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AREA CONSORTIUM

High Reliability Solder Paste Performance in Thermal Cycling

Michael Meilunas

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Introduction

- Five solder pastes were recommended for the 2025 Thermal Cycle Reliability program:
  - Indium Durafuse LT
  - Indium Durafuse HR
  - Aim Rel22
  - Koki HR6C
  - FCT Solder LF-C2

- This presentation is more appropriately about “alternative solder pastes”
  - Durafuse LT offers lower temperature soldering, not necessarily the same class as other materials evaluated

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Test Board 2024 Component Selection

Part	Pitch	Ball Diameter (Approximate)	Class
A-CABGA196-1.0-15mm-DC-LF-305	1.0	0.46mm	BGA/CSP
A-CABGA100-.8mm-10mm-DC-LG-305	0.8	0.46mm	BGA/CSP
A-CTBGA132-.5mm-8mm-DC-LF-305	0.5	0.3mm	BGA/CSP
A-CVBGA97-.4mm-5mm-DC-LF-305	0.4	0.254mm	BGA/CSP
A-MLF68-10mm-.5mm-DC-Sn	0.5	Not Applicable	QFN
A-MLF100-12mm-.4mm-DC-Sn	0.4	Not Applicable	QFN
A-CABGA196-1.0-15mm-DC-LF-LGA	1.0	Not Applicable	LGA
WLCSP72-0.35mm-3.5x3.2mm-DC-LF	0.35	Not Specified (.2 to .22mm?)	WLCSP
~~WLCSP49-0.4mm-3mm-DC-LF~~	~~0.4~~	~~0.25mm~~	~~WLCSP~~
WLCSP100-0.5mm-5mm-DC-LF	0.5	0.3mm	WLCSP
SMR2512		Not Applicable	Resistor
SMR1206		Not Applicable	Resistor
SMR0805		Not Applicable	Resistor
SMR0603		Not Applicable	Resistor

SAC305

SAC305 or SAC405

Leadless

Leadless

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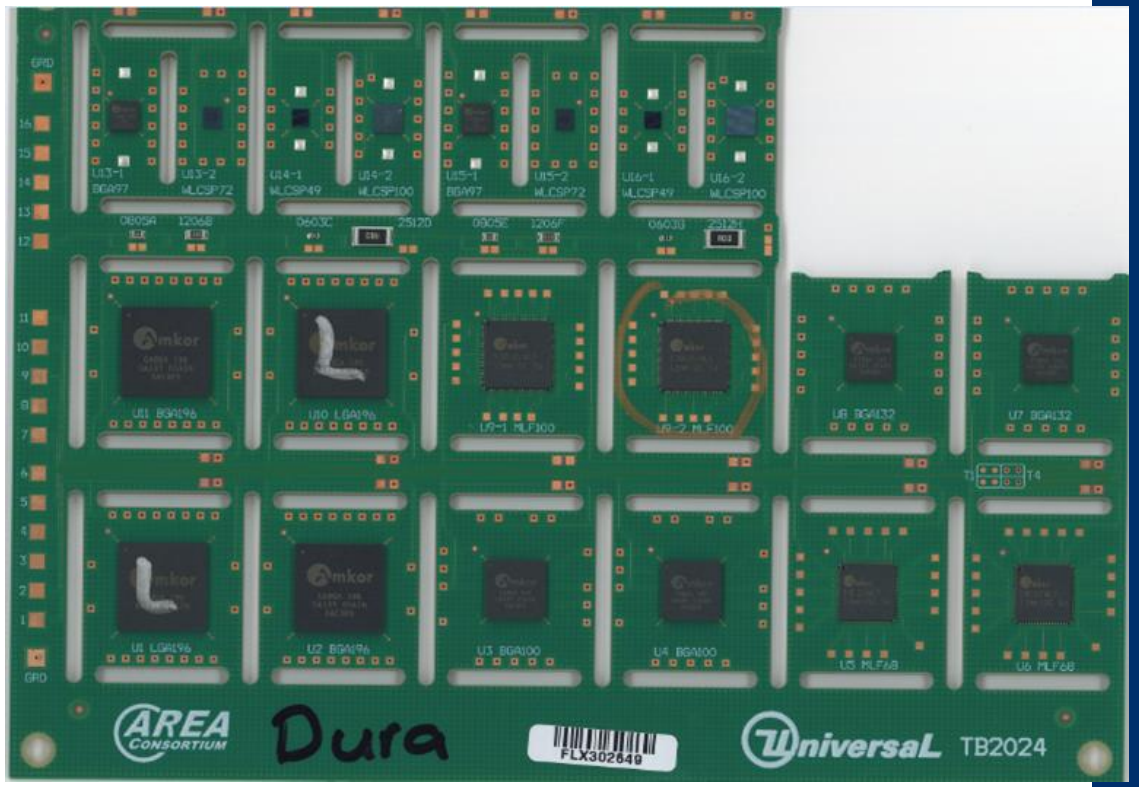
TB2024 Circuit Board

- Copper OSP surface finish
- 2.5mm total thickness
- 8 layer –½ oz base copper per layer
- Layer 1 and 8 plated

- BGA / WLCSP footprints use 100% via-in-pad routing



COMPONENT	Ball Dia. (mm)	Diameters (mm)	
		PCB PAD	PCB MASK
BGA 196	0.46	0.380	0.600
BGA100	0.46	0.380	0.580
BGA132	0.30	0.300	0.400
BGA97	0.25	0.225	0.325
WLCSP72	0.20	0.200	0.280
WLCSP49	0.25	0.228	0.331
WLCSP100	0.30	0.300	0.400

NSMD by request

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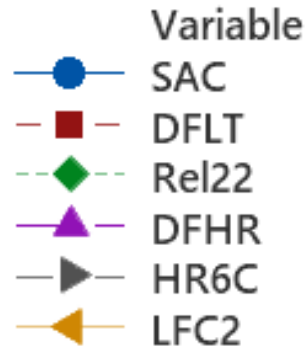
Pastes: Type 4, no-clean

- Six solder pastes were evaluated
  - SAC305 baseline

- Paste applied using 0.10mm thick stencil with 0.075mm patches at WLCSP72 footprints
  - 1:1 Aperture to PCB pad area ratio

Paste	~Alloy Compositions								
	Sn	Ag	Cu	Bi	Sb	In	Ni	Co	Bi
SAC305	Yes	3.0	0.5	--	--	--	--	--	--
Durafuse LT	Yes	2.9	0.2	--	--	12.5	--	--	--
Rel22	Yes	2.8 - 3.2	0.6 - 0.8	2.5 - 2.9	0.5 -0.7	--	0.04 - 0.06	--	--
Durafuse HR	Yes	2.6 - 3.0	0.5 - 0.6	4.8 - 6.0	1.4 - 1.8	0.1 - 0.2	0.04 - 0.06	--	--
HR6C	Yes	3.4	0.7	--	3.5	2.9	--	Yes	--
LF-C2	Yes	3.5	1.0	3.0	--	--	--	--	--



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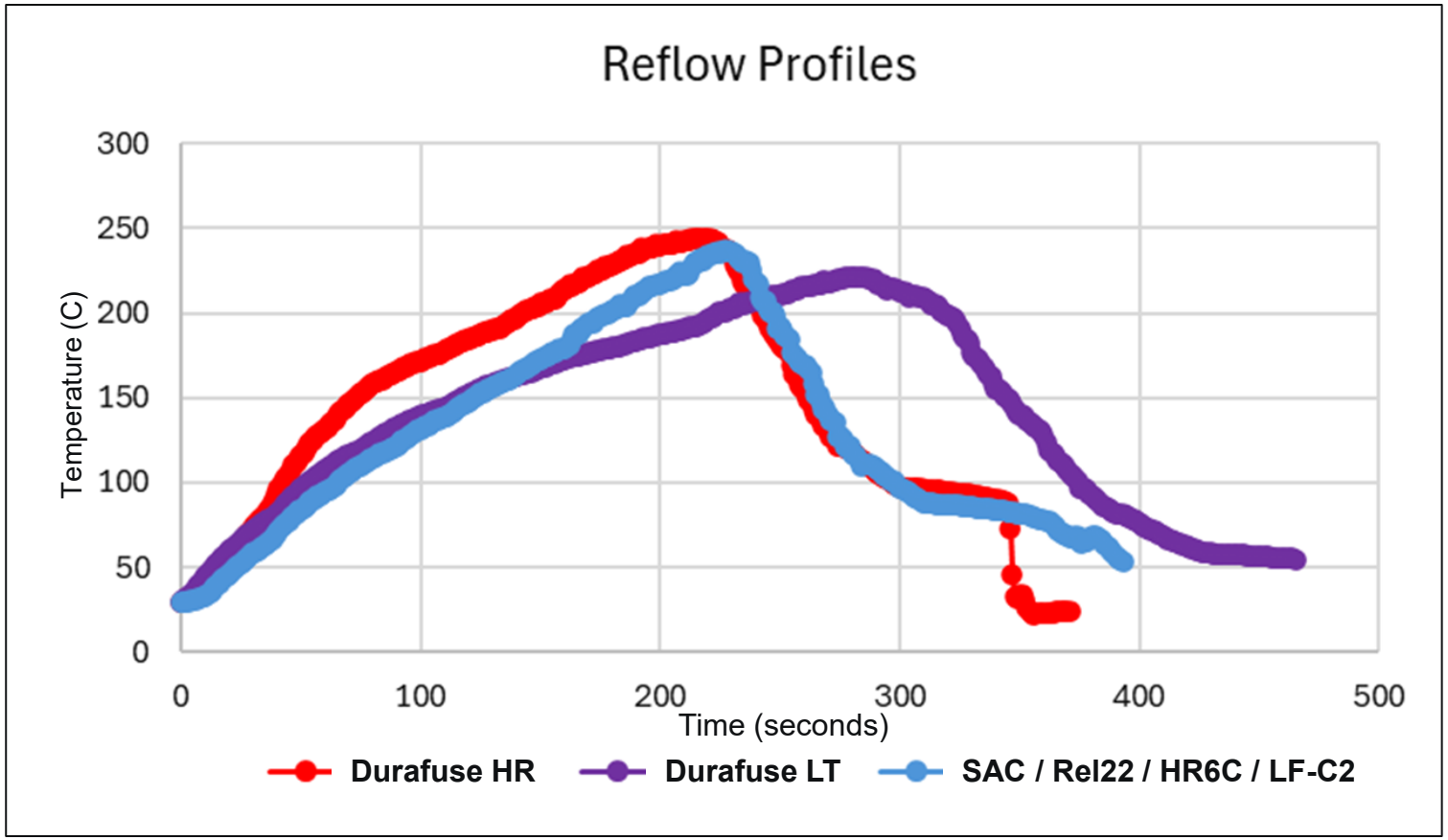
Reflow Profiles

- Nitrogen reflow
  - <300ppm O_2
- SAC, Rel22, HR6C and LF-C2: identical profile (direct ramp)
- Durafuse HR and LT: customized profiles
  - DFHR: similar to SAC profiles
  - DFLT: colder than SAC profiles



Parameter	Durafuse HR	Durafuse LT	SAC / Rel22 / HR6C / LF-C2
Peak Temp (C)	244	221	237
Time above 200C (s)	100	95	64
Time above 217C (s)	71	27	43

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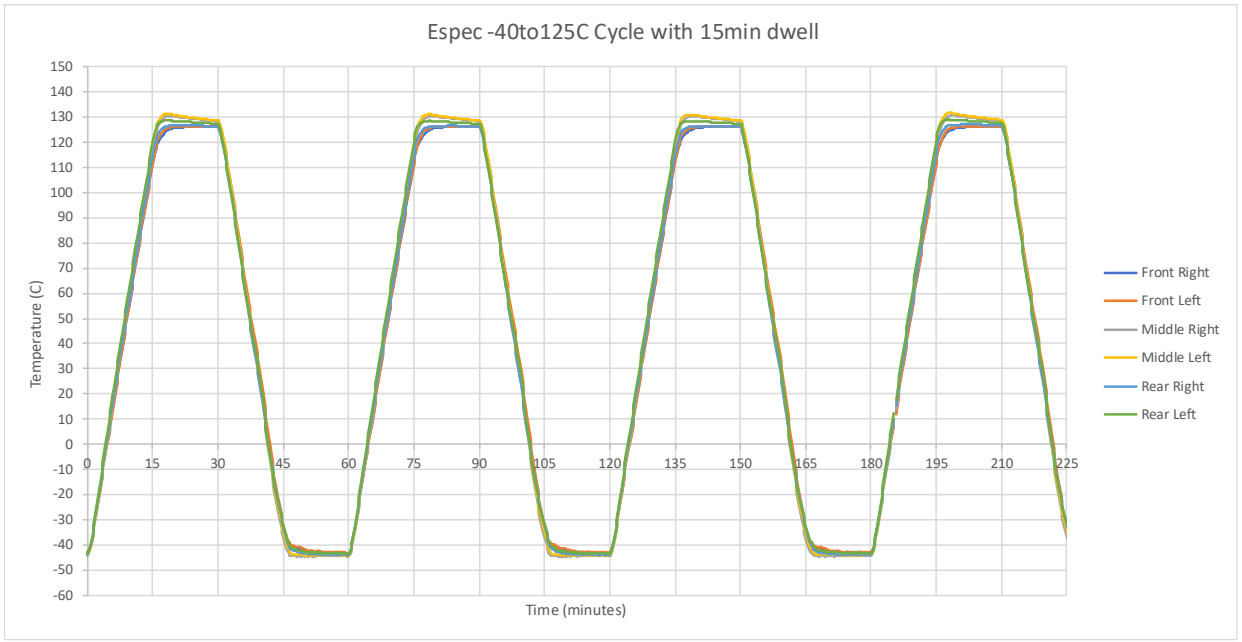
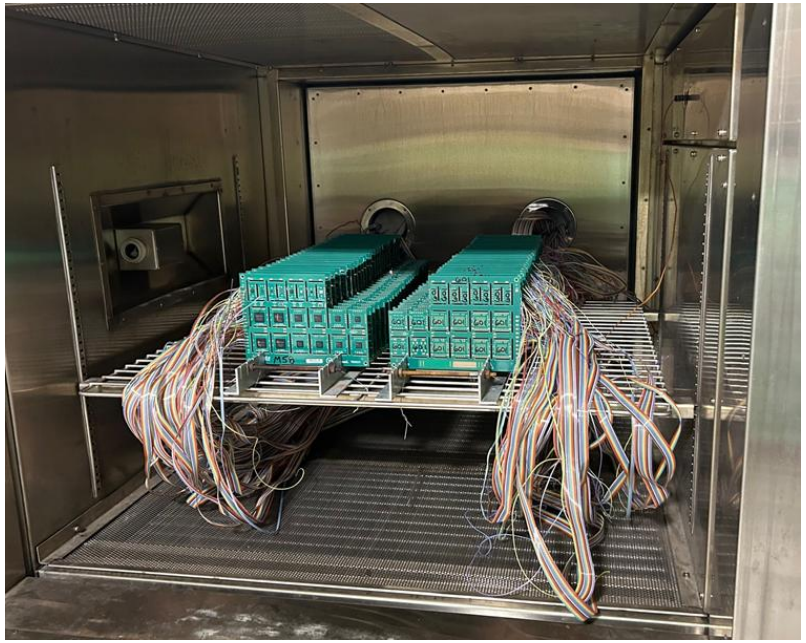
Thermal Cycle Testing

