Board Thickness Effect on Accelerated Thermal Cycle Reliability

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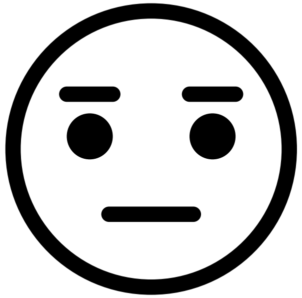
Background

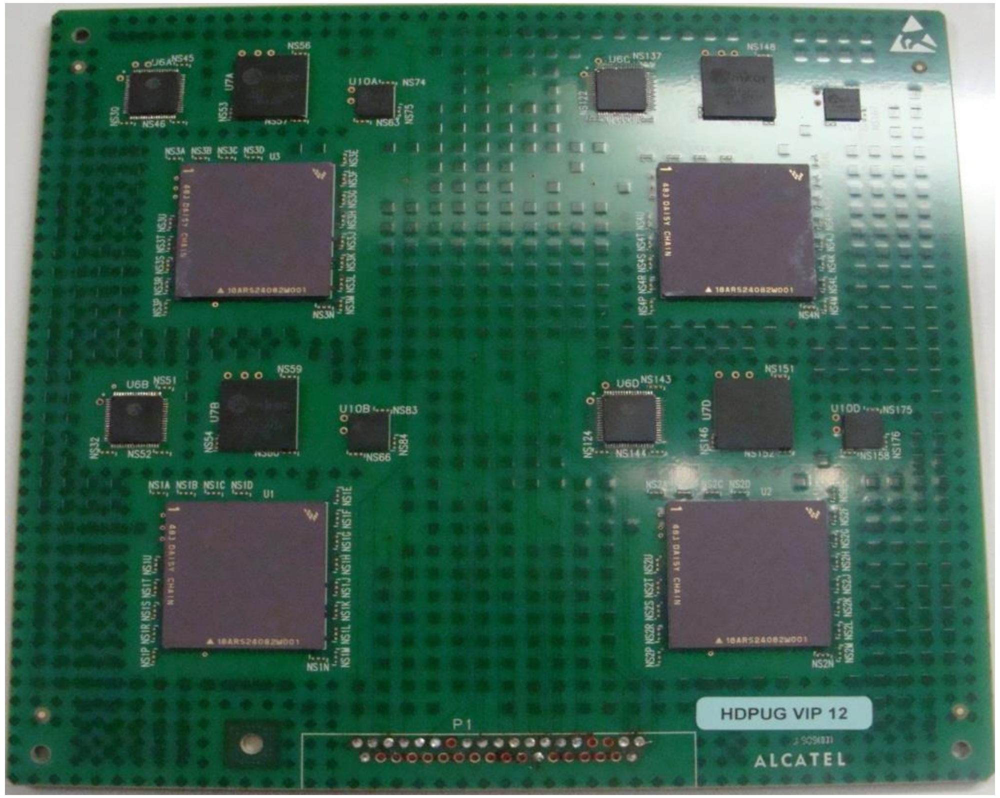
- Thermal cycling data on SMT components, critical to many high reliability applications is often lacking for the appropriate thermal cycle condition.
  - When provided – typically IPC 9701 test profile (TC3) of -40 to +125°C
  - Often for relatively thin PCBs more typical in consumer product applications
- Acceleration factors that enable translating data obtained using one thermal cycling profile to another are questionable.
- ATC data is typically not provided as a function of printed circuit board thickness, particularly for printed circuit boards used in many high reliability applications, which are often thicker, stiffer (higher modulus), and tend to have much higher layer count.
- Modeling suggests in-plane shear strain in a solder joint decreases as the board thickness and overall stiffness or modulus decreases.
  - Along with the decrease in board thickness and strain, the reliability is expected to increase.
- These limitations hinder characterization and prediction of longer product lifetimes in multiple use environments.
  - Published Data is mixed.

