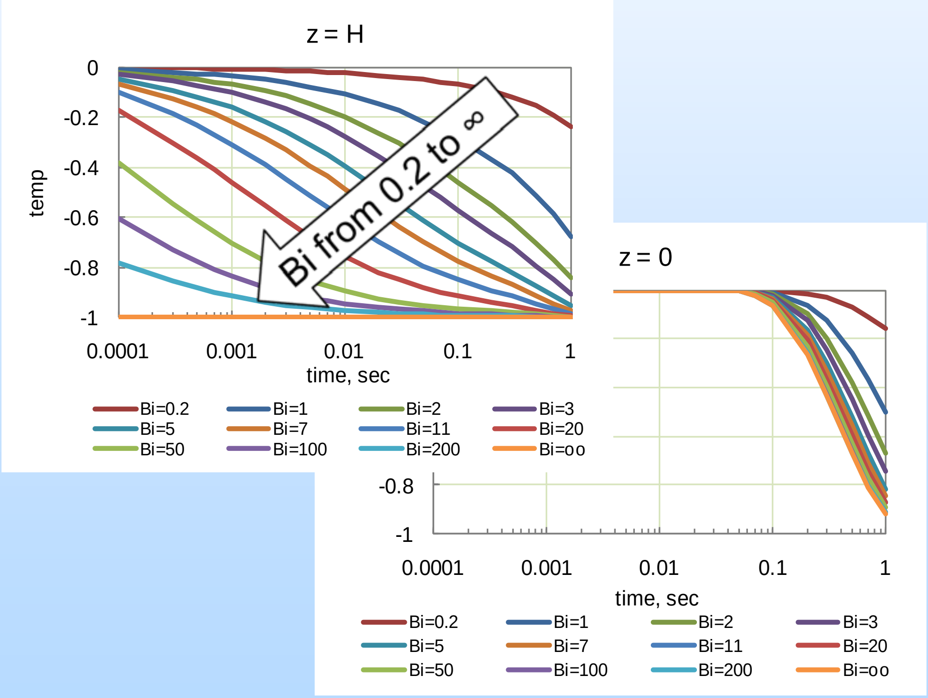


A ceramic plate of thickness *2H* at $T = T_i$ is immersed in media at $T = T_o$

$$\frac{\partial T}{\partial t} - \alpha \frac{\partial^2 T}{\partial z^2} = 0 \qquad \lambda \frac{\partial T}{\partial z} = -h \times \left(T_0 - T\right) \qquad Bi \equiv \frac{h \times H}{\lambda}$$

$\alpha = 1.1\ mm^2/sec,\ H = 1\ mm$





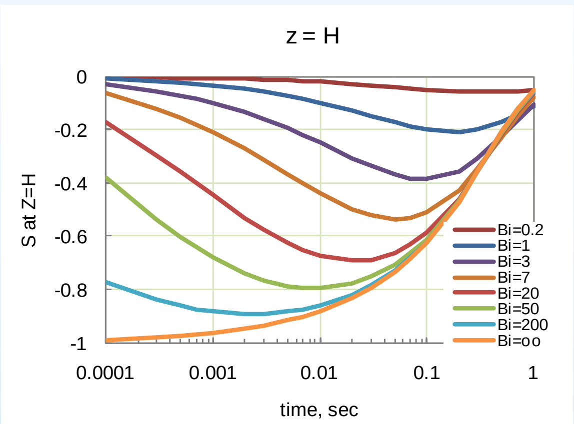
The rate of temperature variations is a strong function of *Bi*