- -40 to 125°C, 60-minute temperature cycle
  - 15-minute dwell times

- Event detection: 500ohm threshold; 200nS duration





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Lifetime Analysis

- The following slides contain 2-parameter Weibull plots for data presentation

- In addition to 2-P Weibull analysis, we performed “Practical Significance” analyses using AI assistance which included “weighing” the results of:
  - 2-P Weibull & 3-P Weibull
  - N06 (first failure among populations of sample size 16)
  - Mann-Whitney (comparison of means)

- The Weibull plots are presented based on SAC305 test results beginning with the least reliable SAC305 assembly (LGA196) and ending with the most reliable SAC305 assembly (SMR “array”)

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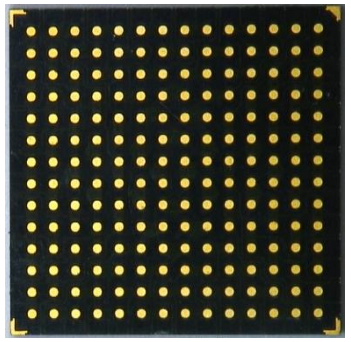
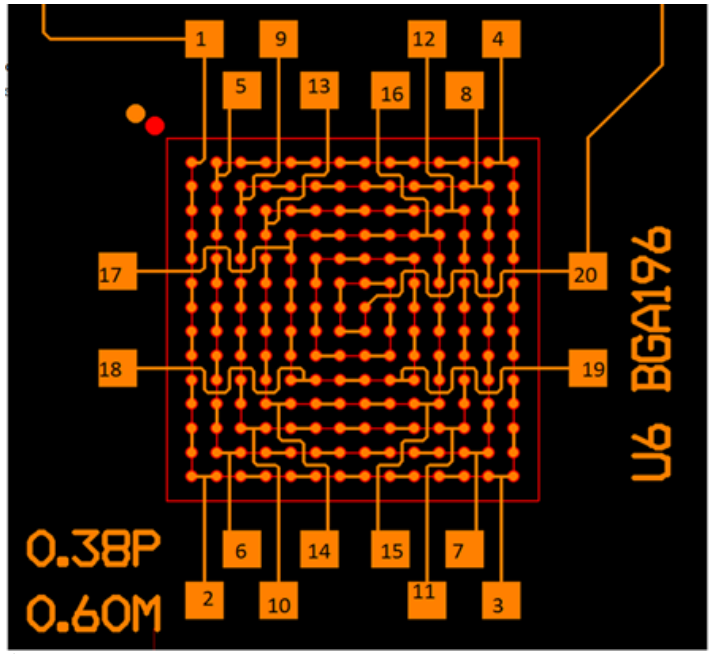
Failure Analysis

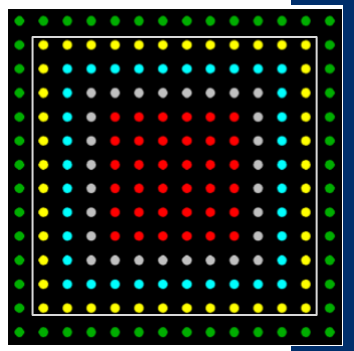
- Failed samples were removed from the cycling chamber on a weekly schedule (typically)
  - Allows us to examine components before additional damage occurs.
    - Cross-section and dye penetrant analyses

- Failure locations are mapped out for every component using the daisy-chain probe pattern found on the test boards

- Failure locations for each population are compiled to look for similarities and/or differences between alloys
  - Different failure locations imply different behaviors







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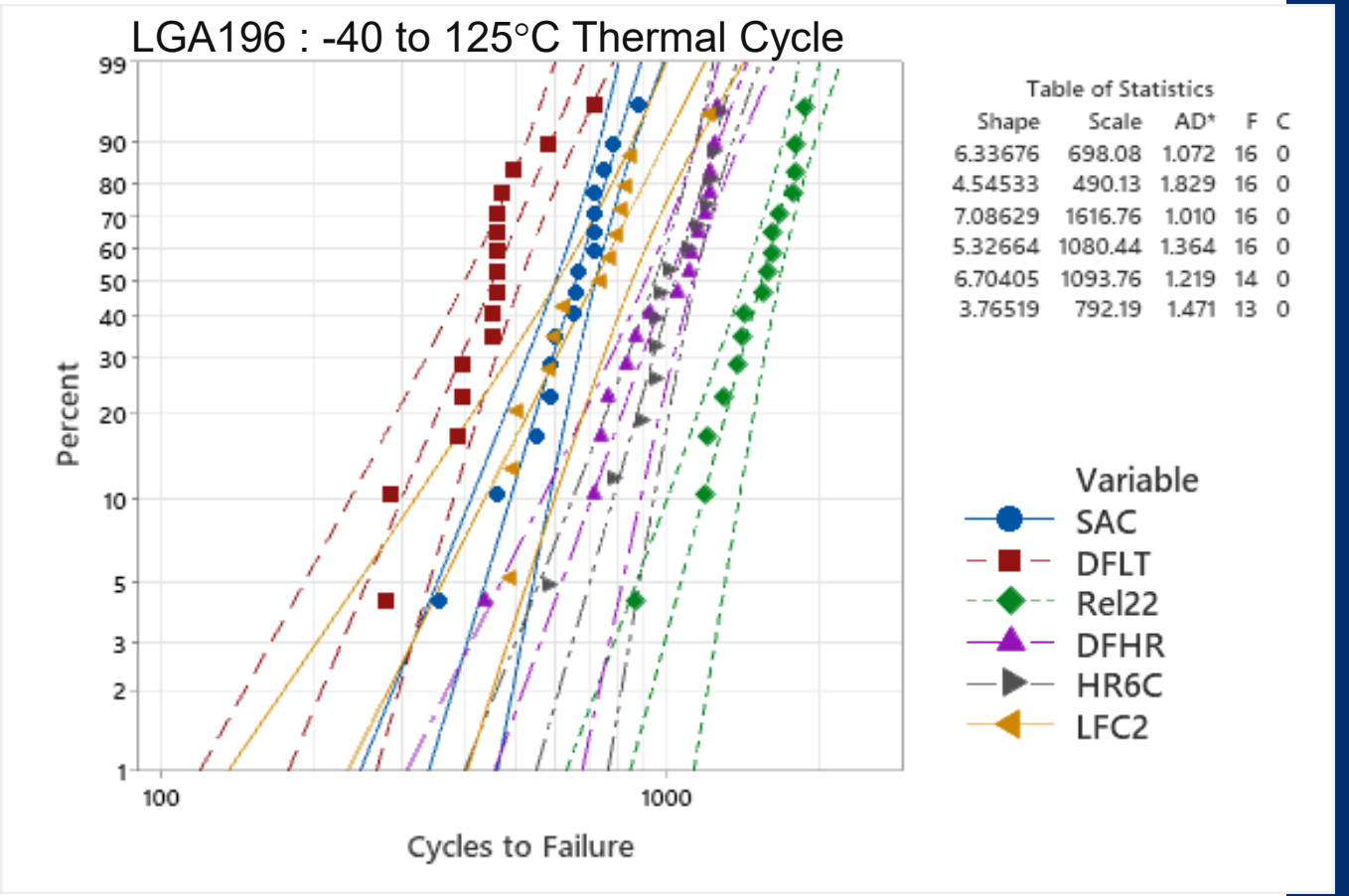
LGA196

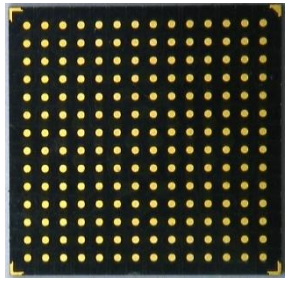
- The LGA196 assembly is the least reliable assembly among the SAC305 populations

- The “high reliability” pastes all performed as well as or better than SAC305
  - Rel22 results are extremely good
  - Durafuse HR and HR6C also impressive

- The Durafuse LT population did not perform as well as SAC305
  - 30% N63.2 reduction



LGA196
1.0mm pitch
15mm body



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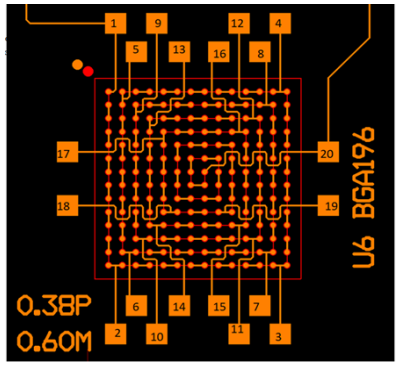
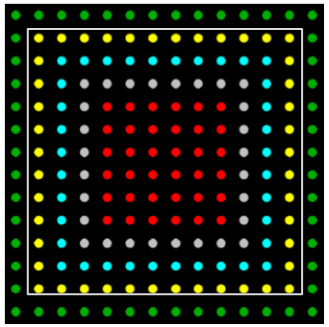
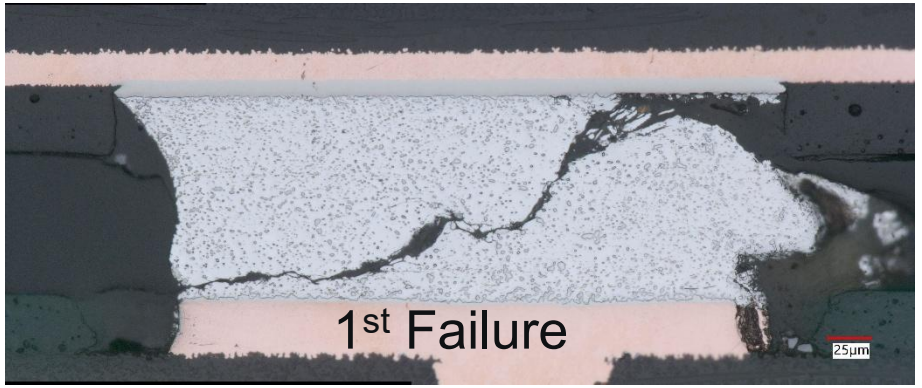
LGA196: SAC305 (Tied 4th)

- All SAC305 samples failed at perimeter solder joint locations with daisy-chain nets 1 to 2 and 3 to 4 most likely to fail, implying corner joint failures.
  - Perimeter joints are outside of the silicon die region and experience high tensile stress during thermal cycling







Barcode	Position	Cycles to Failure	Failure Location(s)																	
			1to2	2to3	3to4	4to5	5to6	6to7	7to8	8to9	9to10	10to11	11to12	12to13	13to14	14to15	15to16	16to17	17to18	18to19	19to20
357	u1	356	x		x																
354	u1	459			x																
361	u1	549			x																
353	u10	587	x																		
360	u10	598	x																		
358	u10	652			x																
353	u1	663			x																
354	u10	664			x																
355	u1	716	x		x																
359	u1	716			x																
360	u1	716		x	x																
355	u10	717			x																
359	u10	752			x																
357	u10	778	x																		
361	u10	877	x																		

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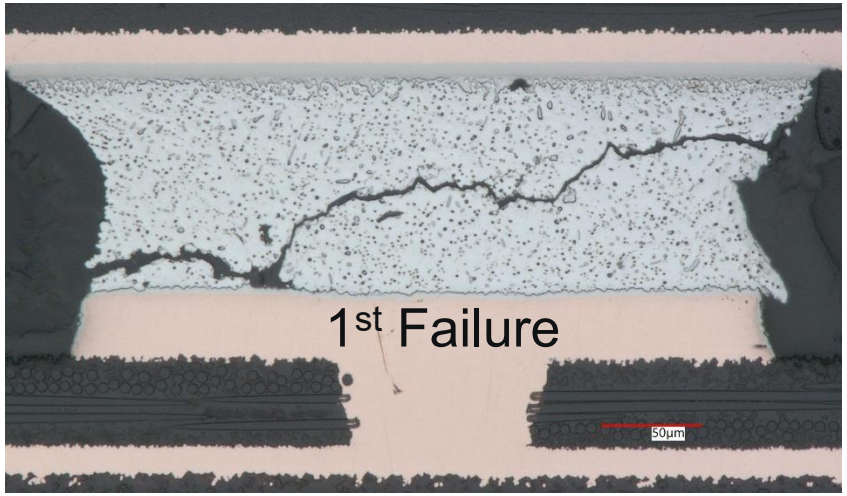
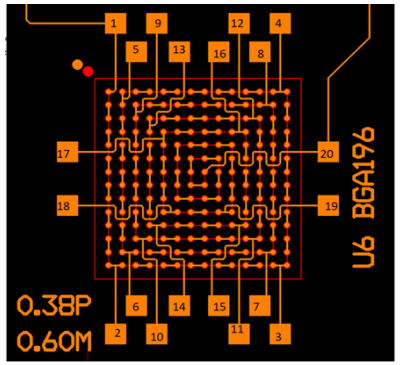
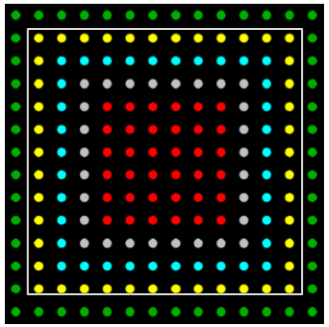
LGA196: Durafuse LT (6th)