Goal

- Test a variety of high strain components on different board thicknesses (40, 62, 93, and 125 mil thick) in two different ATC cycles
  - IPC 9701 TC3 (-40 to +125°C) and
  - IPC 9701 TC1 (0 to +100°C)
- For both SAC and SnPb (SnPb limited to 0 to +100°C ATC and did not include the CBGA)
- Enable creation of acceleration factors to allow assessment of data from a specific board thickness and thermal cycle condition to be "translated" to the other test condition and a different board thickness.
  - Turned out to be "not so simple"

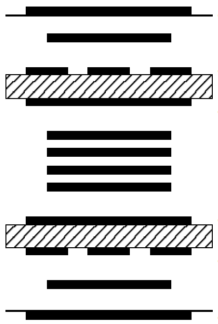


PCB Design



- Re-used from HDPUG Via in Pad project
  - Modified to Cu fill all microvias in pad
- 6 layers, 6.5 x 7 inches
  - 6 layers
  - Isola 370HR material for all stackups
  - Four different thicknesses
    - 40, 62, 93, and 125 mil

Stackups



Layer	Weight	Dk (2 GHz)	Thickness Nom mils	(um)	Material Type
E1	.5oz		1.70	(43)	FOIL
		3.99	3.55	(90)	2113 59% - 370HR
E2	.5oz		0.60	(15)	
		4.26	16.00	(406)	LAM 370HR .016(di.only) 1080/2x7628 .5/.5 RTF 18.25Gx24.25
E3	.5oz		0.60	(15)	
		4.02	19.30	(490)	2116 57% / 2116 57% / 2116 57% / 2116 57% - 370HR
E4	.5oz		0.60	(15)	
		4.26	16.00	(406)	LAM 370HR .016(di.only) 1080/2x7628 .5/.5 RTF 18.25Gx24.25
E5	.5oz		0.60	(15)	
		3.99	3.55	(90)	2113 59% - 370HR
E6	.5oz		1.70	(43)	FOIL

Overall Board Thicknesses (Over Conductor)

	inches	(mm)
nom:	0.0642	(1.63)

- Example (62 mil) stackup shown on the left.
- All 4 stackups:
  - Similar glass styles and resin contents
    - L1-2 and 5-6 always 1x2113, 59% RC
    - 4 plies of 2116 glass style (57% resin content) between Layers 3-4 in all 4 stackups
    - L2-3 and 4-5 varied from 5 to 48 mils to adjust the thickness.
  - Goal was to make these as similar as possible such that the only difference is thickness and associated stiffness.

Components

Part Type	Body Size (mm)	Die Size (mm)	Pitch (mm)	Solder Ball Size (mm)	Solder Ball Alloy	Supplier
CBGA 483	29 x 29	NA	1.27	0.89	SAC405	NTK (solder balls added)
CABGA 192	14 x 14	12.065 x 12.065	0.8	0.46	SAC 305/ SnPb	Practical Components
CTBGA 84	7 x 7	5.08 x 5.08	0.5	0.3	SAC 305/ SnPb	Practical Components
QFN 72 (MLF)	10 x 10	6 x 6	0.5	NA	NA	Practical Components

- All are "High strain" components → First to fail in thermal cycling (i.e. Components of interest). Sample size of 16 per thickness, per component, per solder type.

Assembly

Solder Paste OMNIX 5100 /SnPb	Ramp Rate from Ambient to Peak (°C/sec)	Time Above Liquidus (seconds)	Peak Temperature (°C)	Cool Down (°C/sec)
Supplier Recommendation	0.8 - 1.2	30 - 90	210 - 220	-
40 mil thick board	0.67 - 0.71	52 - 58	212 - 217	3.05 - 3.76
62 mil thick board	0.69 - 0.70	66 - 71	211 - 217	2.03 - 2.85
93 mil thick board	0.71 - 0.73	64 - 71	213 - 219	1.69 - 2.4
125 mil thick board	0.75 - 0.77	70 - 76	211 - 216	1.42 - 2.04

Solder Paste OM338 PT /SAC305	Ramp Rate from Ambient to Peak	Time Above Liquidus (seconds)	Peak Temperature (°C)	Cool Down (°C/sec)
Supplier Recommendation	~1.5	~75	245	~1
40 mil thick board	0.78 - 0.82	53 - 69	234 - 249	2.22 - 3.7
62 mil thick board	0.73 - 0.76	37 - 44	233 - 241	2.15 - 3.23
93 mil thick board	0.69 - 0.71	70 - 83	234 - 244	1.54 - 2.67
125 mil thick board	0.64 - 0.67	77 - 90	234 - 242	1.37 - 1.71

