Understanding PCB Design & Material Warpage Challenges Which Occur During B2B/Module-Carrier Attachment

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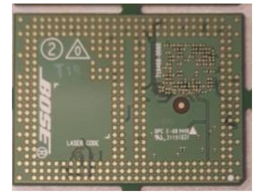
Originally Presented at SMTAI 2016 by Donald Adams and Todd MacFadden of Bose Corporation & Ryan Curry of Akrometrix

Outline/Agenda

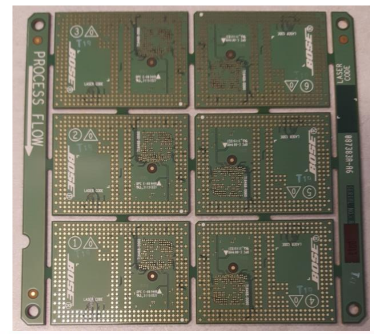
- Problem Description
- Analysis of Issue
- Experiment Phase 1
- Shadow Moiré Description
- Experiment Phase 2
- Conclusions
- Q & A

Module-Carrier Assembly Definitions

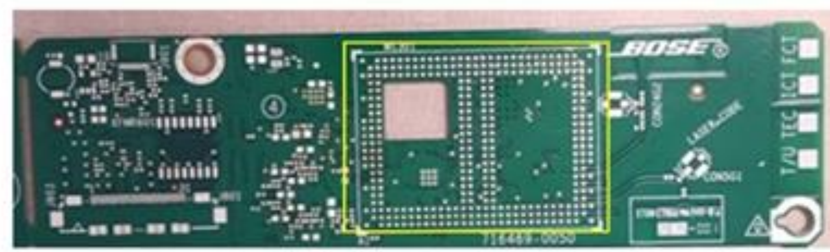
Module: Double-sided PCB with LGA pattern (30mm x 40mm 0.7mm thick)



Module Pallet: 6-up array of modules as received from PCB suppliers



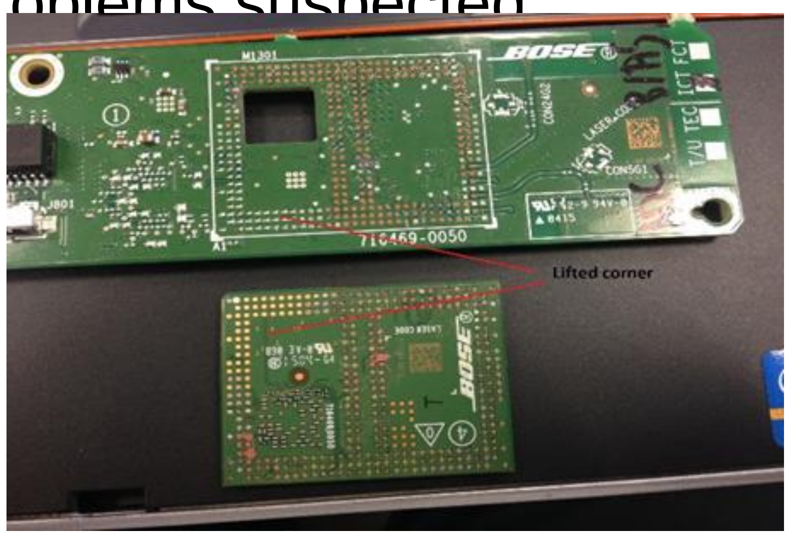
Carrier: Double-sided PCB with corresponding LGA pattern (1.57mm thick)



Module-Carrier: Assembled system

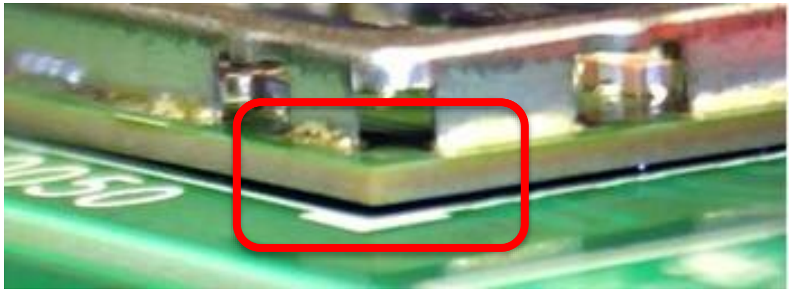
Problem Overview:

- Solder opens between module and carrier
- 50,000 dppm defect rate (target is 5,000 dppm)
- Module-Carrier assemblies are costly to rework
- Lifted corner was noted on failed units; solder paste never made contact with module LGA lands
- Coplanarity problems suspected



Module-Carrier Coplanarity

- LGA solder joints are sensitive to coplanarity issues
- Seating plane is defined by solder paste thickness: approx. 0.18mm
- IPC warpage allowance is 0.75%



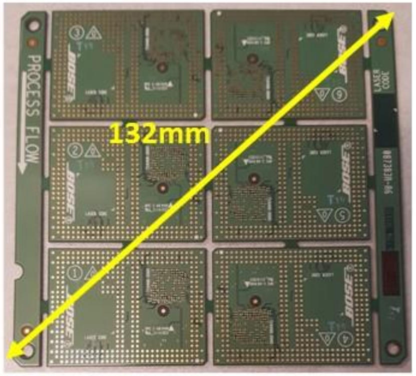
Lifted corner exceeds seating plane of 0.18mm

Module

- IPC Warpage allowance: 0.7mm
- Seating plane: 0.18mm

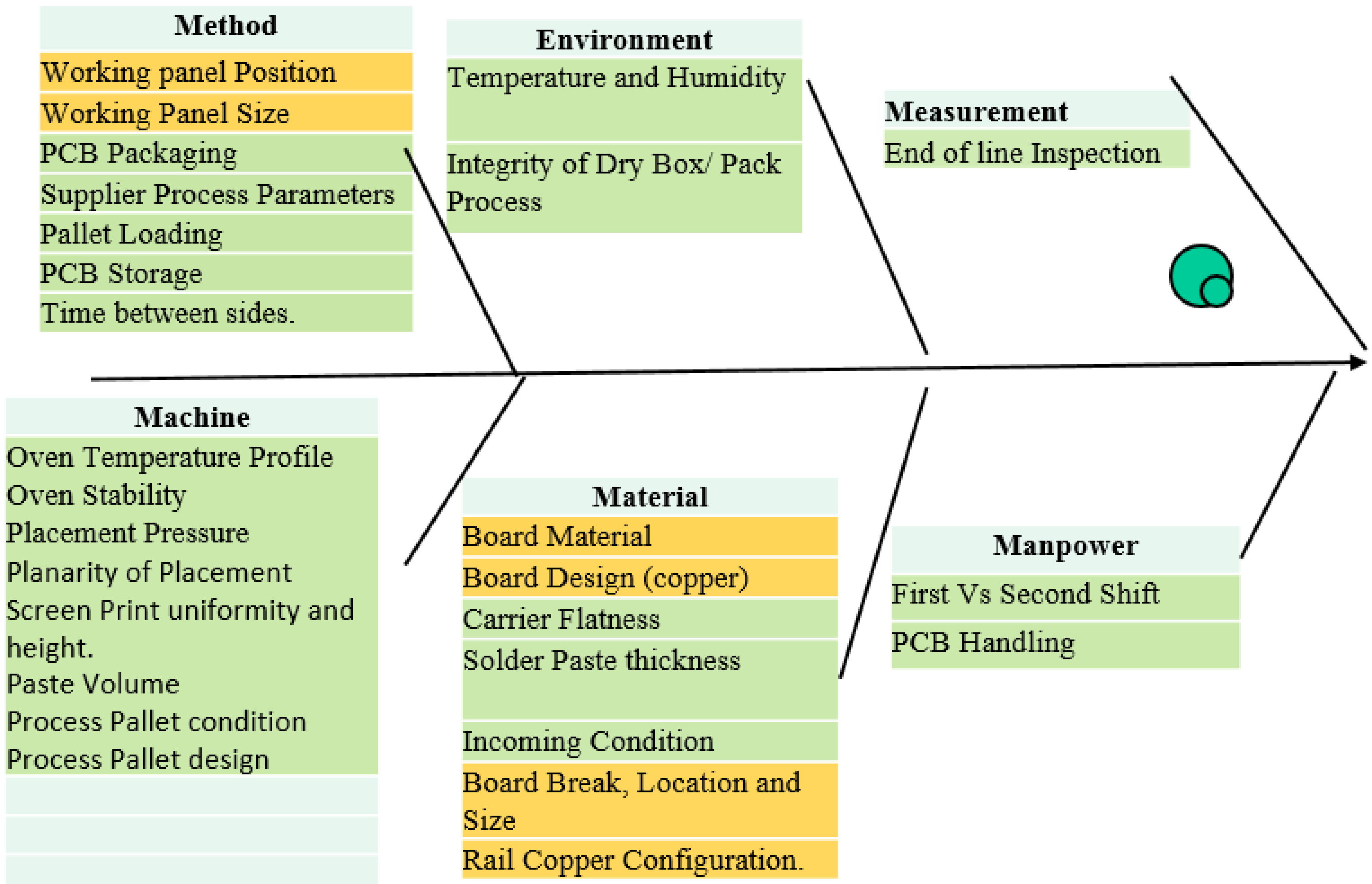
IPC warpage criterion is ~4x too loose!