- All Durafuse LT specimens failed at perimeter solder joint positions
  - Most likely corner joints







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350	u10	277	x		x																
348	u1	284	x			x															
345	u10	385	x		x																
348	u10	394	x		x																
350	u1	395	x		x	x															
352	u1	450	x																		
349	u1	451			x																
352	u10	460	x		x																
344	u10	461	x																		
345	u1	461	x		x	x															
349	u10	461	x		x																
346	u10	469			x																
351	u1	497	x	x	x	x															
346	u1	581			x																
344	u1	715	x																		

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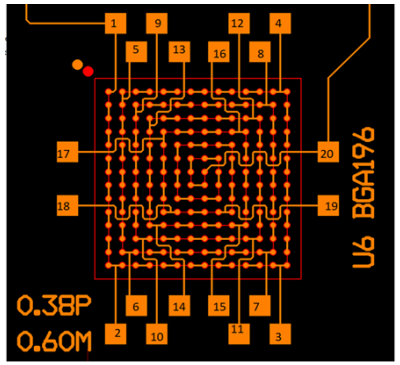
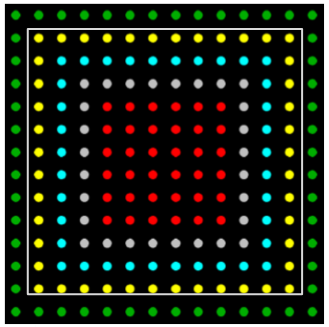
LGA196: LF-C2 (Tied 4th)

- LF-C2 performed similar to SAC (slightly better)
  - At room temperature, we could not find the failure locations using an ohm-meter





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501	u1	489																			
501	u10	497																			
503	u1	505								x											
504	u10	586			x																
499	u10	598																			
499	u1	628																			
502	u1	746																			
500	u10	776								x											
500	u1	797																			
503	u10	818																			
498	u10	830																			
502	u10	851																			
504	u1	1216			x																

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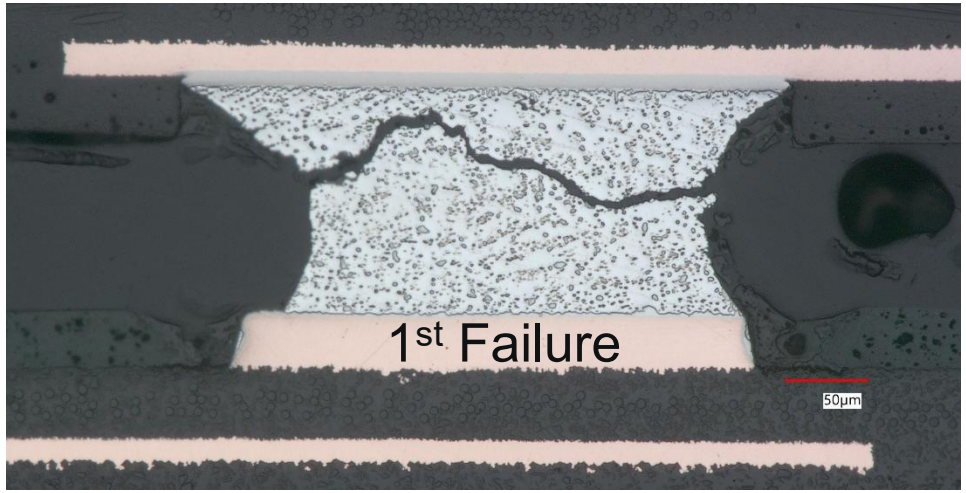
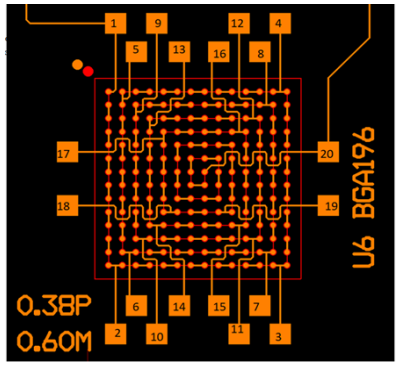
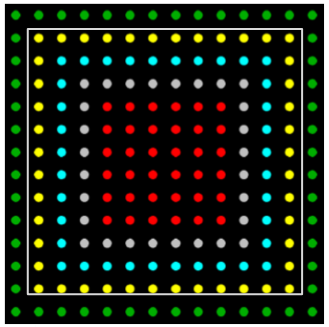
LGA196: LF-C2 (Tied 4th)

- Event detector was used to find failure locations

Corner joint:
Sample preparation probably increased crack width







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503	u1	505								x											
504	u10	586			x																
499	u10	598			x																
499	u1	628	x																		
502	u1	746			x																
500	u10	776								x											
500	u1	797			x																
503	u10	818	x																		
498	u10	830			x																
502	u10	851						x													
504	u1	1216			x																

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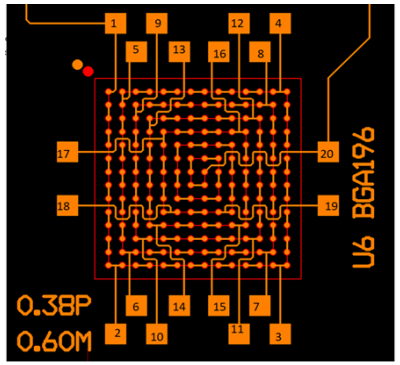
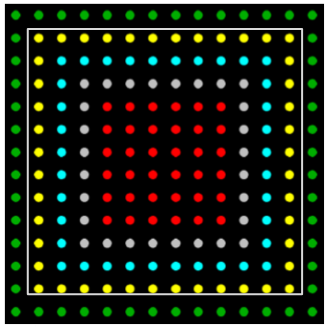
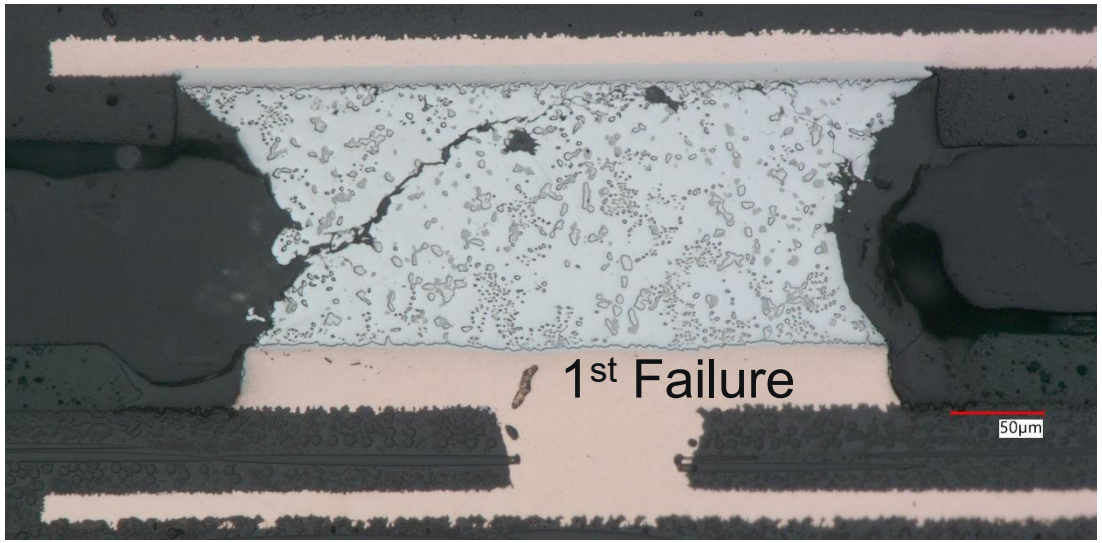
LGA196: HR6C (Tied 2nd)

- HR6C: much better than SAC
  - Failure locations vary;







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492	u10	584			x																
493	u1	786			x																
488	u1	891			x																
491	u10	945							x												
490	u10	946	x																		
493	u10	949							x												
492	u1	972		x																	
489	u10	1009						x													
490	u1	1101							x												
489	u1	1143			x				x												
487	u1	1199							x												
487	u10	1224	x																		
491	u1	1235			x																
488	u10	1277	x																		

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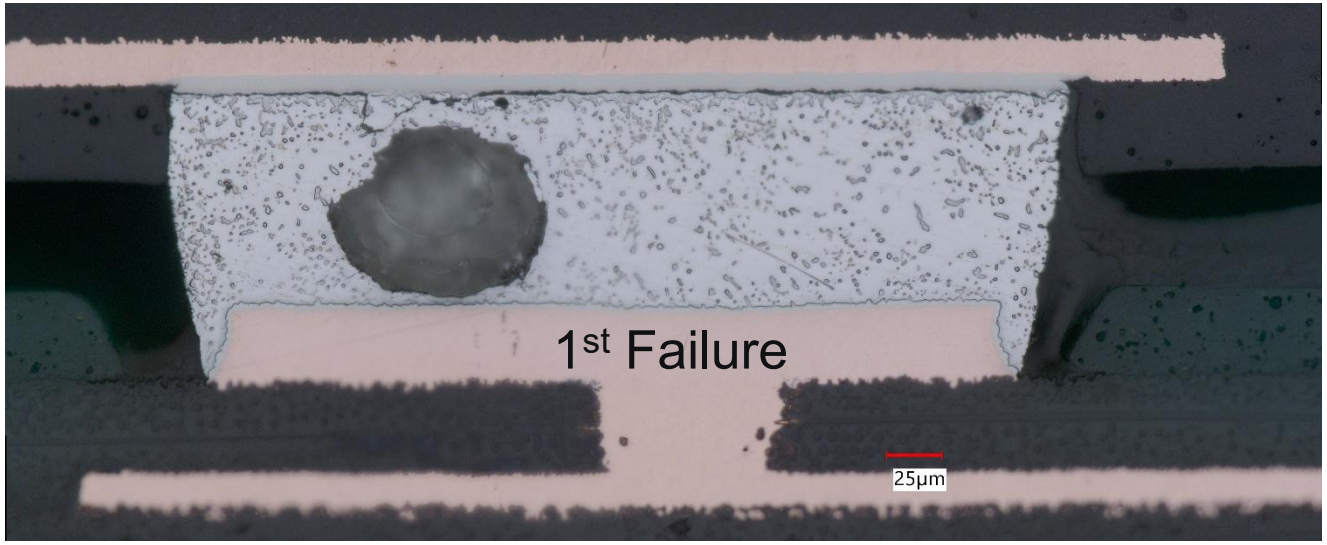
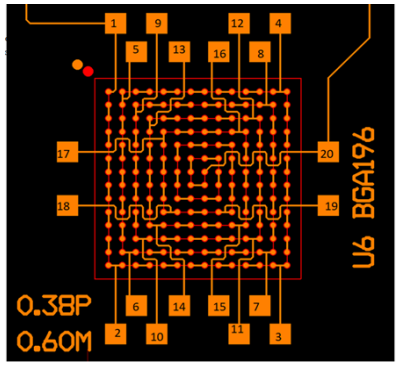
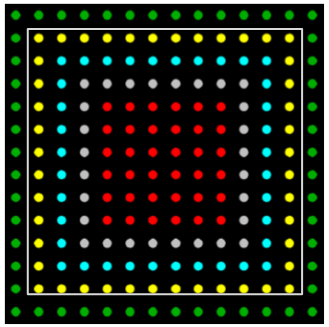
LGA196: Durafuse HR (Tied 2nd)

- Durafuse HR







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374	436	u1								x											
372	716	u10			x																
377	745	u10	x																		
378	770	u1			x				x		x										
374	833	u10								x											
372	867	u1						x													
376	923	u1						x													
379	1047	u10							x												
377	1106	u1								x											
373	1120	u1	x		x																
375	1160	u10						x													
378	1195	u10									x										
379	1218	u1								x											
375	1221	u1									x										
373	1248	u10							x												
376	1259	u10	x																		