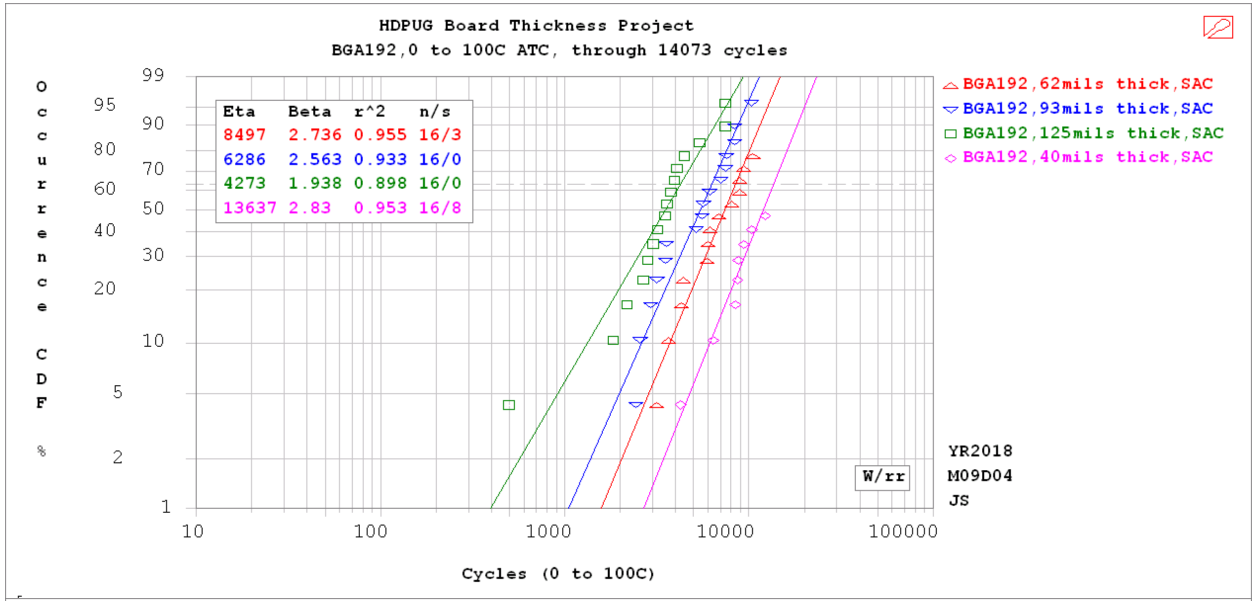
- 8 different reflow profiles
  - Matched (for each alloy) as close as possible over the different board thicknesses
- 5 mil Stencil – same for all
- All boards passed AOI, AXI and electrical continuity

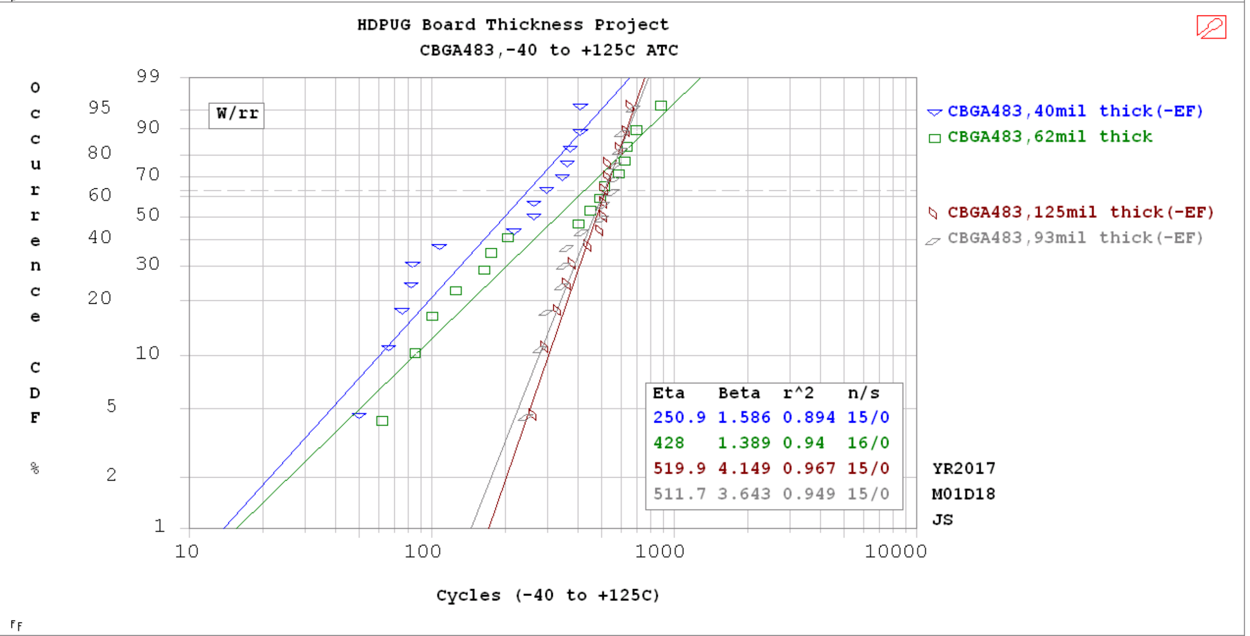
Accelerated Thermal Cycling

Thermal Cycle (IPC 9701)	Minimum Temp. (°C)	Maximum Temp. (°C)	Temp. Range ΔT (°C)	Dwell Time (min.)
TC1	0	100	100	10
TC3	-40	125	165	10