6-up Module Pallet



- IPC Warpage allowance: 2.0mm
- Assumption: to ensure module flatness within seating plane, pallets should be <0.5mm

Process Analysis



Attempts to Improve Yield

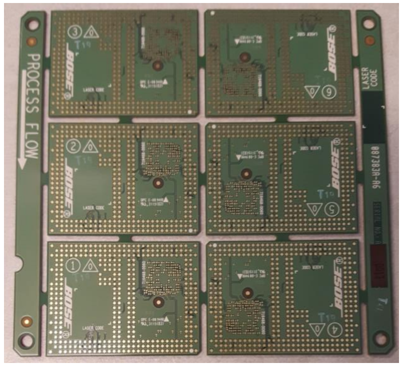
1. Baking modules with weights provided temporary flatness but did not improve attachment yield
2. Increased solder paste height & volume DID NOT solve defects and resulted in solder shorts
3. Reflow profile adjustment had no effect
4. Segregate the most warped pallets at incoming inspection

None of these efforts improved yield

Screening out the most warped pallets improved attachment yield

Screening Modules for Flatness

6-up module pallet



- 100% of incoming module pallets were hand-sorted for warpage
- Sorted into 3 categories:

Group	Warpage		Production Status	Distribution
A	<0.5mm	Minor or none	Acceptable	75%
B	0.5-1.0mm	Moderate	Unacceptable - HOLD	22%
C	>1.0mm	Severe	Unacceptable - HOLD	3%

Using Group A only, yield improved from 50,000 dppm to ~10,000 dppm

- Better, but still unacceptable; target is <5,000 dppm
- Also, hand sorting is not a long-term option

Need to: (1) confirm warpage as root cause and (2) develop long-term solution

How to Improve Attachment Yield?

2-phase approach:

PHASE 1: Verify a correlation between module warpage and attachment yield.

PHASE 2: DoE to isolate the key factors contributing to board warpage make changes and verify improvement.

PHASE 1: Correlating Warpage and Attachment Yield

APPROACH

- Process boards from all three warpage groups (A, B and C)
- Measure warpage of each board various times in the process
- Monitor attachment yield

Population of samples available per warpage group

Group	Warpage		Supplier A	Supplier B
A	<0.5mm	Minor or none	1380	1380
B	0.5-1.0mm	Moderate	1380	1380
C	>1.0mm	Severe	438	726
		TOTALS	3198	3486

Over 6500 samples to be tested

PHASE 1: Correlating Warpage and Attachment Yield

Key Requirements for Success:

1. Large number of samples needed, due to relatively low failure rate
2. Accurate Measurements
3. Quick Acquisition of Data
   - Under 3 minutes
   - Within cycle time preferred to reduce delays
4. Automation of data collection
5. Ability to link data to serial numbers for traceability

PHASE 1: Correlating Warpage and Attachment Yield

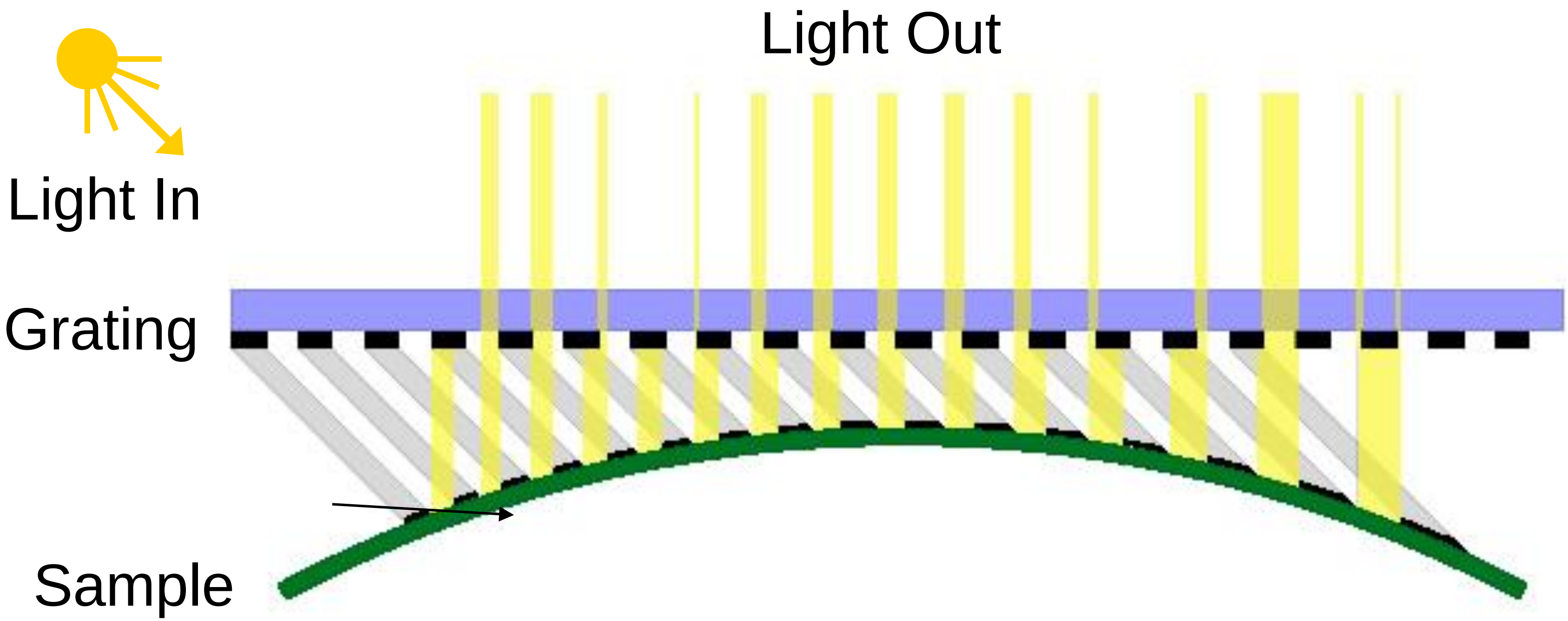
Measurement options considered:

- Hand measuring with pins and gauges – too slow, not accurate
- Use existing 3D solder paste inspection – not developed
- Utilize a metrology contractor near the Tijuana plant – none found
- Develop laser scanner system – too complicated to integrate
- Collaborate with equipment supplier to lease Shadow Moiré system

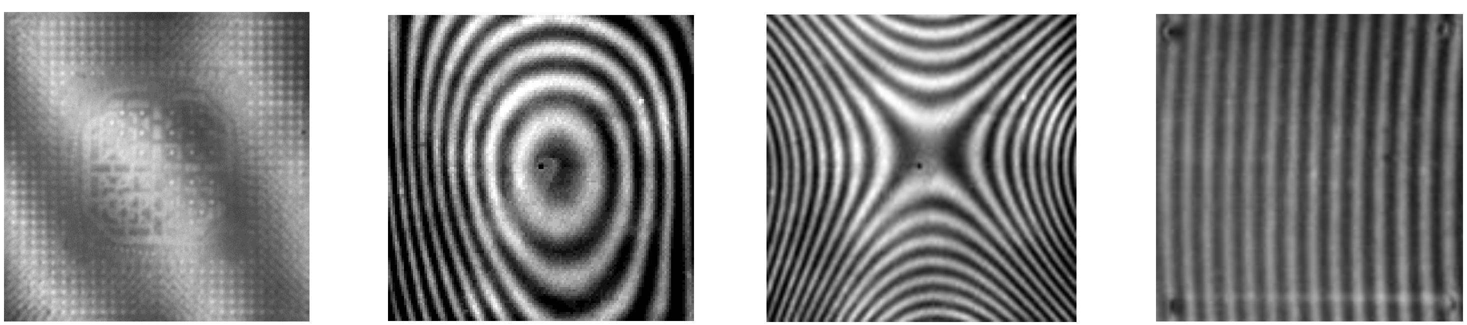
Temporary installation of Shadow Moiré system at factory enabled:

1. Ability to take **<u>thousands</u>** of measurements very quickly
2. Accurate measurements
3. Ability to assess warpage in localized regions of PCB
4. Multiple measurements throughout assembly process
5. Automated data acquisition to facilitate analysis

A Brief Explanation of the Shadow Moiré Technique



Example Fringe Intensity Images



PHASE 1: Warpage Correlation Results

- Strong apparent correlation between warpage and attachment yield

Group	Warpage		Total Samples Measured	Failure Rate (ppm)
A	<0.5mm	Minor or none	2760	513
B	0.5-1.0mm	Moderate	2760	28751
C	>1.0mm	Severe	1164	50301

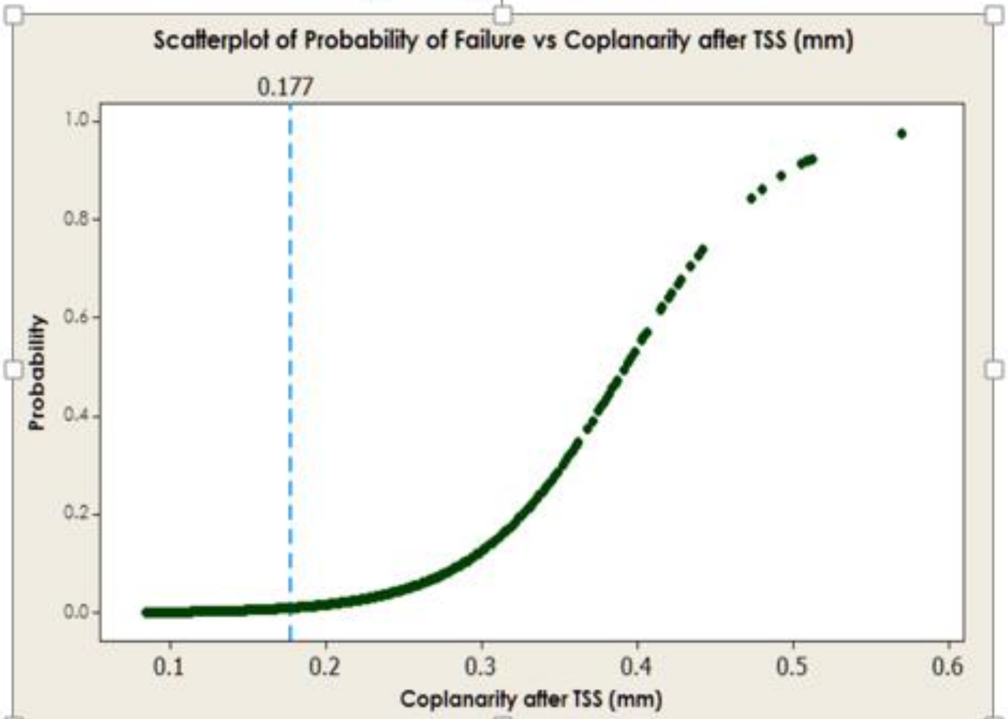
Greater warpage directly correlated to worse attachment yield

PHASE 1: Warpage Correlation Results (cont.)

Statistically significant failure probability

- 1.08% failure rate at 0.177mm coplanarity
- Degree of warpage of as-received pallets correlates to probability of failure increases

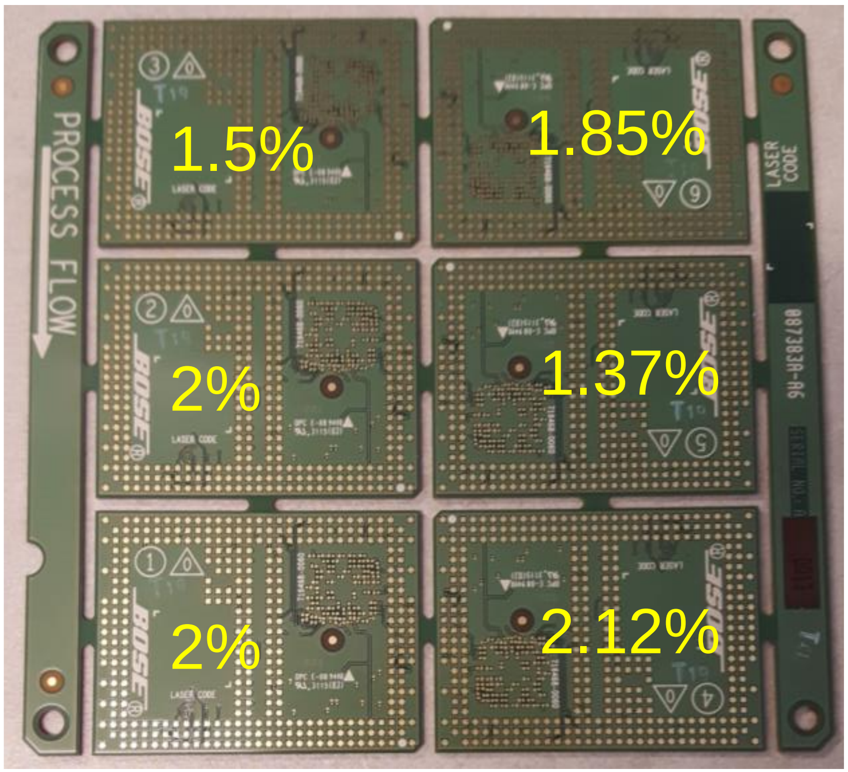
Logistic Regression curve



Confirming statistical significance was possible only because of the large number of datapoints enabled by the Shadow Moiré system

PHASE 1: Warpage Correlation Results (cont.)