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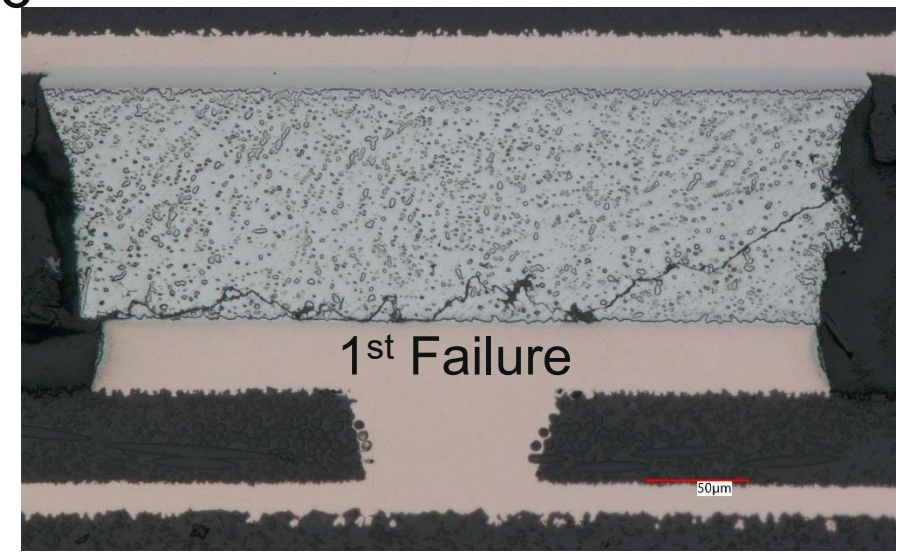
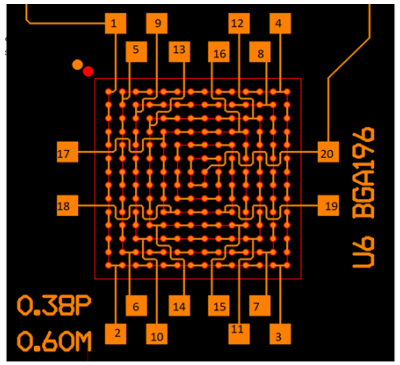
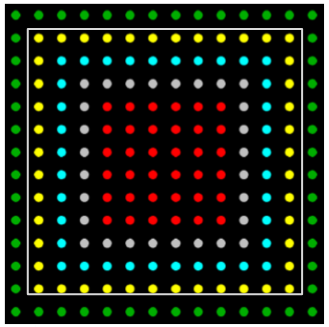
LGA196: Rel22 (1st)

- Rel22 paste resulted in the most reliable LGA196 test assemblies







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369	u10	868			x																
365	u1	1194			x																
364	u10	1211				x															
370	u10	1303	x																		
367	u1	1379																			
363	u1	1420								x											
363	u10	1426			x																
367	u10	1588			x																
365	u10	1616								x											
368	u10	1626			x																
368	u1	1681			x																
366	u1	1785						x		x											
366	u10	1798				x															
364	u1	1804								x											
370	u1	1893							x												

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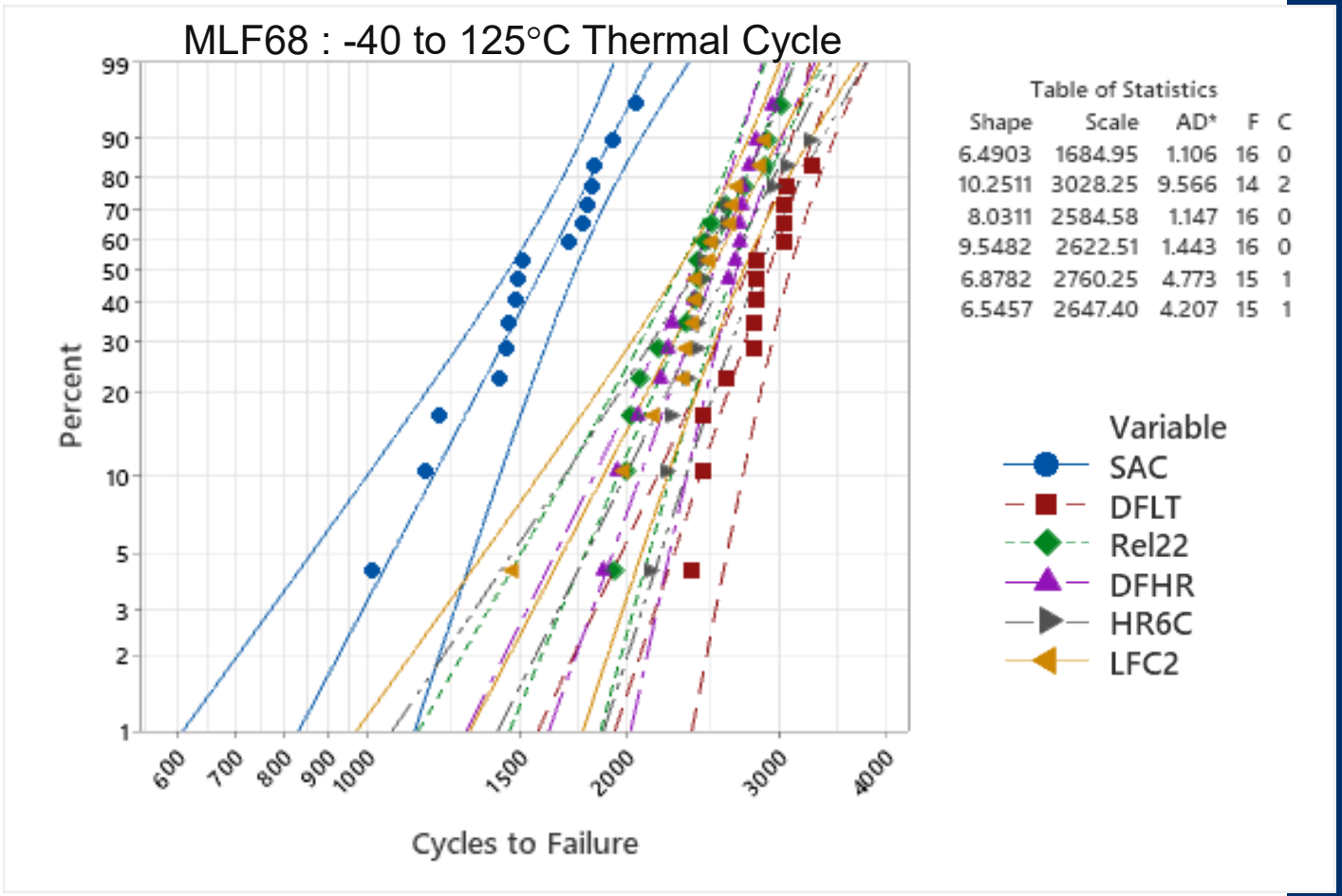
MLF68

- The MLF68 contains a matte Sn finish
- All alternative alloys performed significantly better than SAC305
- Note that Durafuse LT is arguably the best performer
  - Low performer among LGA196
- Note that Rel22 is arguably the worst among alternative alloys
  - Best performer among LGA196



MLF68
0.5mm pitch
10mm body

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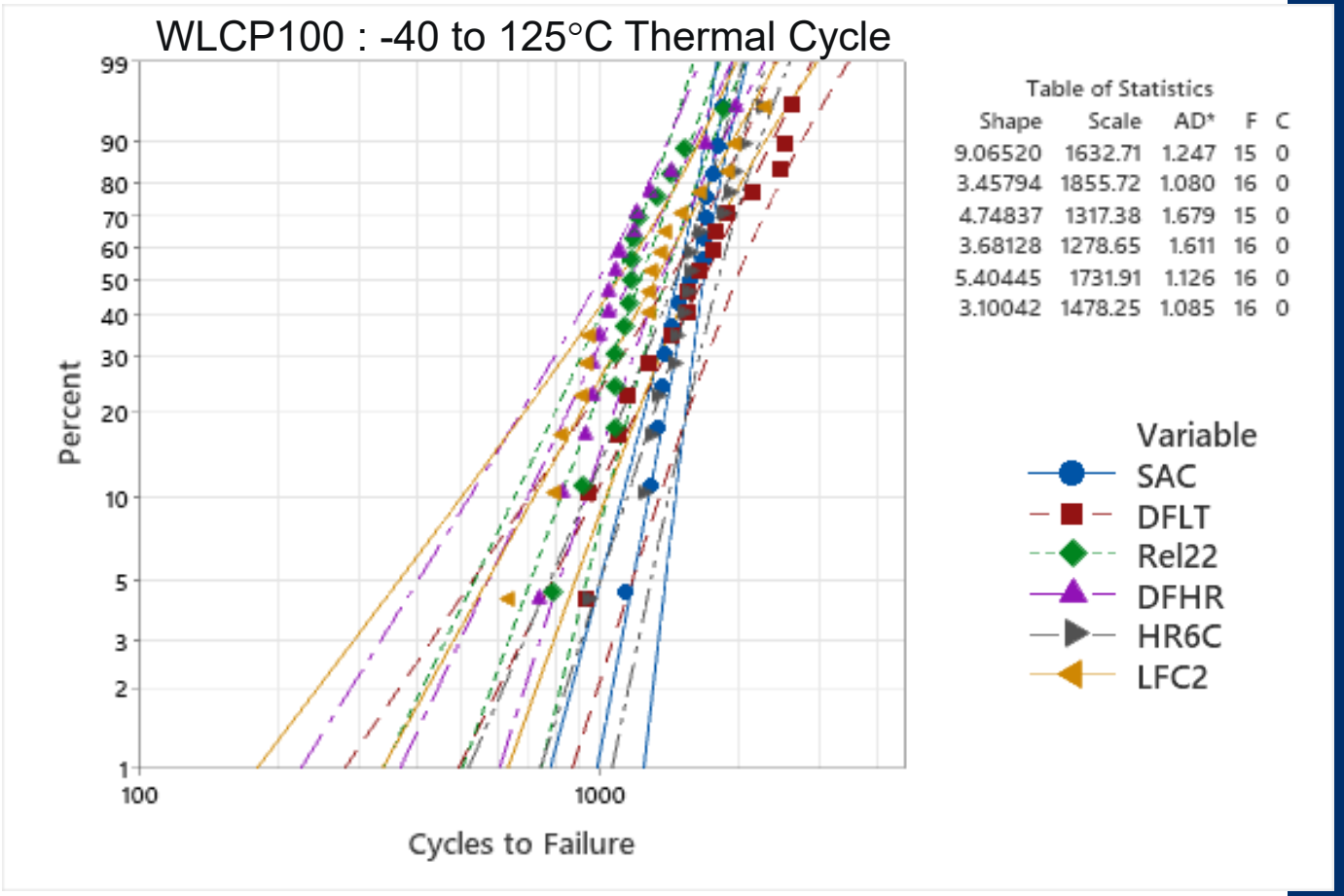
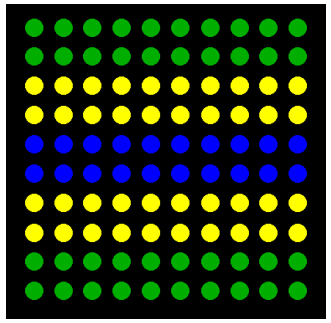
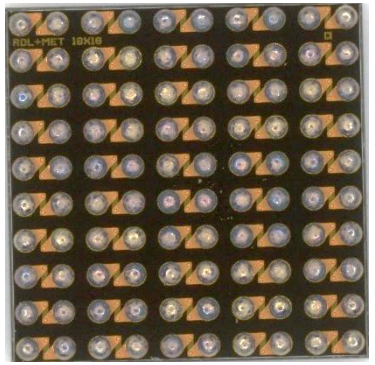
WLCSP100

- There are clearly differences among the populations in terms of performance, but nothing “disastrous”
  - The WLCSP joints are small; paste accounts for a large percentage of the final composition
  - All samples fail at or near the corners of the package as would be expected
    - Shear stresses are greatest at corner joints with WLCSP





WLCSP100
0.5mm pitch
5mm body



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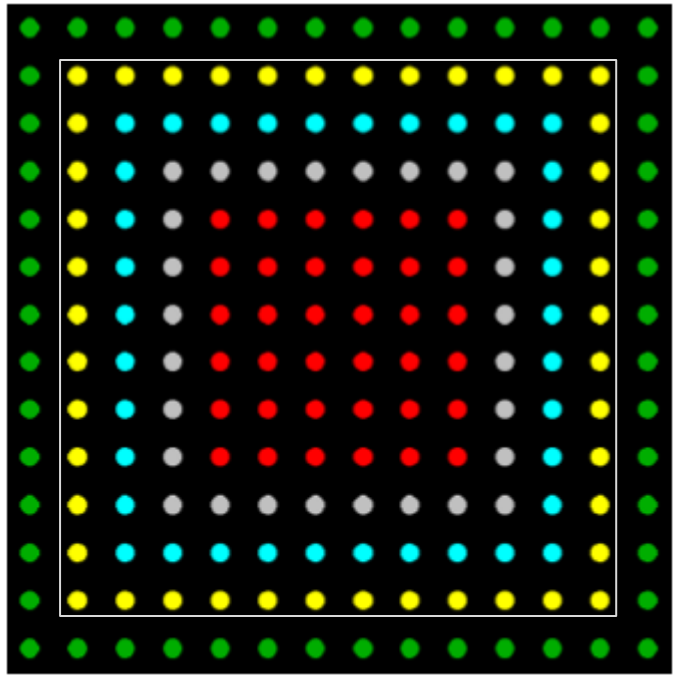
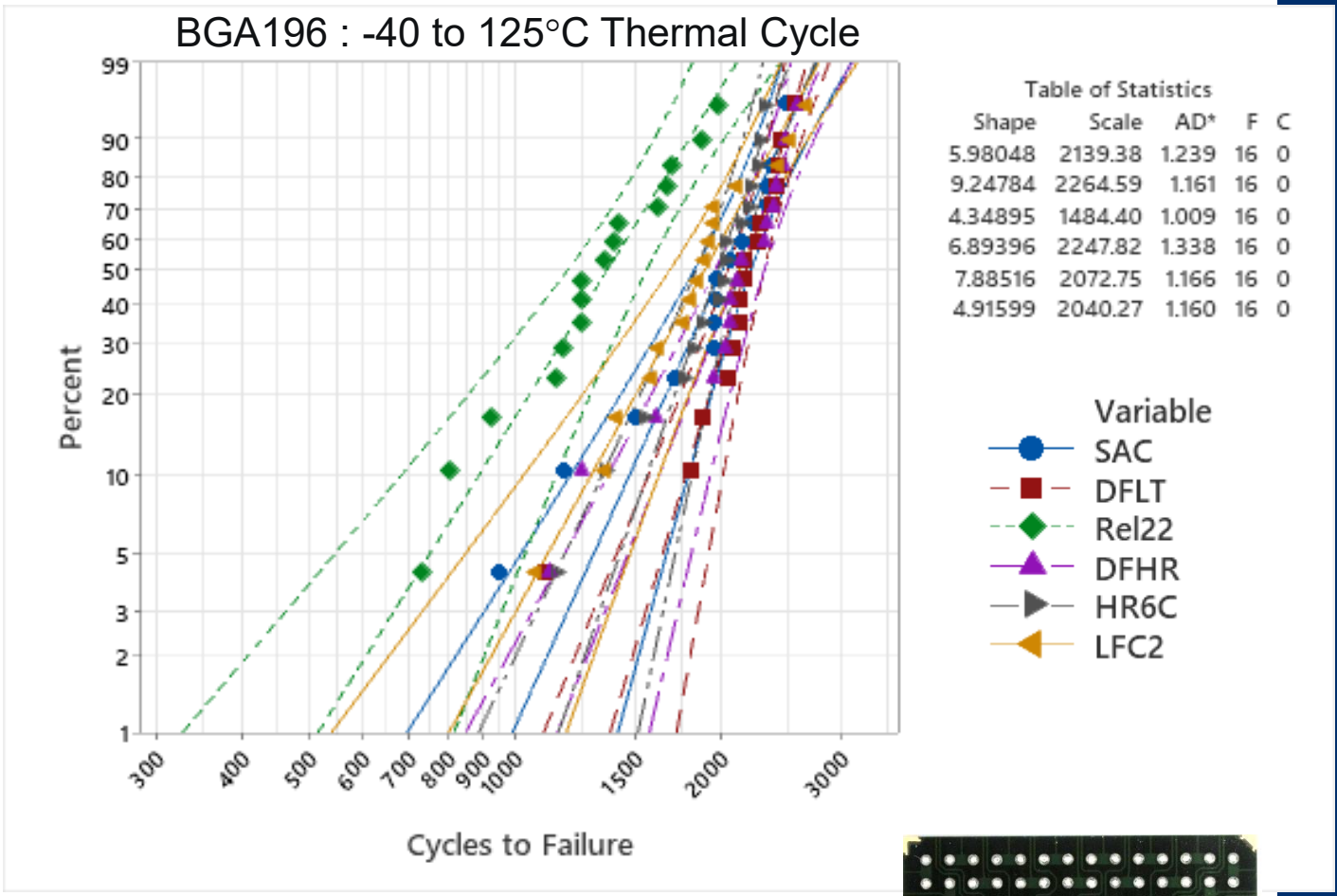
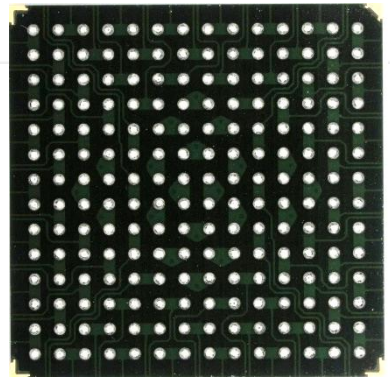
BGA196