- Each component is on a single net
- Each net is monitored "in-situ" with event detectors
- Failure threshold set at 1000 Ω
- Cycled to at least Characteristic life (63% failures)
  - -40 to +125°C tested to >5000 cycles
  - 0 to +100°C tested to >15000 cycles

Weibull Analysis





- Extensive Weibull Analysis
  - With a few exceptions, the Weibull plots had a good fit and reasonable r^2 values.
  - In some cases, example top left, plots looked exactly as expected → characteristic lifetimes decreasing as expected as the board thickness increased.
  - However, others showed very low beta values for some parts and/or the failure order did not track with thickness, example bottom left

Comparison of Thermal Cycles

CBGA483 SAC		CTBGA84 SAC	
Thickness	Eta AF (-40to+125/0-100)	Thickness	Eta AF (-40to+125/0-100)
40	2.99	40	Not calculable
62	3.89	62	2.79
93	3.41	93	2.67
125	2.68	125	2.83
Average	3.24	Average	2.76
CABGA192 SAC		**QFN72 SAC**	
Thickness	Eta AF (-40to+125/0-100)	Thickness	Eta AF (-40to+125/0-100)
40	3.42	40	1.63
62	2.74	62	2.50
93	4.06	93	2.46
125	2.77	125	2.99
Average	3.25	Average	2.39

- Acceleration Factors between test conditions varied by component type, solder alloy, and board thickness
  - Vary from a low of 1.6 to a high of 4.1.
  - ***Extremely difficult to compare these thermal cycle conditions without having details on a specific part or part type***

SAC vs. SnPb in 0-100°C ATC

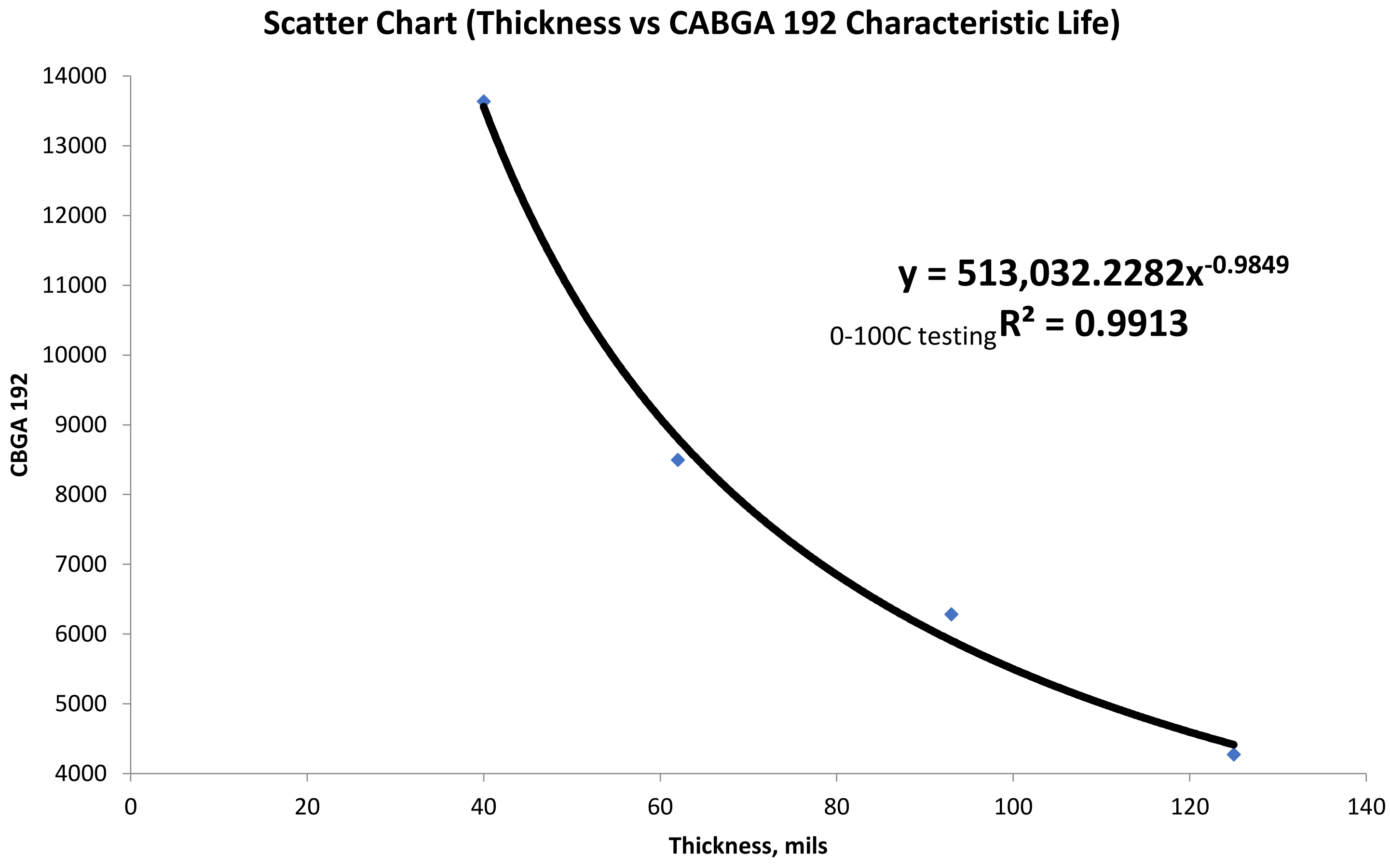
CABGA192 SnPb		
Thickness	Eta AF (SAC/SnPb,0-100)	Beta Compare(SAC/SnPb,0-100)
40	2.26	0.28
62	1.58	0.41
93	1.65	0.16
125	1.43	0.17
Average	1.73	0.26