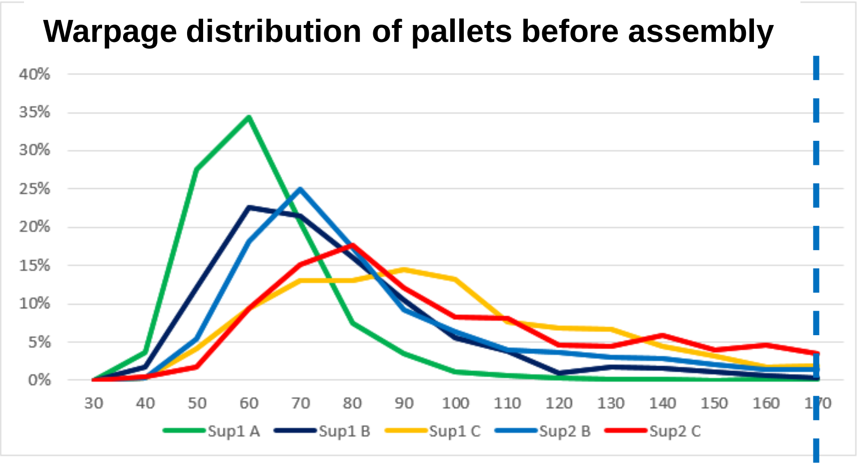
Was module location in the pallet significant?

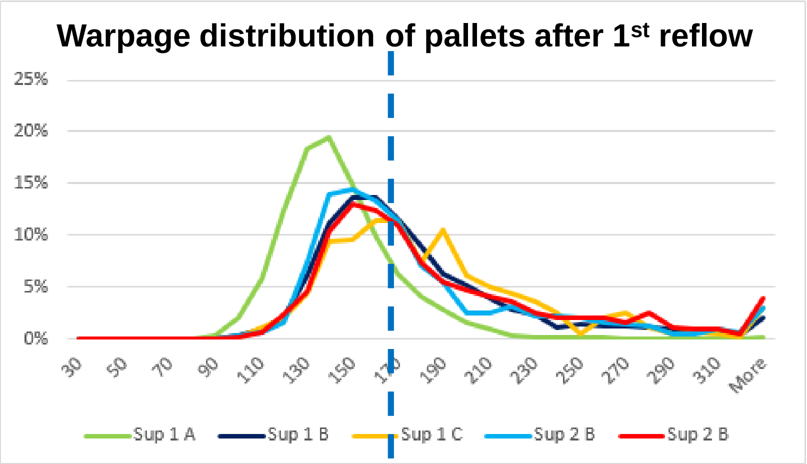


- P-Value is high (=0.793)
- NO. Location of a module in the pallet is NOT significant

PHASE 1: Warpage Correlation Results (cont.)

Module Coplanarity at room Temperature



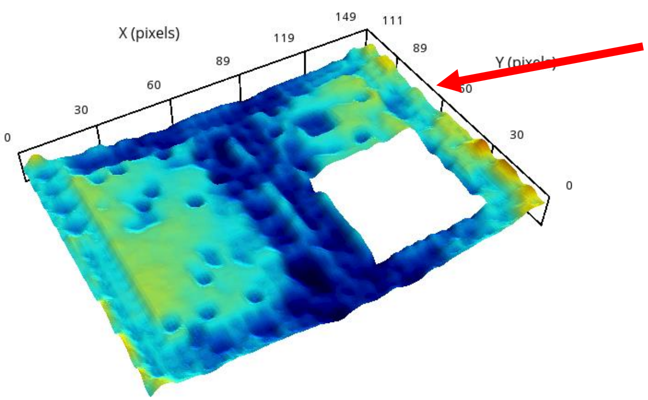


Target coplanarity: 0.17mm

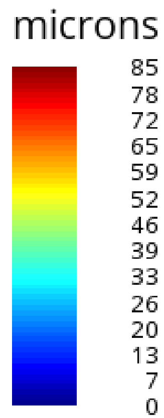
These charts show that the overall degree of warpage increased after 1 reflow cycle compared with initial measurement