- SAC305 component
- Rel22 not so good; all other pastes are perform somewhat similarly





BGA196
1.0mm pitch
15mm body



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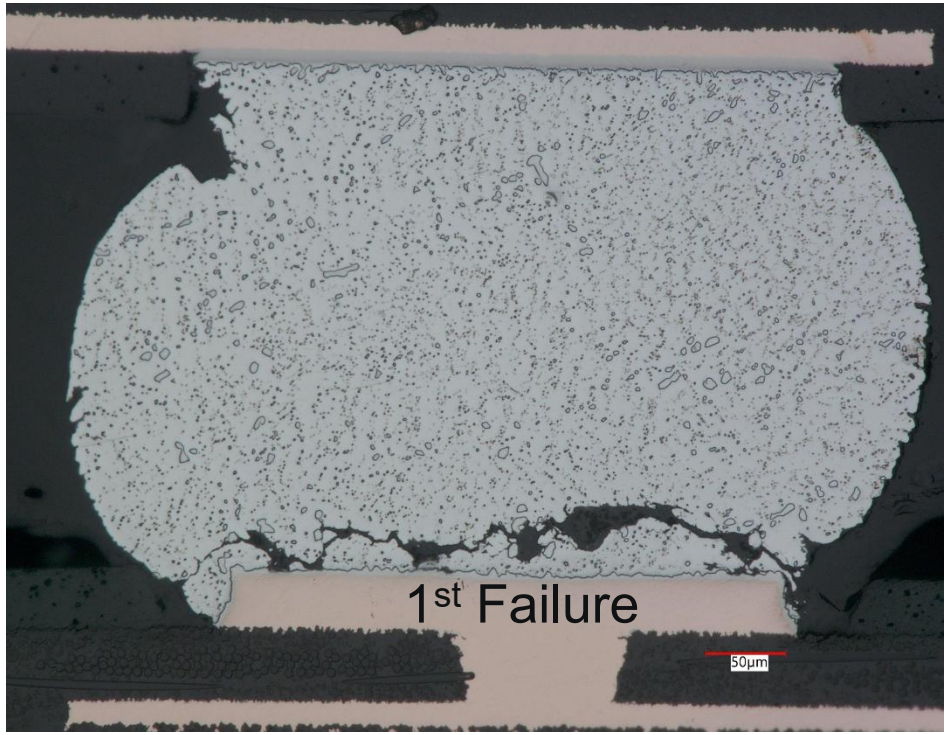
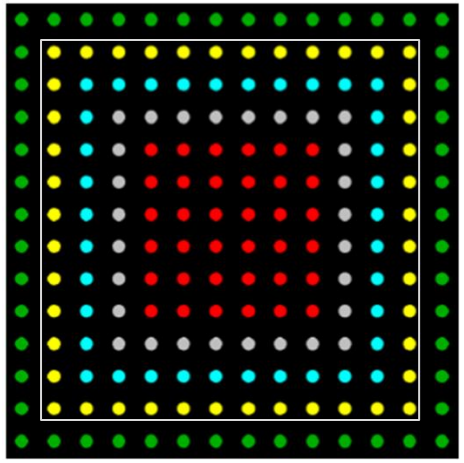
BGA196: SAC (Tied 1st)

- SAC305: Average performer for BGA196
- Corner joint failure dominates;
  - Warpage stress
  - Bulk solder failure
- Around 1900+ cycles we see other joint positions begin to fail





Barcode	Position	Cycles to Failure	Failure Location(s)																	
			1to2	2to3	3to4	4to5	5to6	6to7	7to8	8to9	9to10	10to11	11to12	12to13	13to14	14to15	15to16	16to17	17to18	18to19	19to20
358	u2	944			x																
361	u11	1174			x																
357	u2	1503	x																		
361	u2	1708			x																
360	u2	1948			x																
357	u11	1953								x				x			x				
355	u11	1962			x																
359	u11	1969			x				x												
354	u11	2067						x													
354	u2	2146			x					x											
358	u11	2225							x												
360	u11	2331			x																
359	u2	2344											x								
355	u2	2471			x																

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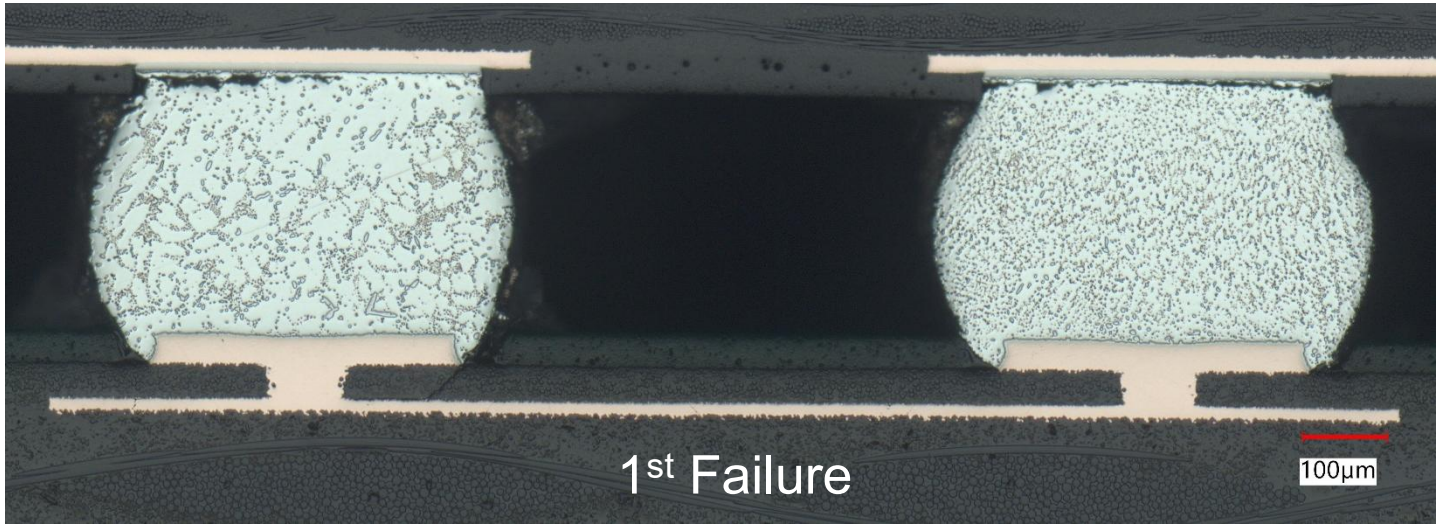
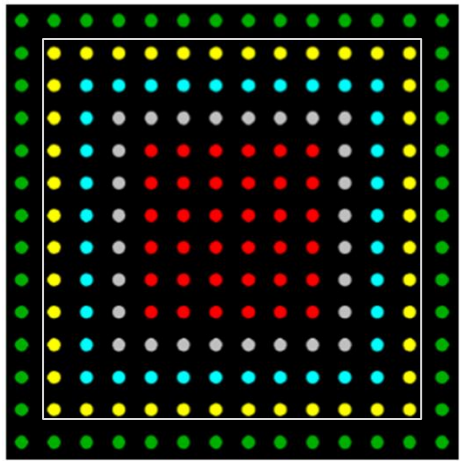
BGA196: Durafuse LT (Tied 1st)

- Durafuse LT is a top performer with BGA196
  - Shear fatigue failures
  - PCB pad cratering (but not electrical failure)
  - DFLT was worst performer with LGA196





Barcode	Position	Cycles to Failure	Failure Location(s)																	
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344	u11	2072							x												
344	u2	2381							x												
345	u11	2167							x												
345	u2	1879							x												
346	u11	2444					x			x											
348	u11	2132							x	x											
348	u2	2128					x							x							
349	u11	1104	x																		
349	u2	1810									x										
350	u11	2406								x											
350	u2	2561					x														
351	u11	2276			x																
351	u2	2421						x													
352	u11	2162			x				x												
352	u2	2268					x		x												

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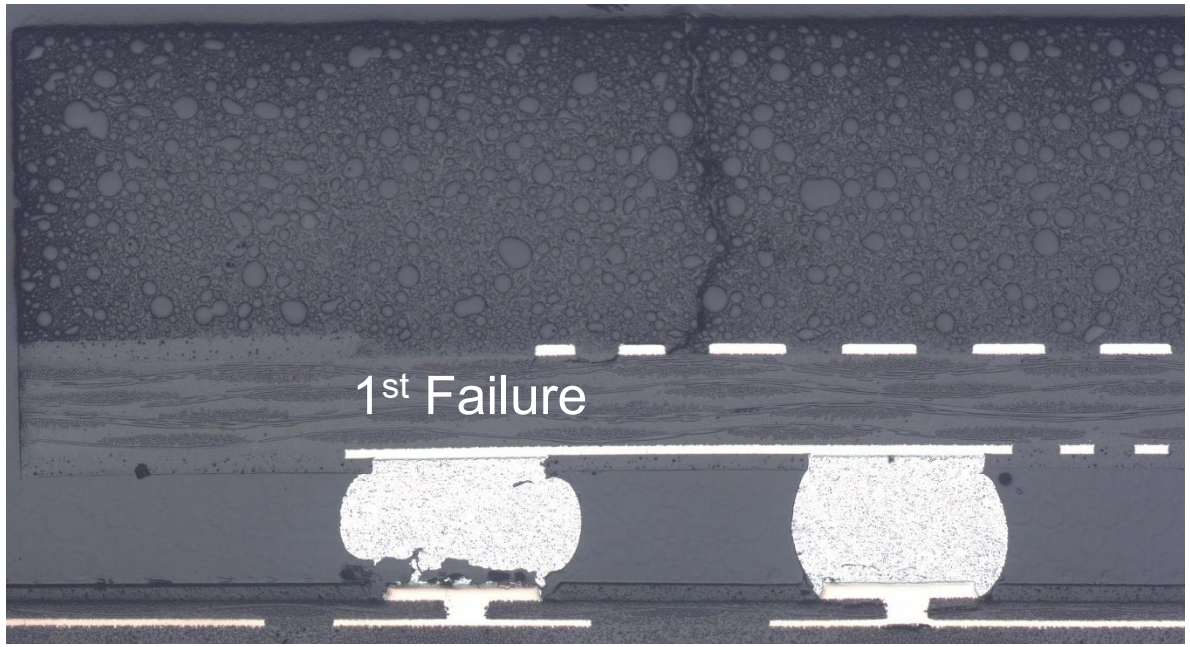
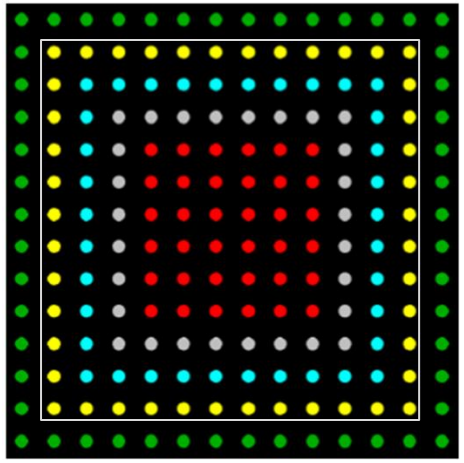
BGA196: Durafuse HR (Tied 1st)