CTBGA84 SnPb		
Thickness	Eta AF (SAC/SnPb,0-100)	Beta Compare(SAC/SnPb,0-100)
40	Not calculable	Not Calculable
62	1.85	2.09
93	1.99	0.80
125	2.23	0.76
Average	2.02	1.22

QFN72 SnPb		
Thickness	Eta AF (SAC/SnPb,0-100)	Beta Compare(SAC/SnPb,0-100)
40	0.55	0.74
62	1.02	1.23
93	1.20	0.54
125	1.15	0.98
Average	0.98	0.87

- For the 2 BGA parts, SAC outperforms SnPb consistently
  - A lot of variation with different thicknesses
  - Weibull Beta values considerably less than for SnPb (1 exception → 40 mil thick CTBGA84
- For the QFN 72 Characteristic life is very similar between SAC and SnPb, but SAC is considerably worse for the thin, 40 mil thick, boards.
  - Weibull beta values “mostly” less
  - Again dependent on thickness difference.

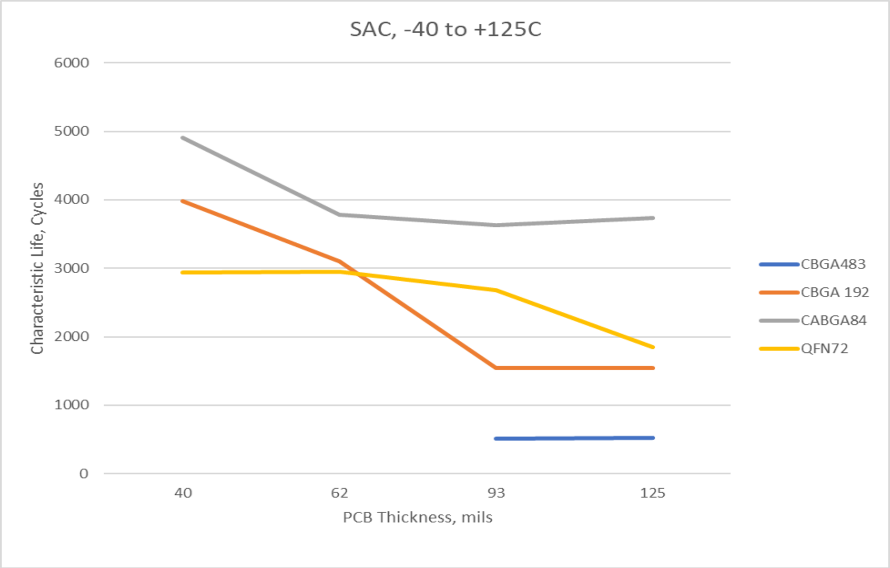
Correlation of Lifetime to Board Thickness