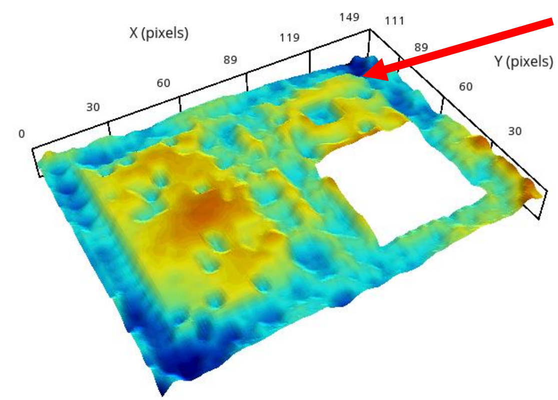
PHASE 1: Warpage over Reflow

Thermal shadow moiré analysis enables view of module and carrier during reflow

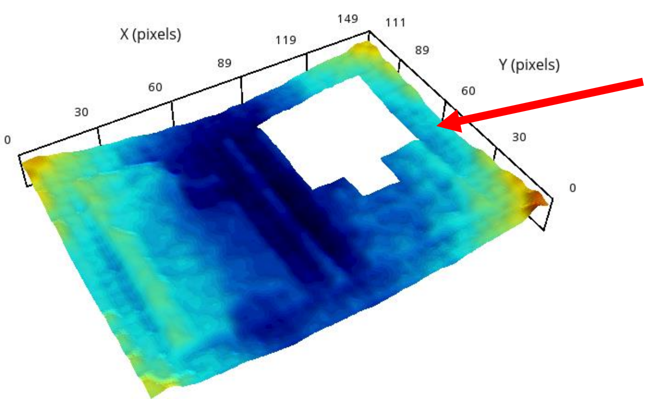


Carrier Room Temp

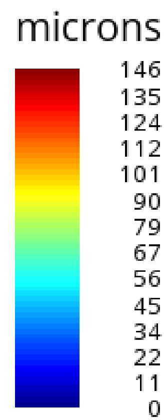


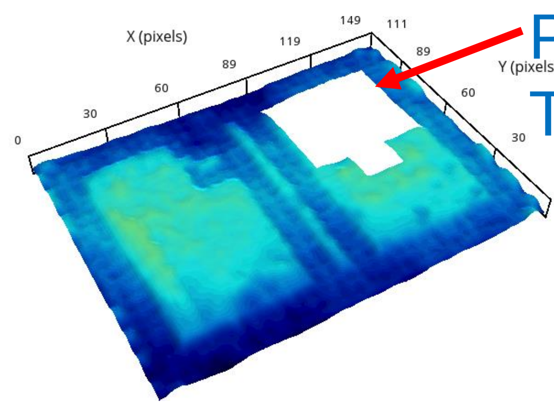


Carrier Peak Temp



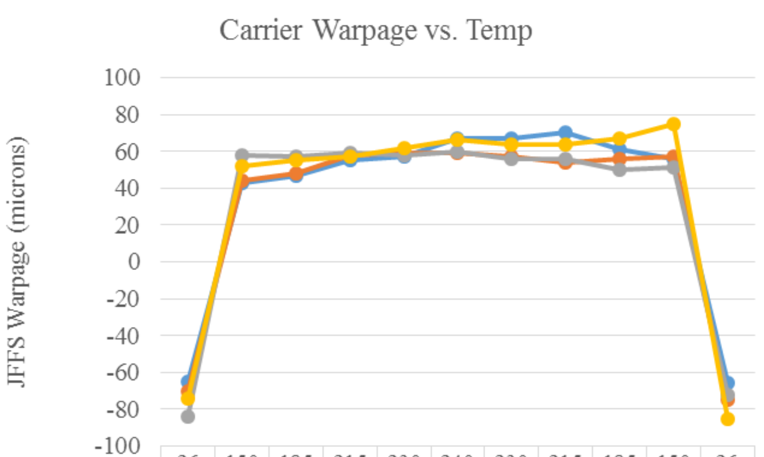
Module Room Temp



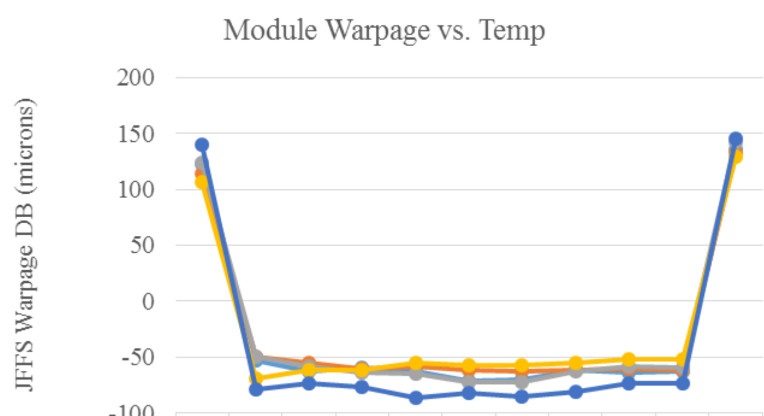


Module Peak Temp

Additional Data Point: Warpage over Reflow



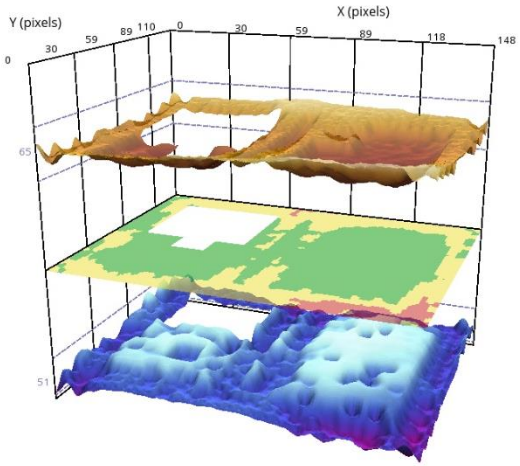
	26	150	185	215	230	240	230	215	185	150	26
Carrier 1	-65	43	47	55	57	67	67	70	61	56	-66
Carrier 2	-70	44	48	58	59	59	57	54	56	57	-75
Carrier 3	-84	58	57	59	58	60	56	56	50	51	-72
Carrier 4	-74	52	55	57	62	66	64	64	67	75	-85



	26	150	185	215	230	240	230	215	185	150	26
Module 1	123	-53	-63	-59	-63	-71	-70	-61	-64	-63	136
Module 2	114	-50	-55	-60	-58	-61	-63	-62	-60	-61	132
Module 3	124	-50	-58	-64	-65	-72	-72	-63	-58	-59	142
Module 4	107	-69	-61	-61	-55	-57	-57	-55	-52	-52	129
Module 6	140	-79	-73	-77	-86	-82	-85	-81	-73	-73	146

- Individual Module and Carrier boards behave very similarly over reflow
- Module is significantly more warped at room temp
- During reflow, module board generally “smiles” while carrier board “frowns” – moving away from each other

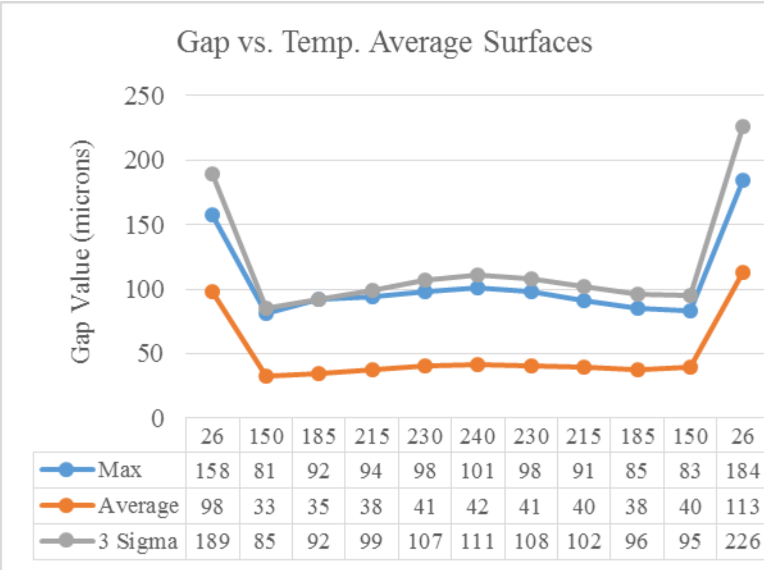
Additional Data Point: Interface Analysis over Reflow



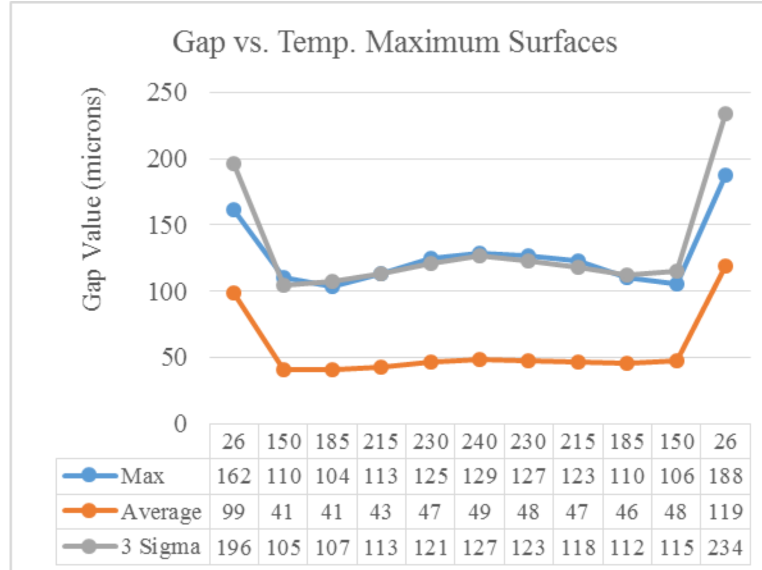
Peak Reflow Temperature Warpage Overlay Plot

- Paste thickness ~165 microns at RT
- Collapses to roughly half that height at liquidus
  - Gap Pass/Warning/Fail Map
  - Pass <50 microns
  - Warning >50 but <82 microns
  - Fail >82 microns
- High gap values indicative of possible open joints - paste is not in contact with both surfaces
- Failure locations correlate well with actual opens seen in production