- Durafuse HR was among the best performers for BGA196
  - First failure shows significant sample damage
    - PCB pad cratering
    - Body cracking





Barcode	Position	Cycles to Failure	Failure Location(s)																		
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374	u2	1124			x																
379	u11	1259	x																		
372	u11	1614			x																
377	u2	1962							x												
378	u2	2036												x							
375	u2	2072								x											
373	u2	2074								x				x							
376	u2	2122								x											
377	u11	2152			x																
373	u11	2322								x											
378	u11	2344			x	x				x											
374	u11	2400									x										
376	u11	2410		x										x							
379	u2	2471	x																		
375	u11	2500							x												
372	u2	2588								x											

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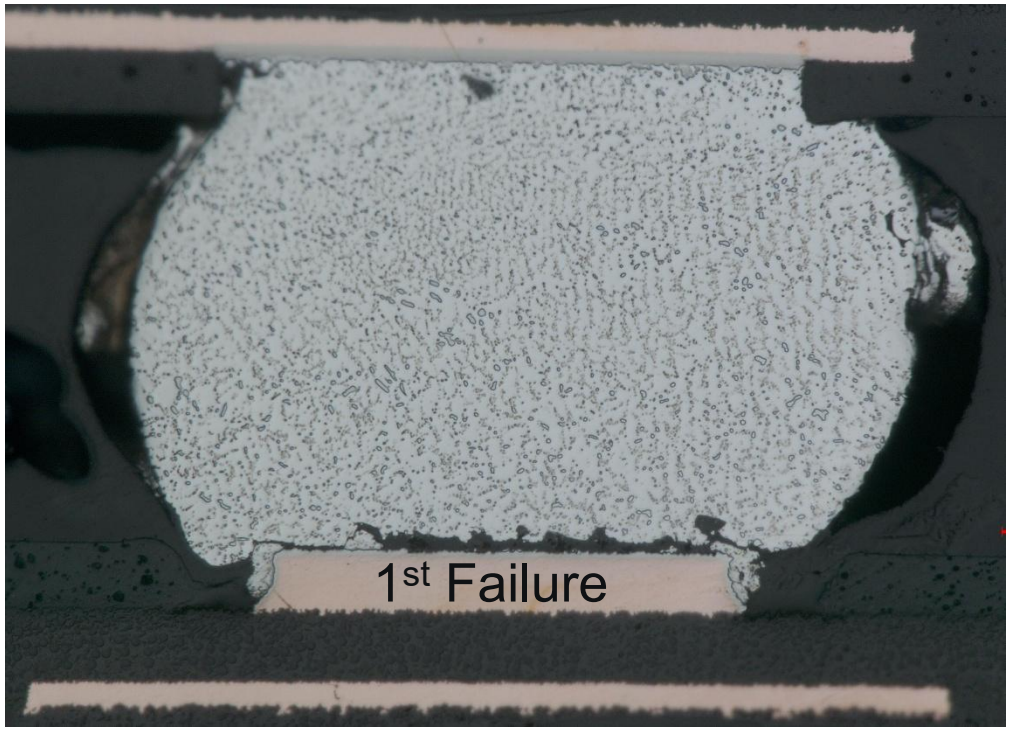
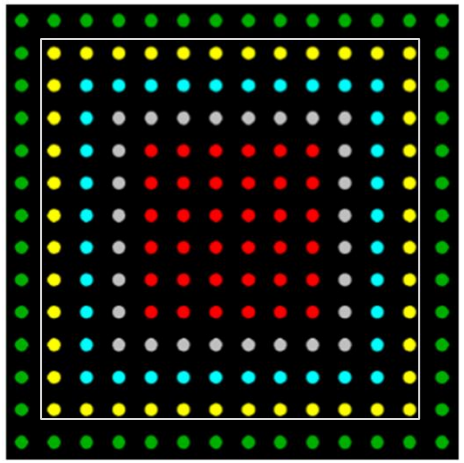
BGA196: Rel22 (6th)

- Rel22 was the worst performer with BGA196
  - 30% lower N63.2 than SAC305
  - Corner joint failures
    - IMC region failure
- Rel22 was best performer with LGA196





Barcode	Position	Cycles to Failure	Failure Location(s)																	
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368	u11	734			x																
370	u11	802			x																
370	u2	923			x																
364	u2	1149	x																		
368	u2	1182	x																		
367	u11	1257	x																		
364	u11	1259	x																		
366	u2	1259			x																
369	u2	1356	x																		
363	u2	1396			x																
366	u11	1427			x																
363	u11	1624			x																
365	u2	1671			x																
365	u11	1705	x																		
369	u11	1879						x													
367	u2	1986						x		x											

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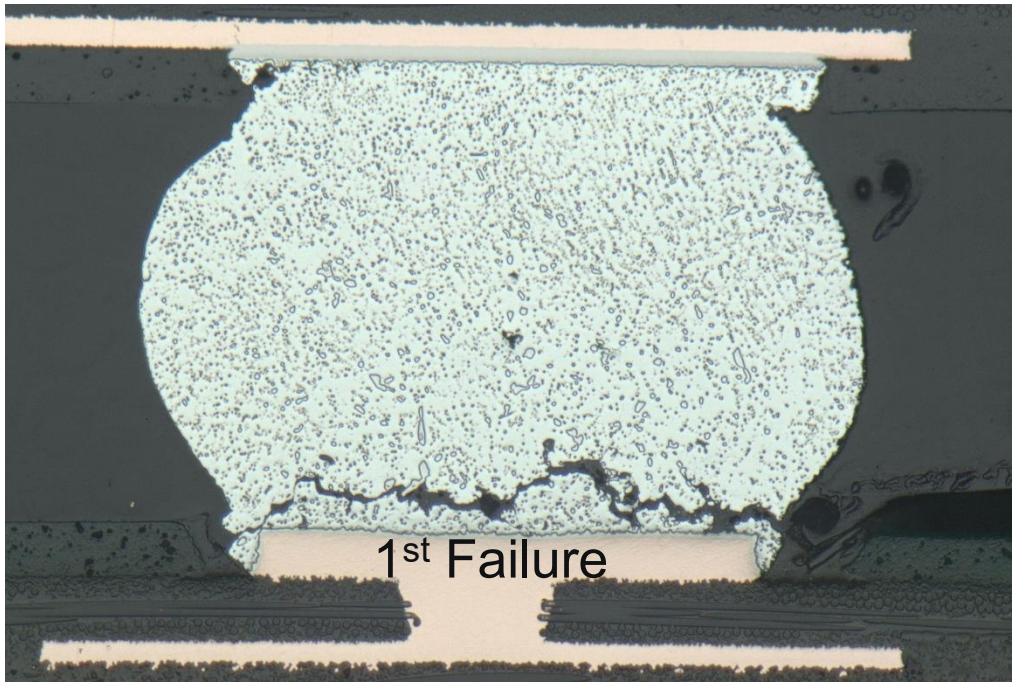
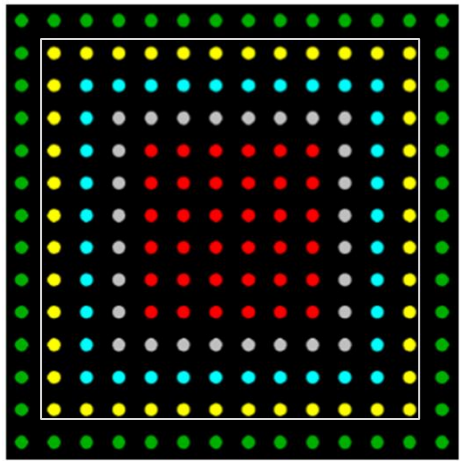
BGA196: HR6C (Tied 1st)

- HR6C did well; earliest failures are corner joints with transition to other locations





Barcode	Position	Cycles to Failure	Failure Location(s)																	
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494	u2	1154	x		x																
489	u2	1357			x																
489	u11	1544			x																
491	u2	1766	x																		
493	u11	1823			x																
494	u11	1889	x																		
490	u11	1985						x		x				x							
487	u2	2013	x		x																
492	u11	2028							x				x								
487	u11	2033	x				x														
491	u11	2155			x																
493	u2	2207			x																
490	u2	2214						x		x				x							
488	u2	2273							x				x								
488	u11	2295	x				x			x											
492	u2	2333											x		x						

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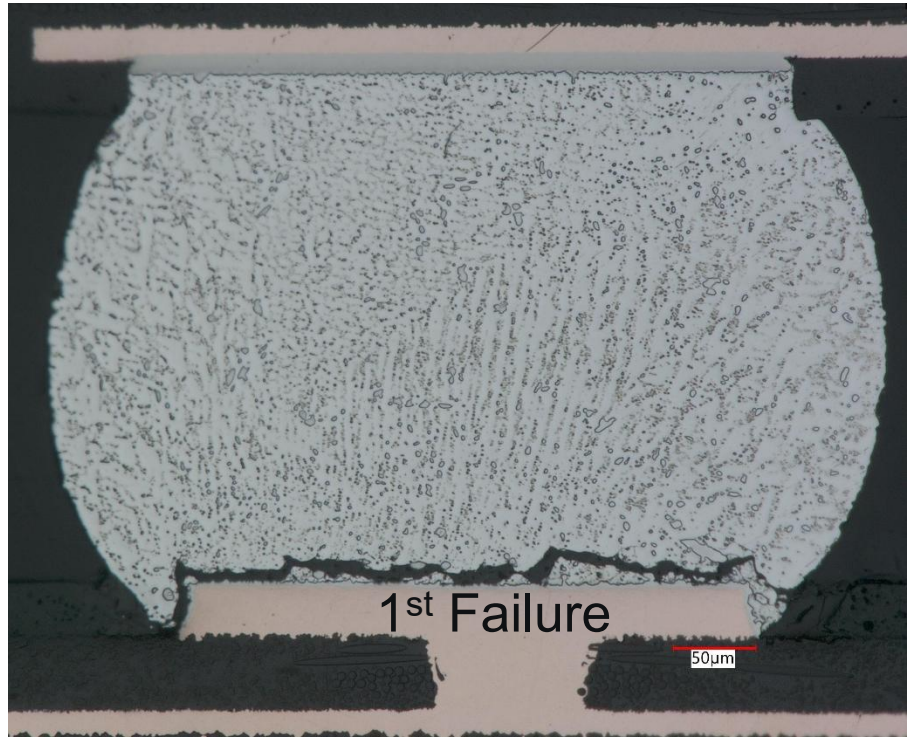
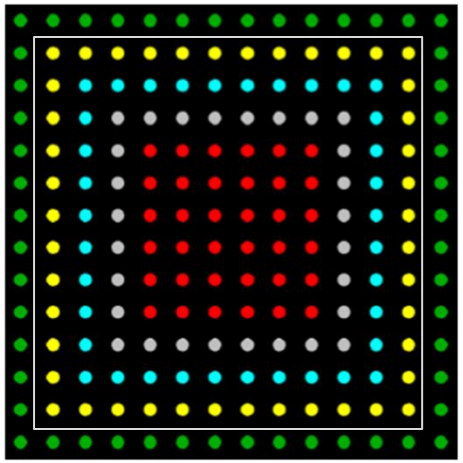
BGA196: LF-C2 (5th)

- LF-C2 is not quite as good as SAC305; primarily corner joint failures with cracking near PCB side





Barcode	Position	Cycles to Failure	Failure Location(s)																	
			1to2	2to3	3to4	4to5	5to6	6to7	7to8	8to9	9to10	10to11	11to12	12to13	13to14	14to15	15to16	16to17	17to18	18to19	19to20
499	u11	1070	x																		
499	u2	1357	x																		
500	u11	1410			x																
498	u2	1586	x																		
501	u11	1625																			
502	u2	1775	x																		
503	u11	1804	x																		
501	u2	1860	x																		
497	u2	1893			x																
500	u2	1921			x																
503	u2	1954			x																
504	u2	1961		x																	
502	u11	2111	x																		
504	u11	2444					x				x										
498	u11	2530	x							x	x										
497	u11	2677						x		x					x						