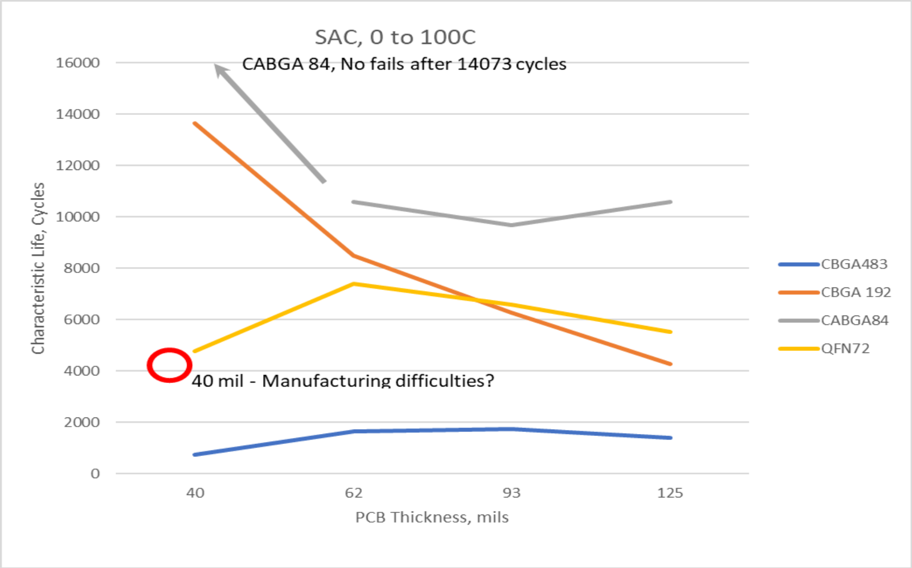


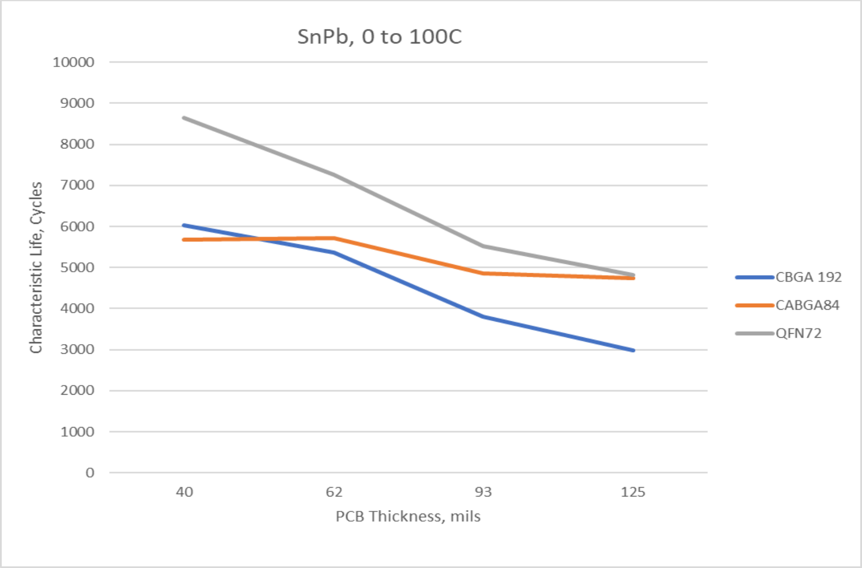
Power Law Fit for SAC305 CABGA192 (CTF as a Function of Board Thickness)

- In a few cases, there is an excellent correlation to a Power Law fit of the data.
  - This was the expected result.

Correlation of Lifetime to Board Thickness (2)