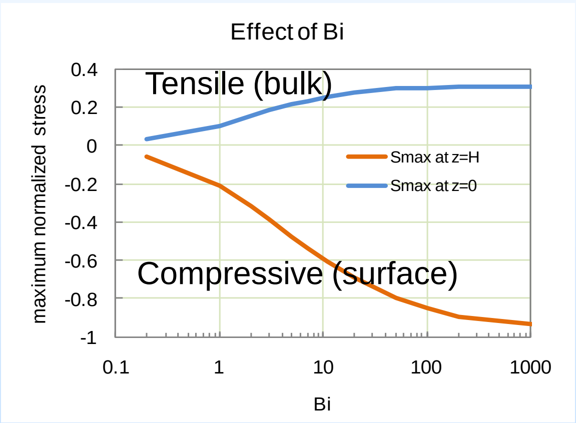
Modeling TS Stresses

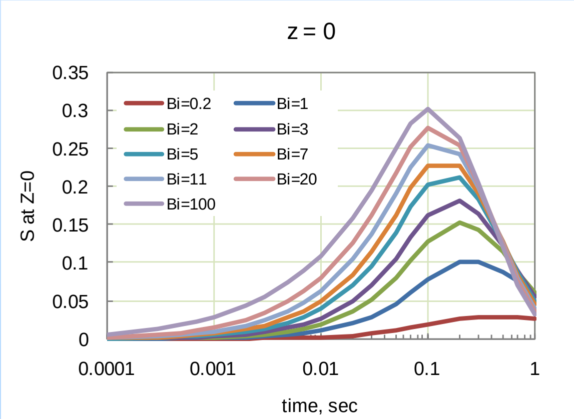
Stress distributions can be calculated based on T(z,t):

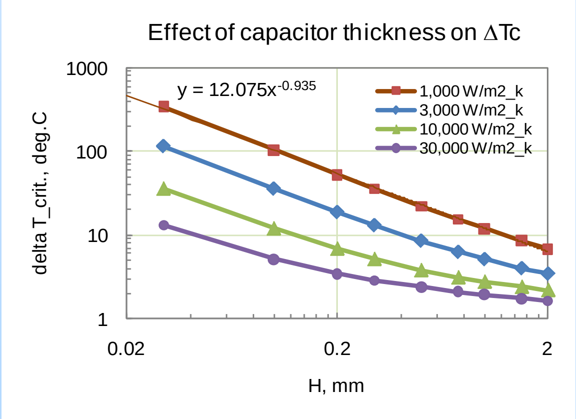
$$\sigma(z,t) = -\overline{E}\times\overline{\alpha}\left\{\left(T(z,t)-T_i\right)+\frac{1}{2H}\int_{-H}^{H}\left(T(z,t)-T_i\right)dz\right\}$$

$$\overline{\sigma} = \frac{\sigma(z,t)}{\sigma_{\max}} = \frac{\sigma(z,t)}{E\times\alpha\times(T_i-T_0)}$$



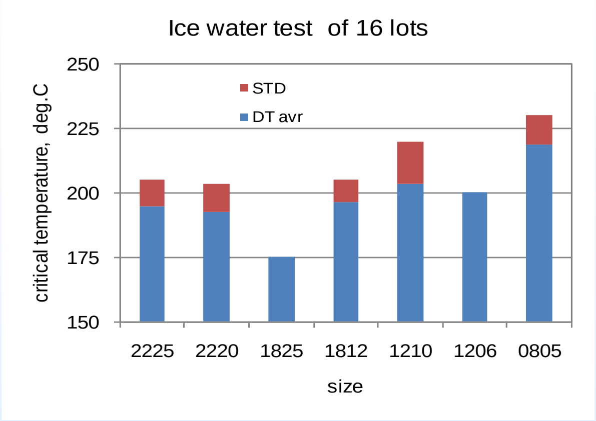


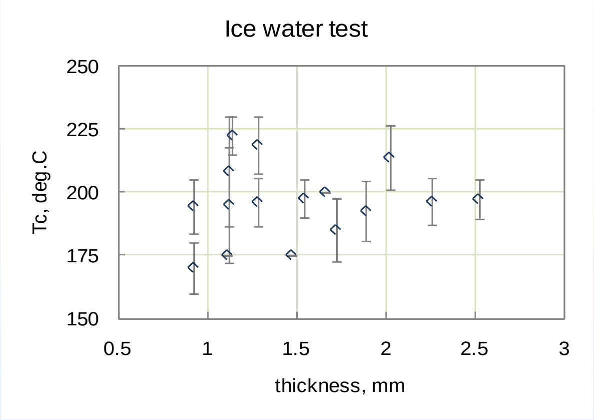


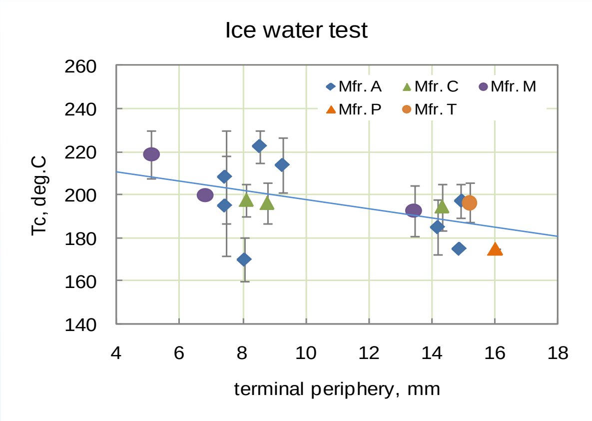


- The level of maximum stresses varies substantially with the heat transfer conditions.
- During hot TS maximum tensile stresses are much less than compressive.
- Cold TS is much more stressful than hot TS.
- Larger parts experience greater stresses during thermal shock testing.