Additional Data Point: Interface Analysis over Reflow



	26	150	185	215	230	240	230	215	185	150	26
Max	158	81	92	94	98	101	98	91	85	83	184
Average	98	33	35	38	41	42	41	40	38	40	113
3 Sigma	189	85	92	99	107	111	108	102	96	95	226

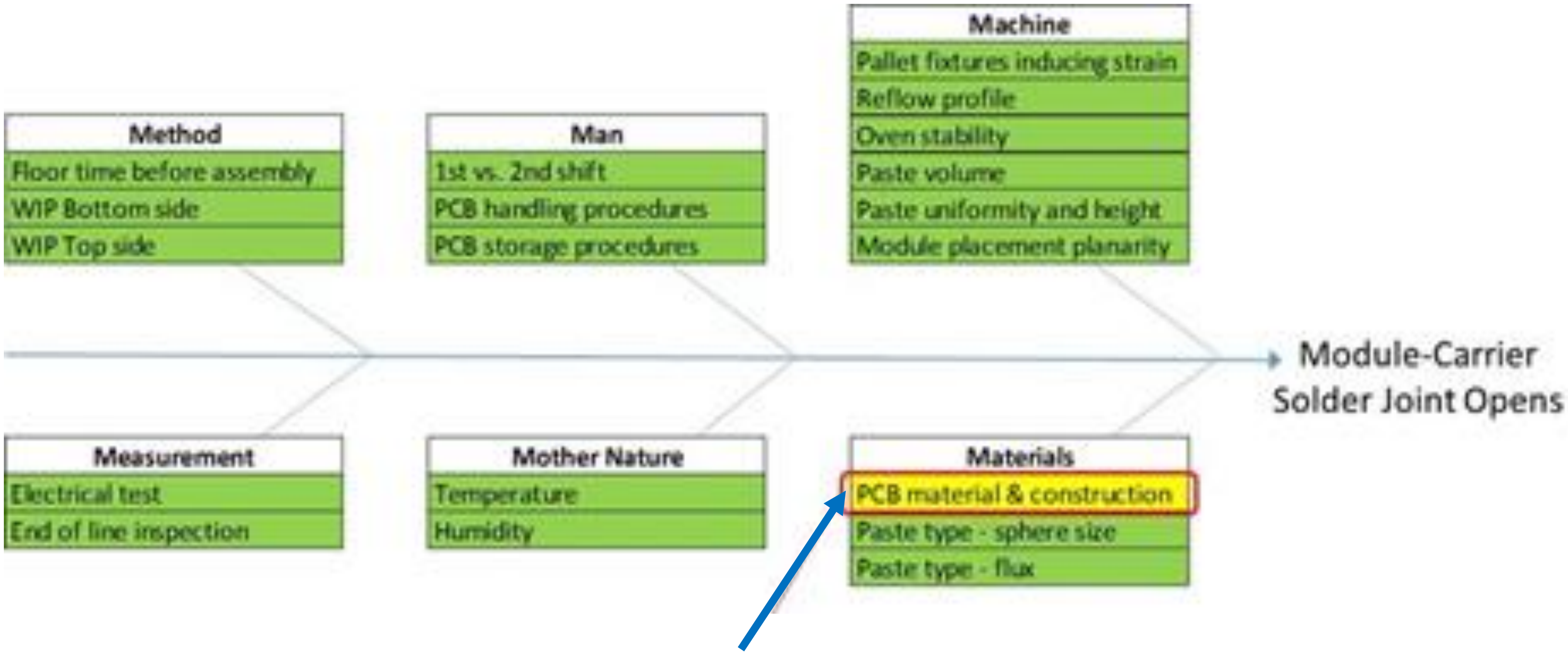


	26	150	185	215	230	240	230	215	185	150	26
Max	162	110	104	113	125	129	127	123	110	106	188
Average	99	41	41	43	47	49	48	47	46	48	119
3 Sigma	196	105	107	113	121	127	123	118	112	115	234

Gap values over temperature: indicates temperatures where gap between the two surfaces is larger than the paste thickness

- For the average case, gap values were below paste thickness at all temperatures except RT
- For the maximum cases, gap values were over the limit: seen as opens in production

PHASE 2: Factors that Influence PCB Warpage



PCB materials and construction

Identified as most significant factors

PHASE 2: PCB Materials and Construction DoE

Key variables evaluated

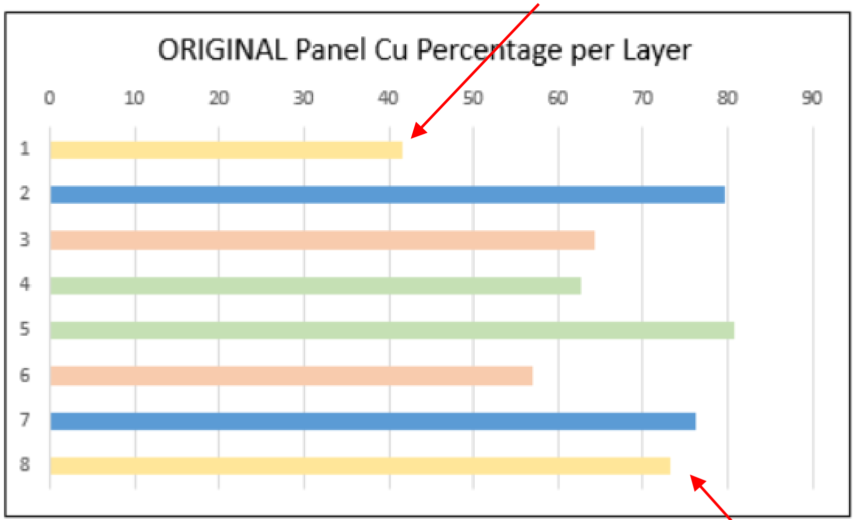
1. Copper balance layer-to-layer
2. Laminate type
3. Palletization tabs between modules
4. Breakoff rail copper
5. Supplier-to-supplier variation
6. Pallet location in supplier working panel

PHASE 2: PCB Materials and Construction DoE

1. Layer-to-layer copper balance

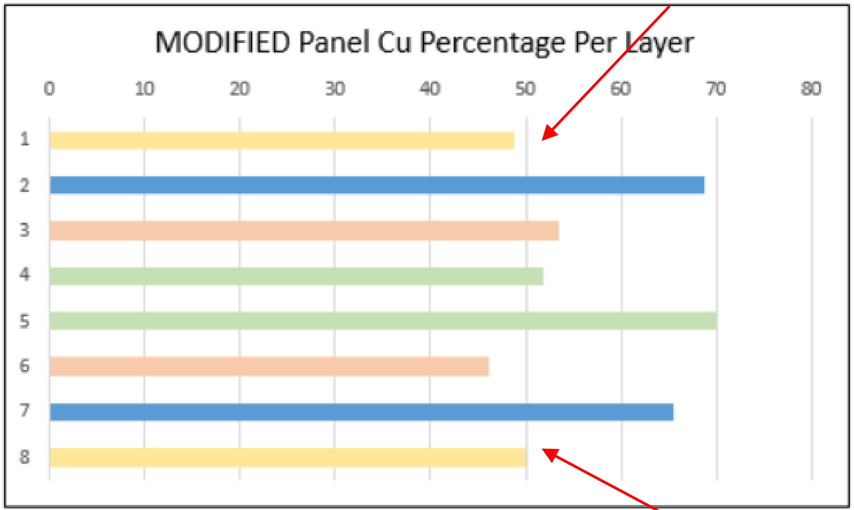
- Layers 1 and 8 were modified to create more balanced construction