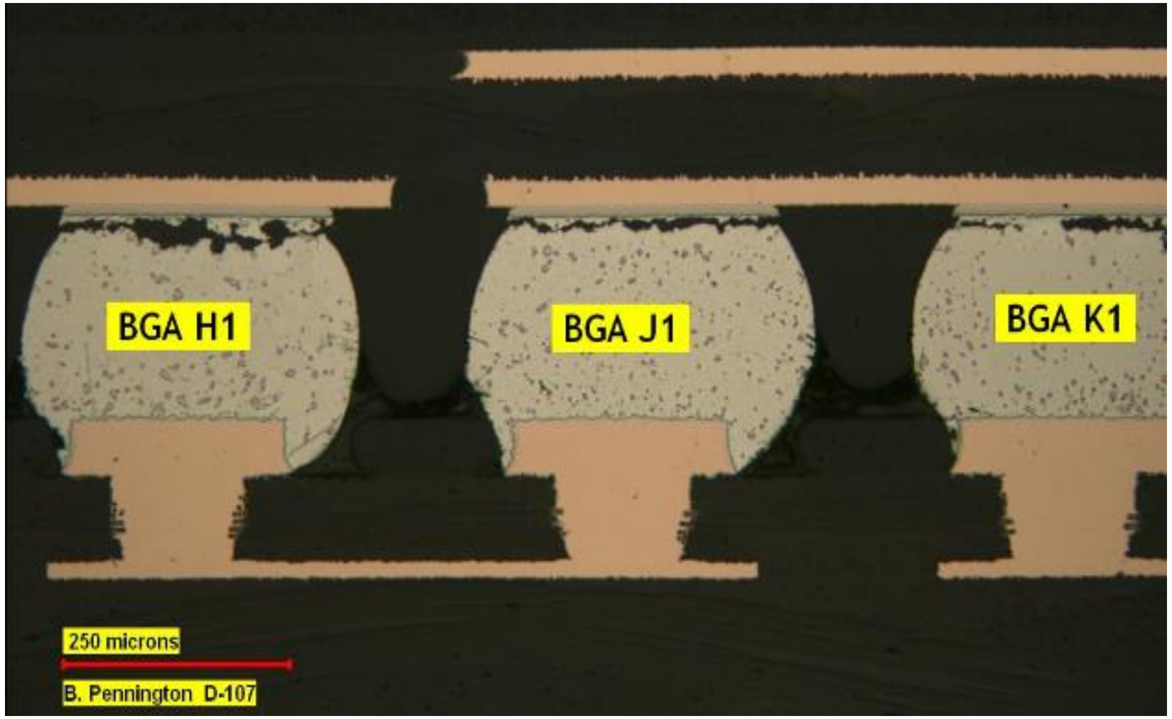






- However – as shown here, Much of this data did **NOT** have a good correlation to board thickness.

Failure Analysis



- Extensive FA
  - Dye and Pry
  - Cross-sections
  - Warpage analysis
- Failure analysis did not identify any unusual failure modes or any manufacturing anomalies.
  - Failure mode was consistently solder fatigue
- Weibull fit did not suggest competing or dual failure modes.
  - → FA should be representative of the failures identified
- **No reason to attribute manufacturing anomalies to the results.**

Discussion: CBGA 483

- In -40 to +125°C ATC, Weibull beta ~ 2 and below for the 40 and 62 mil thick PCBs.
  - Typical beta values for this component expected to be around 4.
  - The r^2 are reasonable for this data and no indications of a dual failure mode.
  - Assembly X-ray examination and FA did not identify anything anomalous.
  - 125 and 93 mil thick results → more as expected Weibull beta values near 4. However, the failure data for these two thicknesses are not statistically different.
- In 0-100°C ATC, 2 failure modes identified on the 40-mil thick PCB.
  - This is "probably" manufacturing related, though nothing in either FA or the assembly report that would suggest this.
  - Even after accounting for different failure modes and early failures the results do not track as expected with the thickness of the boards.
  - The worst performance occurred on the 125 mil (thickest) and the 40 mil (thinnest) PCBs.
  - There is no statistical difference between the 125 and 40 mil thick failure distributions.
  - The "best" performing thickness was 93 mils, which is not expected.
  - Ranking from best to worst for CBGA is 0-100°C is 93> 62 > 125=40.

Discussion: BGA 192

- -40 to +125°C ATC →relatively low Weibull Beta for all thicknesses, from ~ 2 to 3.
  - Not terribly low for SAC solder but < expected.
  - The 125-mil & 93 mil thickness failure distributions are not statistically different.
  - The 40 & 62 mil thickness failure distributions are not statistically different.
  - The ranking from best to worst performing is 40=62>90=125.
- 0-100°C ATC similar relatively low Beta ~2-3 were seen for the SAC. SnPb Beta 6-16
  - For high strain components → common for SAC beta < SnPb beta values in ATC.
  - All cases→ Weibull fit is good and r^2 is good.
  - For both SAC and SnPb → reliability performance tracks exactly as expected ranked from best to worst as follows for thickness: 40>62>93>125 mil thickness PCB.
  - SAC → data fits extremely well to a power law correlation shown previously
  - SnPb → follows power law fit if the 40-mil thickness is ignored.