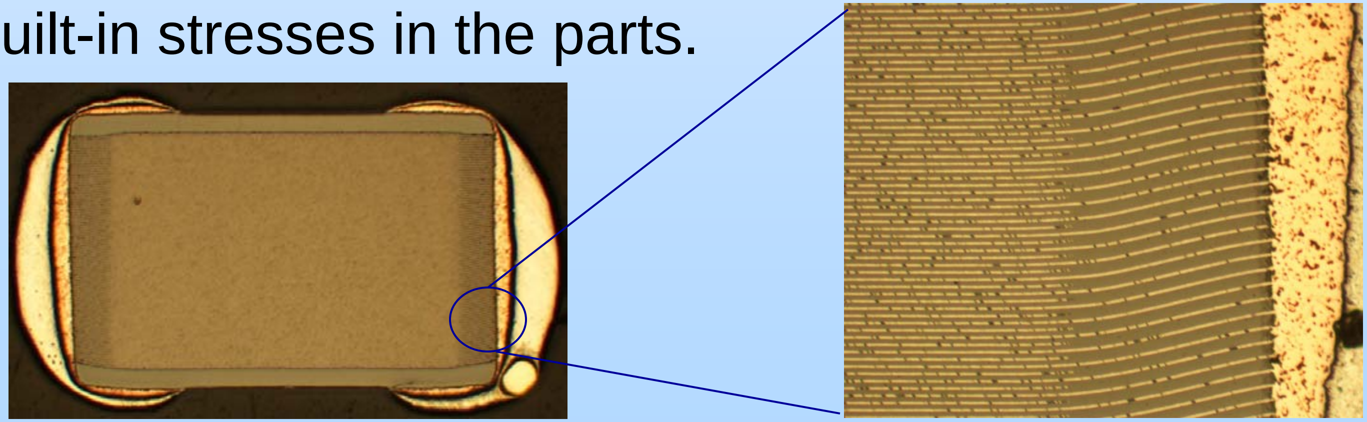
Effect of Size on Critical Temperature







- None of the geometrical factors have a strong correlation with the critical temperature measured by IWT.
- There is a trend of decreasing ΔT_c with the periphery of terminals.
- The cracks originate mostly at the terminal areas and are likely due to built-in stresses in the parts.



Conclusion/Highlights/Accomplishments

- Existing MIL-spec requirements do not address properly issues related to the robustness of MLCCs to soldering-induced stresses.
- The rate of heat transfer, part size, and direction of temperature variations are the most critical parameters of TS testing.
- Cold TS is more stressful than hot TS because the strength of ceramics to tensile stresses is substantially less than to compressive stresses.
- Different lots have different susceptibility to soldering-related fracturing. This susceptibility can be evaluated by TSD test.
- Cracking might occur during post-soldering cooling. IWT is an effective method to quantitatively assess resistance of MLCCs to cold TS.
- There is a trend of decreasing ΔT_c with the size of periphery of parts. TS resistance of MLCCs depends strongly on the level of built-in stresses.
- Recommendation. To assure reliable manual soldering:
  - Develop NASA workmanship recommendations/requirements;
  - Test the parts at TSD-300 conditions (guidelines to be developed);
  - Test the parts at specific assembly conditions for critical applications.

List of Acronyms

- MLCC – multilayer ceramic capacitor;
- IWT – ice water testing;
- TSD – terminal solder dip;
- LND – liquid nitrogen drop test;
- LDC – lot date code;
- VH – Vickers hardness;
- STD – standard deviation;
- K1C – in-plain fracture toughness;
- TC – thermal cycling;
- CTE – coefficient of thermal expansion;
- ER – established reliability;
- QCI – quality conformance inspection;
- HV – high voltage;
- RT – room temperature;
- LN – liquid nitrogen;
- RH - relative humidity;
- DCL – direct current leakage;
- T – temperature;
- Bi – Biot modulus;
- h is the coefficient of heat transfer, λ is thermal conductivity, and α is thermal diffusivity.