41.5%



73.3%

48.7%



50.0%

PHASE 2: PCB Materials and Construction DoE

2. Laminate type – 3 different versions were tested:

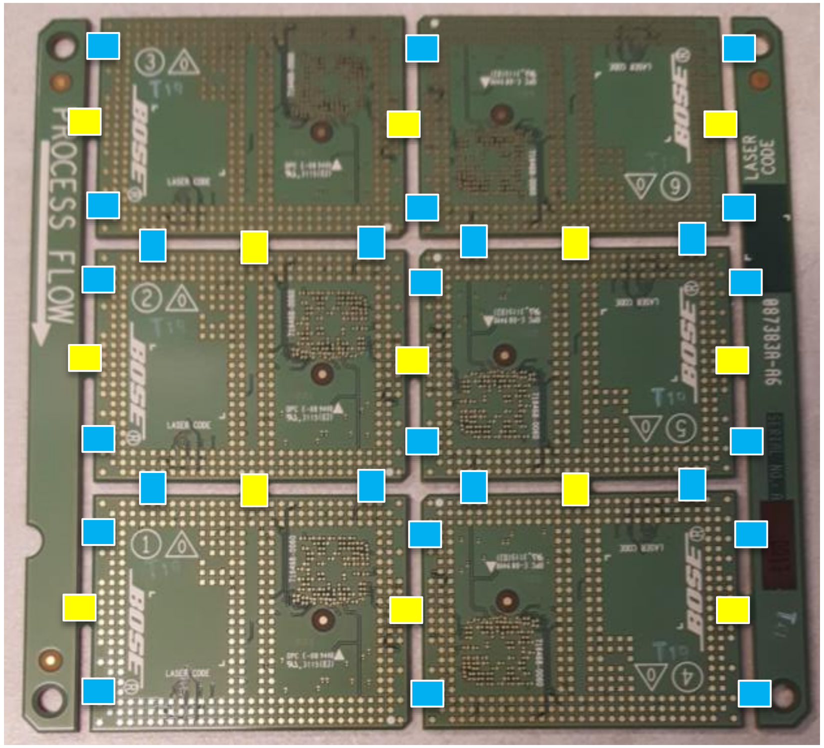
- Material A – control (original)
- Material B – higher Tg, better CTE & dimensional stability
- Material C – hybrid (BT resin core, Material A elsewhere)

PHASE 2: PCB Materials and Construction DoE

3. Board Breaks

Original design has one breakoff tab in center of module. (yellow)

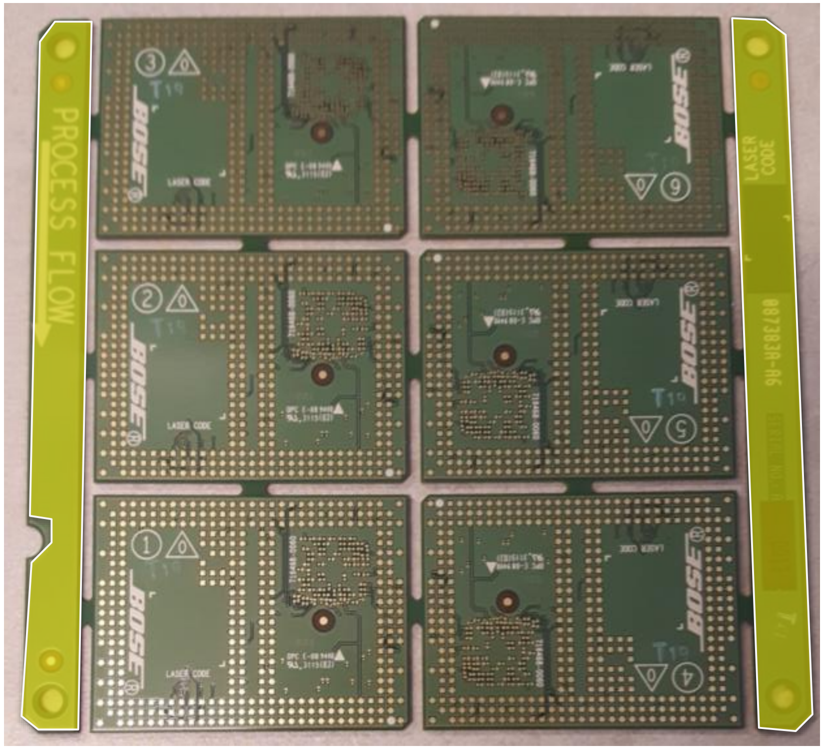
Modified design has tabs at each corner. (Blue)



4. Rail Copper

Original breakoff rails have nearly solid copper content on each layer.

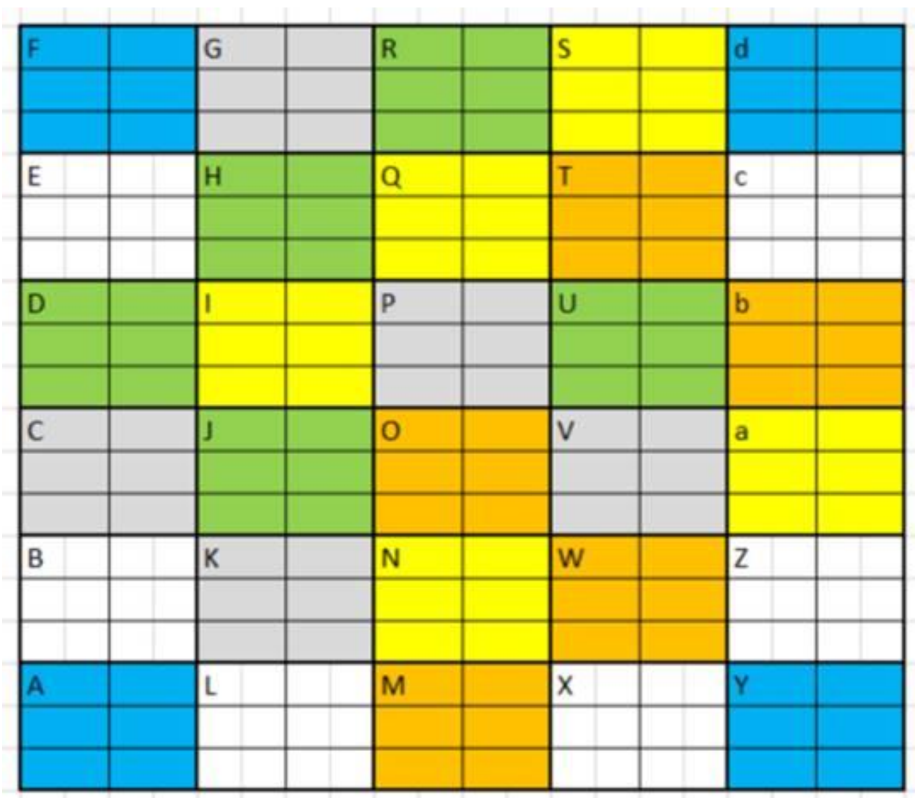
Modified Rails have most of the copper removed



PHASE 2: PCB Materials and Construction DoE

5. Supplier variation – 2 different suppliers

6. Location of pallet in suppliers' working panel



Corner vs. non-corner locations

Group Color ID	Sample description	Working Panel Locations
Grey	Original artwork: non-corner location	C, G, K, P, V
Blue	Original artwork: corner location	A, F, Y, d
White	Original artwork: extras	B, E, L, X, Z, c
Green	Modified artwork: reduced Cu in Bose breakoff rails	D, J, H, R, U
Yellow	Modified artwork: extra panelization tabs	I, N, Q, S, a
Orange	Modified artwork: balanced Cu etch	M, O, T, W, b

PHASE 2: PCB Materials and Construction DoE

Group Matrix

20 groups were planed

18 actually tested

Control boards had no copper or routing changes.