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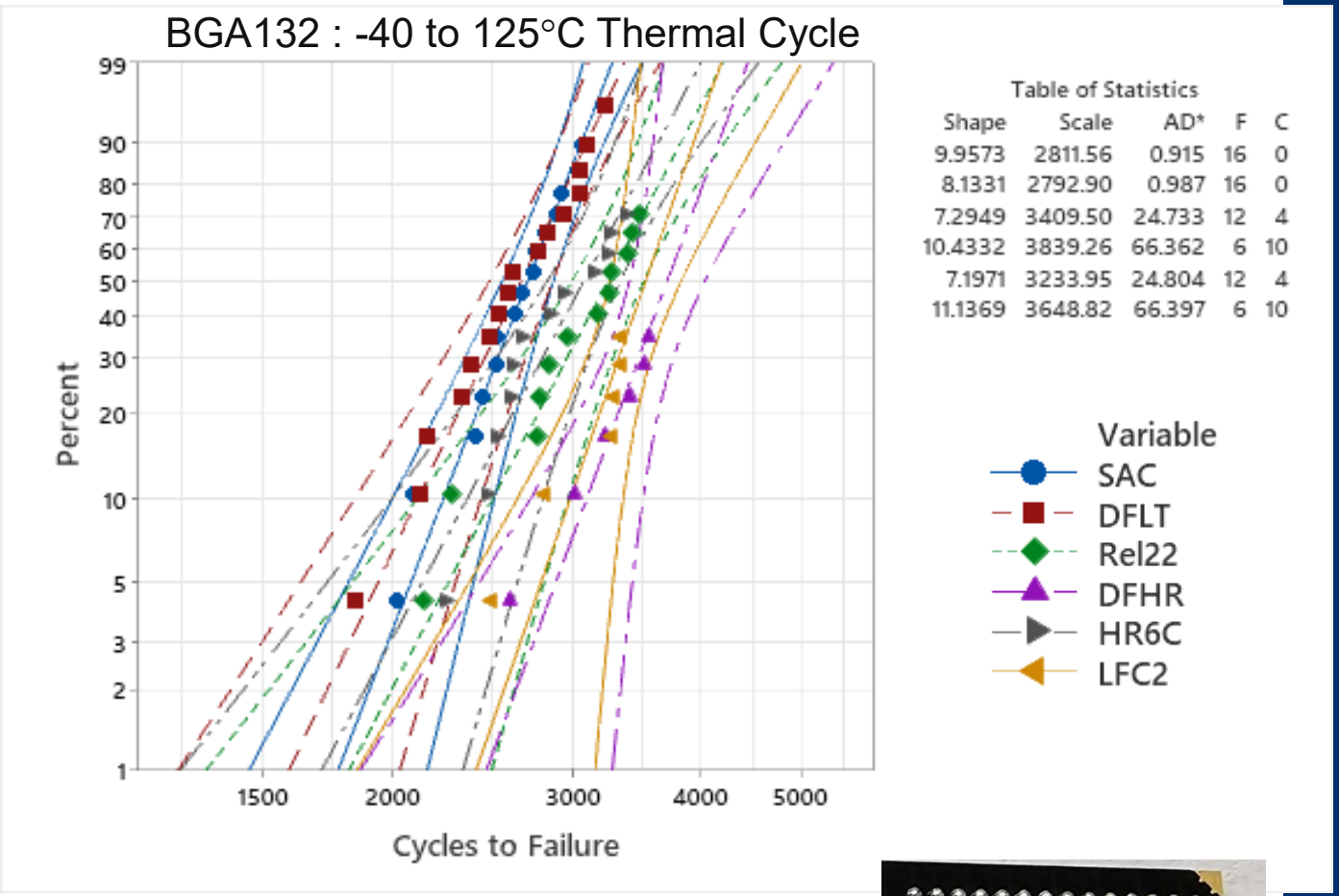
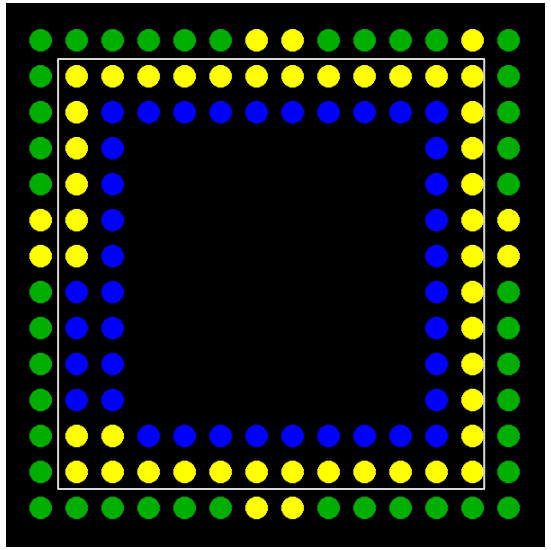
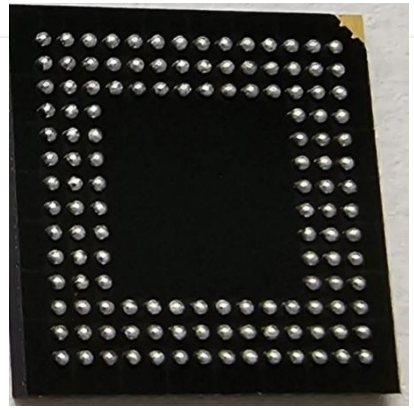
BGA132

- Everything is as good as or better than SAC305
- Joints located at yellow positions tend to fail (shear fatigue dominates)





BGA132
0.5mm pitch
8mm body



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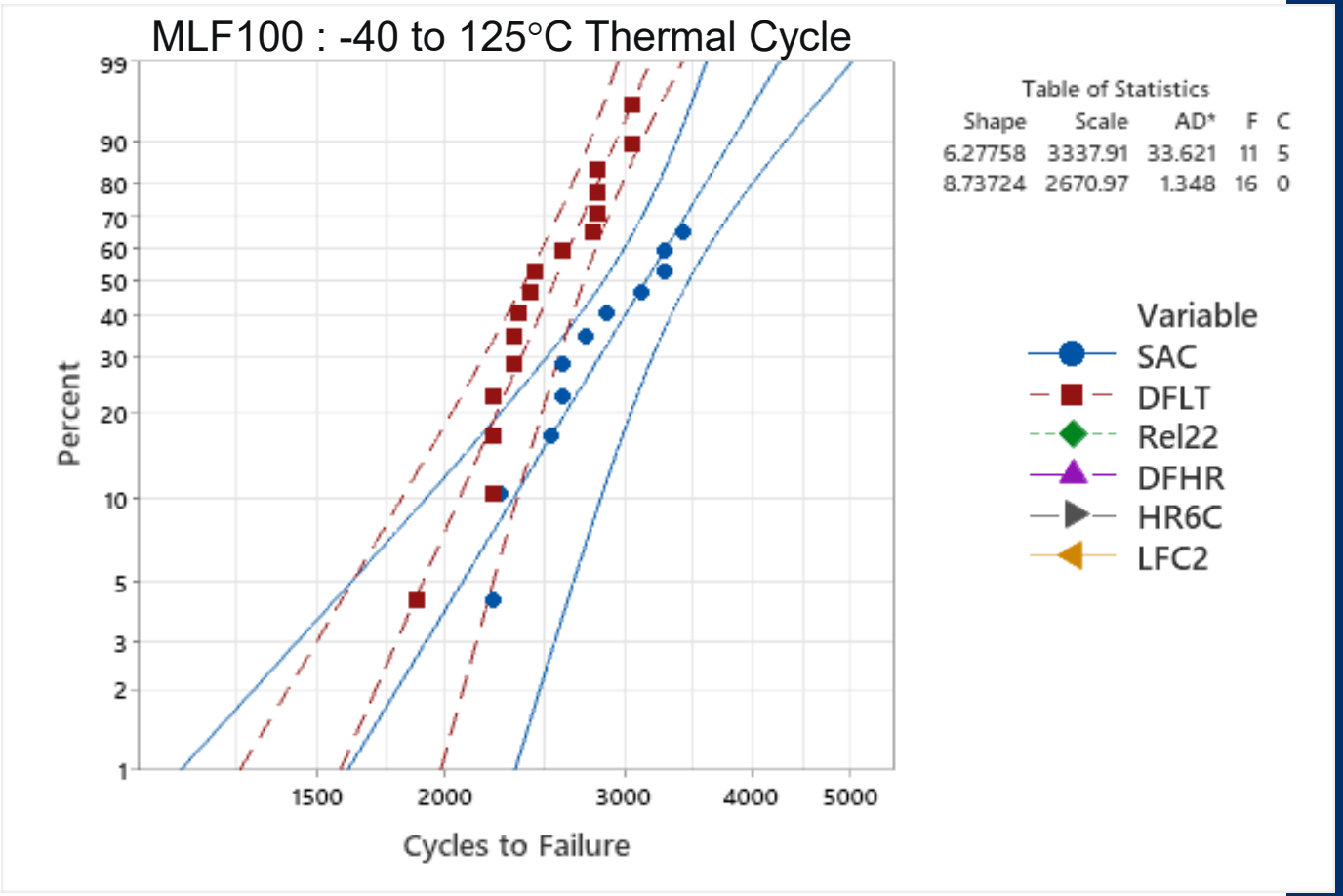
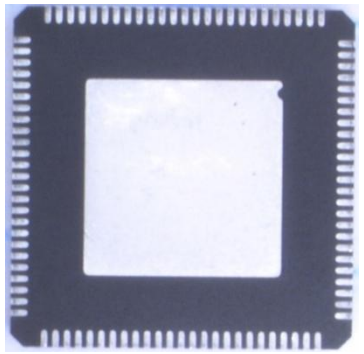
MLF100

- Component contains matte Sn finish
- The high reliability alloys haven't failed – much better than SAC305
- Durafuse LT isn't as good as SAC
  - DFLT did very well with MLF68



MLF100
0.4mm pitch
12mm body



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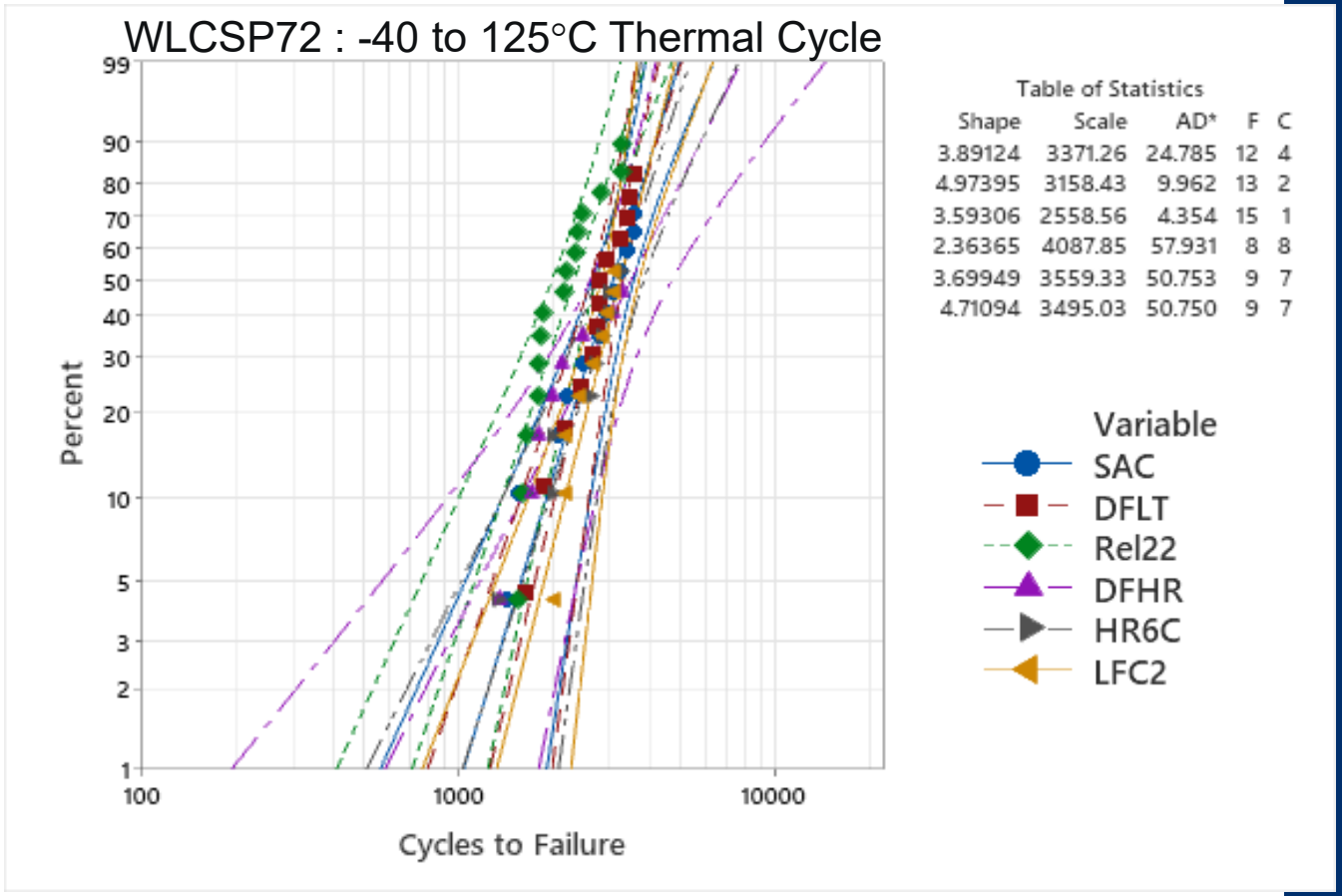
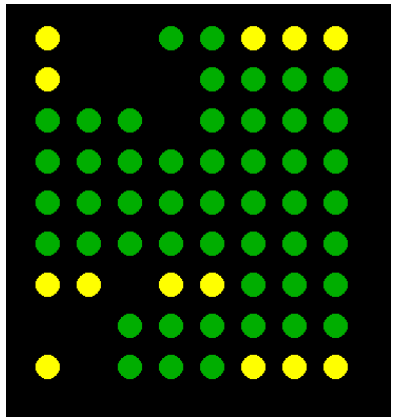
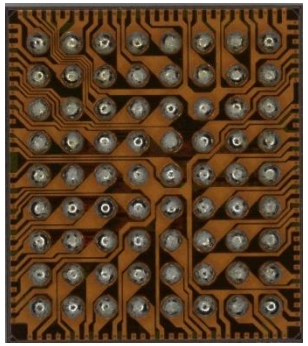
WLCSP72

- Corner joint failures dominate as would be expected
- Rel22 not as good as SAC305, but other alternative alloys are similar to SAC305