Discussion: BGA 84

- -40 to +125°C ATC:
  - Results for the 62, 93 and 125 mil thick PCBs → statistically same.
  - 40 mil thick PCBs performed considerably better.
- 0-100°C ATC:
  - With SAC solder, again 62, 93 and 125 mil thick PCBs → statistically same.
    - 40 mil thick PCBs performed considerably better.
  - For SnPb assemblies→2 failure modes on the 40 mil thick PCBs based on Weibull.
    - 40 and 62 mil results (with or w/o excluding 2 failure modes) → statistically same.
    - If 40 mil thickness data is excluded, → expected power law fit of the failure data vs. thickness is reasonable.
    - The ranking is 40=62> 93> 125 mils thick.

Discussion: QFN 72

- -40 to +125°C ATC with SAC solder
  - 40, 62, and 93 mil thickness results are statistically the same.
  - 125-mil thickness performs worse.
  - Theory → the relatively large die attach area which is soldered is adding stiffness locally to the thinner PCBs, resulting in a similar performance, but has less effect on the thicker 125 mil thickness, which already is stiffer.
- 0-100°C ATC
  - With SAC solder, the thinnest board (40 mil thickness) is the worst performer.
    - Results are not in order vs. thickness.
    - Best to worst the ranking is 62>93>125>40 mil thickness. The 40 mil is "out of order".
  - For SnPb solder, the results are close to what we expected to see with a Power Law fit of the data vs. board thickness.

Conclusions

- Modeling simulations suggest that the in-plane shear strain in a solder joint decreases as the board thickness and overall stiffness or modulus decreases → which should result in increased reliability.
  - In general, industry test data support this finding but → correlation between PCB thickness and thermal cycling results are not always consistent or predictable.
  - In this test→ only a few cases where the reliability ↓ monotonically as board thickness ↑. In some cases, it does not track at all with board thickness
- Though many of the Weibull Beta values were low, there was no evidence of manufacturing defects in the assembly build reports, X-ray inspection data or FA.
  - The FA process is a limited random sampling, but the findings largely are consistent with the Weibull statistics, build reports, and non-destructive X-Ray inspection.
  - In theory, dynamic warpage during thermal cycling could create some out of plane strain, which might result in early failures and mixed mode cracking. However, when these earlier failures are removed from the plots there is no significant effect on the relationship between reliability and thickness.
  - Warpage measurements on the boards were well within normal expected results and do not explain any of the behavior.

Conclusions (2)

- For the high strain components in this test, -40 to +125°C (TC3) ATC profile appears to be a poor choice, at least for the Pb-free SAC305 solder.
  - High strain and aggressive ATC drives fast failures → difficult to assess differences due to board thickness.
    - The aggressive testing essentially "levels the playing field."
- Acceleration factors, between the different test conditions are inconsistent and not usable for a generic rule comparing results between different test conditions.
- Severe use environments might require TC3 ATC conditions, but the TC3 cycle does not translate consistently to less severe use (or even ATC) environments
  - Not effective for distinguishing performance differences between board thicknesses.
  - Perhaps the results would be different for testing lower strain components?

Conclusions (3)

- It is not possible, based on this data, to estimate the solder joint reliability differences between components soldered on different thicknesses of boards.
  - Clearly package dependent.
- Comparing the performance at -40 to +125°C and 0-100°C is at best a crude estimate as there are significant differences between board thicknesses and component types.
- The characteristic lifetime of the SAC BGAs significantly outperformed the same components with SnPb solder.
- The QFN72 soldered with SAC had a similar characteristic life to SnPb except on the thinnest construction, where SnPb significantly outperformed the SAC soldered QFN.

Possible Future Work

- There is still much to understand in the relationship of board thickness to solder joint reliability. Modeling of the PCB/Component/Solder Joint relationship for these components could allow for a greater understanding of these results.
  - Need to have measurements of the coefficient of thermal expansion (CTE) and modulus for the components and printed circuit boards used in the tests.
  - Future work begins by making those measurements.
- -40 to +125°C (TC3) ATC profile drives failures fast and shortens test times for most of the components but makes it difficult to assess differences due to board thickness.
  - 0 to +100°C (TC1) thermal cycling profile does not drive failures fast and lengthens test times but makes it possible to assess differences due to board thickness.
  - Future test plans should include the common 0 to +100°C (TC1) ATC but also consider another slightly more aggressive profile.
    - Example: compared -40 to +125°C profile, a profile of -40 to +100°C reduces both the upper temperature extreme and strain (ΔT). This profile has been shown to result in substantially more cycles to failure than -40 to +125°C but shorter test times than 0 to +100°C

Acknowledgements

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