WLCSP72
0.35mm pitch
~3.5x3.2mm body



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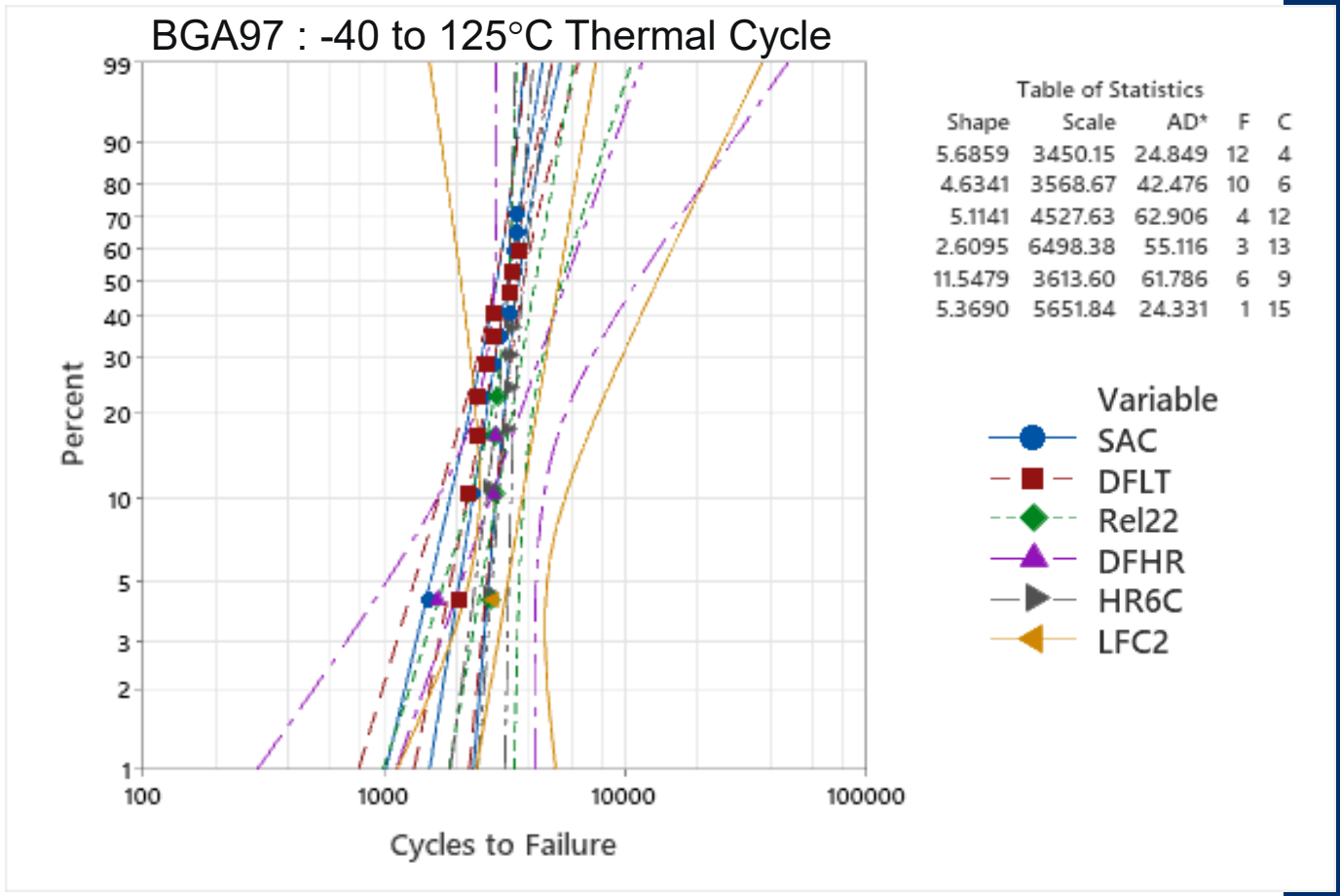
BGA97

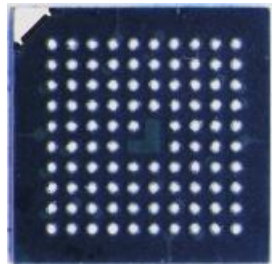
- This is a small device and tends to survive many cycles
  - Warpage stress is not an issue
  - Parts fail below die shadow, not at corners

- Often, the PCB and component body show damage before we see solder joint failures

- Overall, all paste options perform similarly based on available data



BGA97
0.4mm pitch
5mm body



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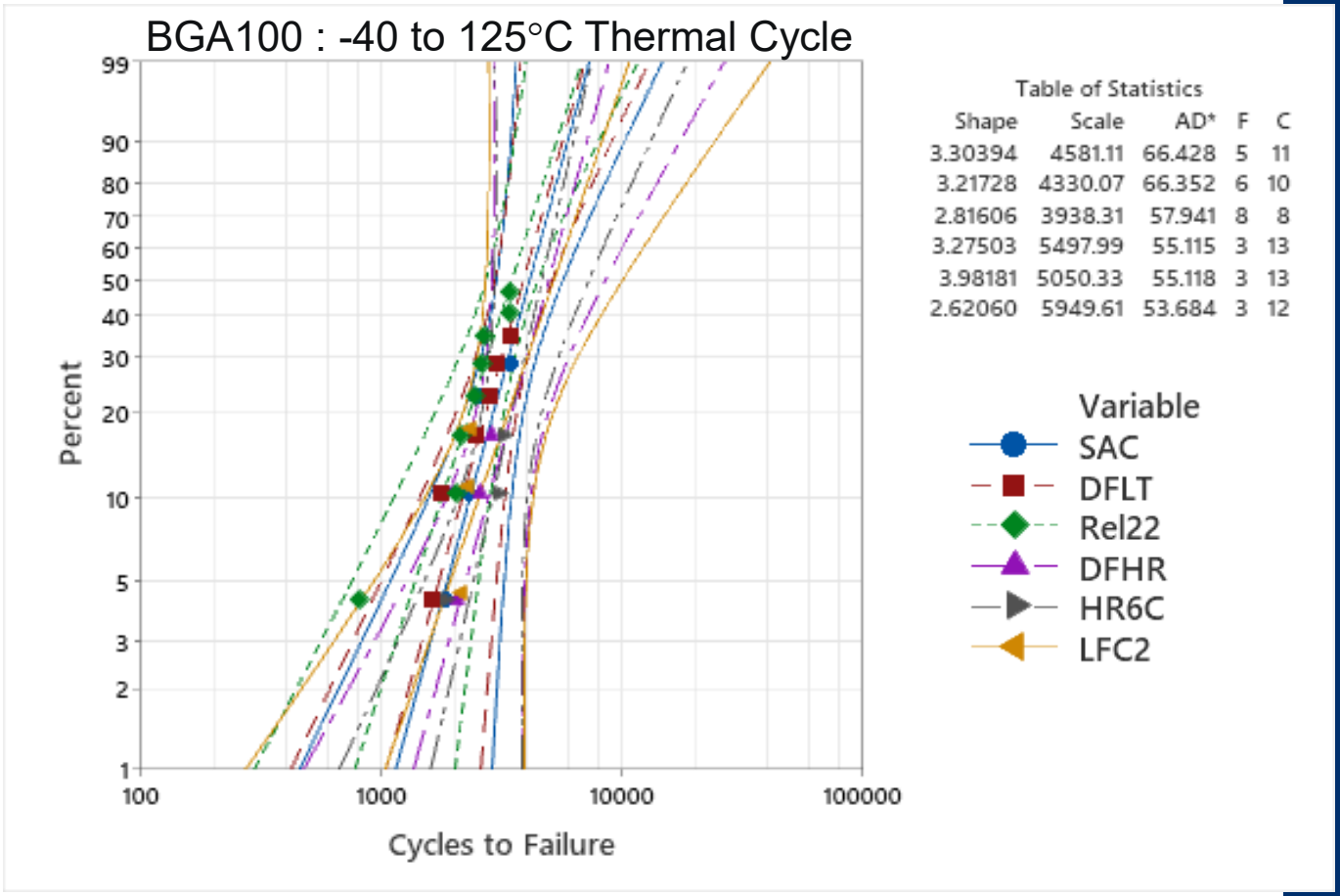
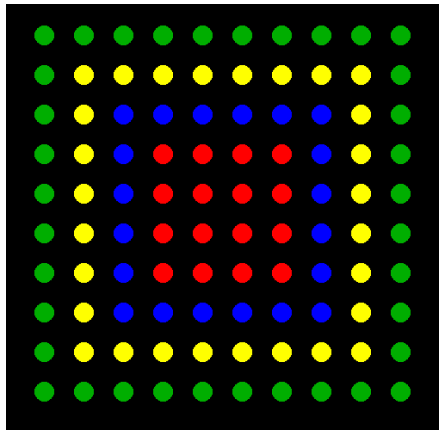
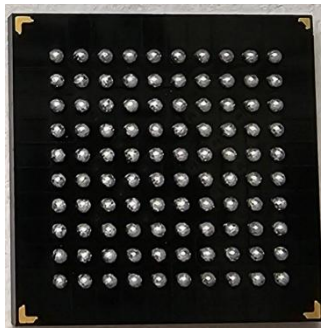
BGA100

- This is a small device and tends to survive many cycles
  - Warpage stress is not an issue
  - Parts fail below die shadow, not at corners
- Rel22 not as good as SAC, but not a terrible result





BGA100
0.8mm pitch
10mm body



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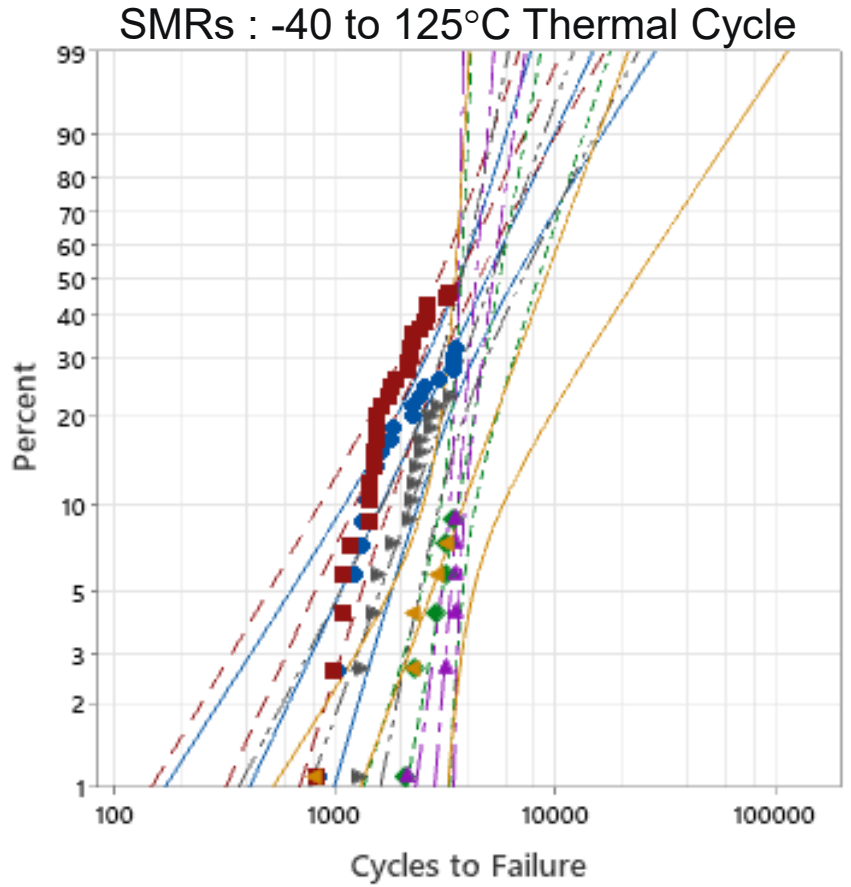
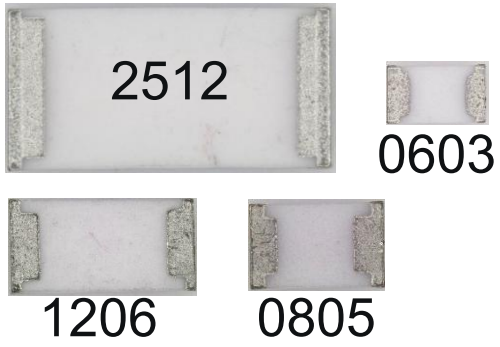
Surface Mount Resistors

- I’ve lumped all the resistors together
  - 2512 body size tends to fail first
  - 0603 tends to survive the longest
- Durafuse LT is not quite as good as SAC but the N15 numbers are nearly identical, so not a big deal if using “warranty” concept analysis





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Results Summary

	Paste					
	SAC305	DFLT	Rel22	DFHR	HR6C	LFC2
LGA196	T-4	6	1	T-2	T-2	T-4
MLF68	6	1	T-2	T-2	T-2	T-2
WLCSP100	T-1	T-1	T-5	T-5	T-1	4
BGA196	T-1	T-1	6	T-1	T-1	5
BGA132	T-6	T-6	3	T-1	4	T-1
MLF100	5	6	T-1	T-1	T-1	T-1
WLCSP72	T-1	T-1	6	T-1	T-1	T-1
BGA97	6	6	T-1	T-1	6	T-1
BGA100	6	6	6	T-1	T-1	T-1
SMRs	5	6	T-1	T-1	4	T-1

Overall Ranking (1 through 6)
90% Confidence Weibull

	Paste				
	DFLT	Rel22	DFHR	HR6C	LFC2
LGA196	X				
MLF68					
WLCSP100		X	X		X
BGA196		X			
BGA132					
MLF100	X				
WLCSP72		X			
BGA97					
BGA100		X			
SMRs					

Ranking Relative to SAC
“Practical Significance”
Green = comparable or better
2P-Weibull / 3P-Weibull / Mann-Whitney / N06

- I never find a solder paste that consistently outperforms others across multiple variables
- Durafuse HR, HR6C and LF-C2 perform very well overall relative to SAC305
- Durafuse LT isn’t really in the same class as the other alternative pastes, yet overall performance was “OK”
- I would say Rel22 was also “OK”, BG196 results were quite bad; needs further investigating?

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A Few More Notes

- Alternative alloys like the ones discussed today are often very strong and can generate significant component and/or PCB damage at levels not typically encountered with SAC305 or SnPb
  - Timely failure analysis is required
  - Dummy components don’t always tell the whole story
  - Don’t just examine solder joint integrity
    - Look for pad cratering
    - Look for trace and via failure / damage
    - Look for component body damage
      - Especially with ceramic and silicon based devices
- I will argue one last time that the solidification temperature of a solder alloy affects its stress state for the remainder of its lifetime
  - Higher solidification temperature equals higher stress

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Questions?

- meilunas@uic.com

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