Supplier	Material	Group	Attribute
Supplier 2	Existing Material	A	Control Working Panels Non Corner
Supplier 2	Existing Material	B	Control Working Panels Corner
Supplier 2	Existing Material	C	Reduced copper density in the rails
Supplier 2	Existing Material	D	With extra routing tabs moved to corners
Supplier 2	Alternate Material	F	Control Working Panels Non Corner
Supplier 2	Alternate Material	G	Control Working Panels Corner
Supplier 2	Alternate Material	H	Reduced copper density in the rails
Supplier 2	Alternate Material	I	With extra routing tabs moved to corners
Supplier 1	Existing Material	K	Control Working Panels Non Corner
Supplier 1	Existing Material	L	Control Working Panels Corner
Supplier 1	Existing Material	M	Reduced copper density in the rails
Supplier 1	Existing Material	N	With extra routing tabs moved to corners
Supplier 1	Existing Material	O	With Balanced Copper
Supplier 1	Hybrid	P	Control Working Panels Non Corner
Supplier 1	Hybrid	Q	Control Working Panels Corner
Supplier 1	Hybrid	R	Reduced copper density in the rails
Supplier 1	Hybrid	S	With extra routing tabs moved to corners
Supplier 1	Hybrid	T	Balanced Copper
Not Received			
Supplier 2	Existing Material	E	Balanced Copper
Supplier 2	Alternate Material	J	Balanced Copper

PHASE 2: PCB Materials and Construction DoE

Post Top Side Coplanarity Results

Experimental group ID	Sample size	Average (mm)	Std. Dev. (mm)	Minimum (mm)	Maximum (mm)	Statistical comparison of averages (averages with the same letter are statisticaly the same)
G	126	0.18521	0.04169	0.107	0.377	A
R	150	0.17858	0.01971	0.141	0.272	A B
B	162	0.16978	0.02435	0.122	0.27	B C
F	198	0.16952	0.02185	0.117	0.283	B C
H	222	0.16729	0.01843	0.101	0.237	C D
I	162	0.16709	0.01641	0.135	0.225	C D
D	144	0.16681	0.01932	0.124	0.253	C D
M	150	0.16179	0.0293	0.114	0.37	C D E
A	216	0.15954	0.01855	0.107	0.263	D E
C	198	0.15665	0.02128	0.107	0.257	E F
P	330	0.15061	0.01876	0.097	0.302	F G
T	150	0.14999	0.01627	0.099	0.2	F G
S	150	0.14711	0.01503	0.109	0.188	G H
Q	120	0.14579	0.03695	0.087	0.336	G H
L	120	0.14574	0.04084	0.085	0.282	G H
O	150	0.13748	0.02493	0.076	0.217	H I
K	330	0.13364	0.0302	0.084	0.277	I
N	150	0.13341	0.02881	0.084	0.293	I

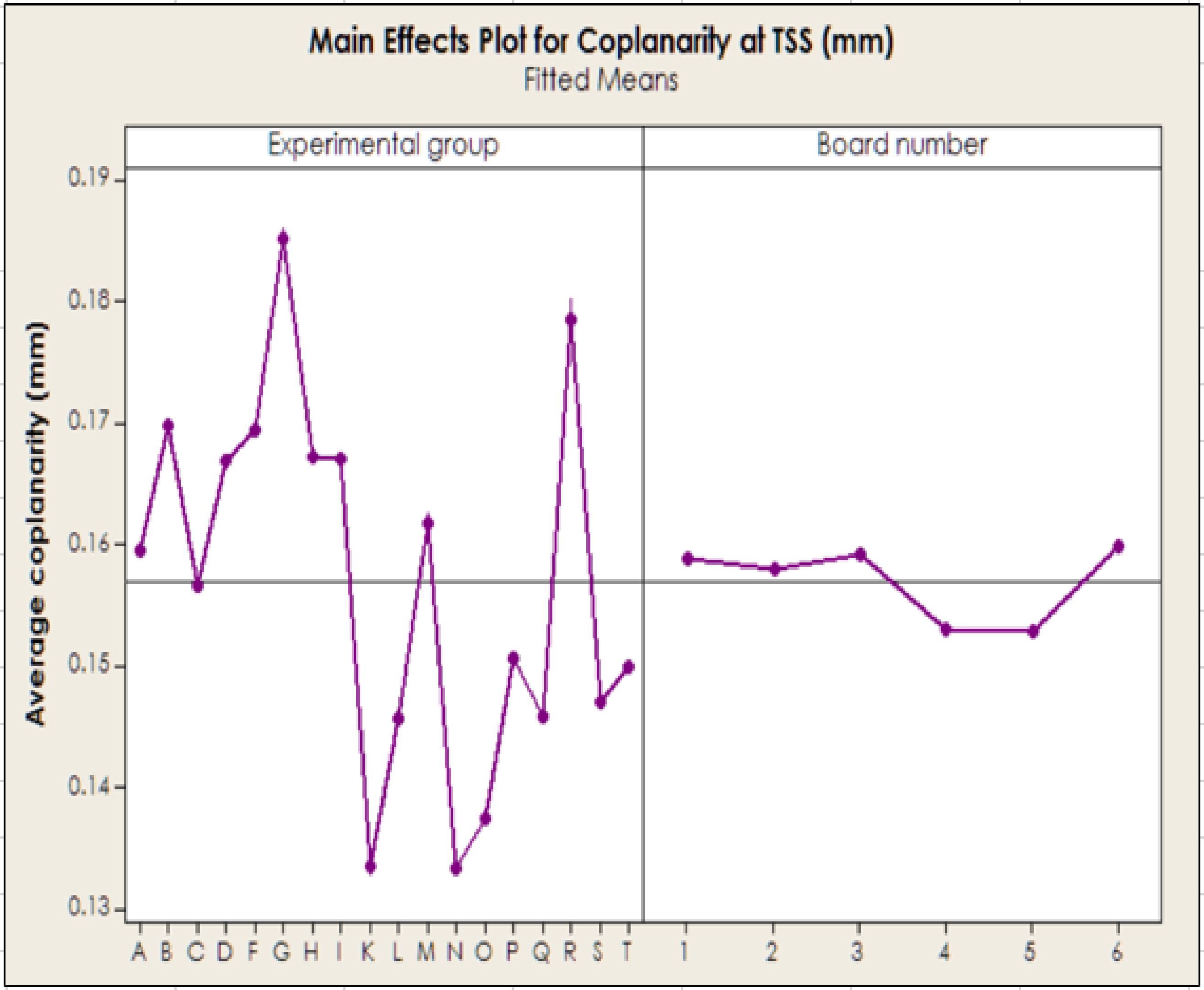
Variations were all from supplier one, and used the existing material.

Group K Used the existing material, working panel non corner.

Group N Used the existing material, with additional board breaks

Group O Used the existing material, with balanced copper top and bottom.

PHASE 2: PCB Materials and Construction DoE



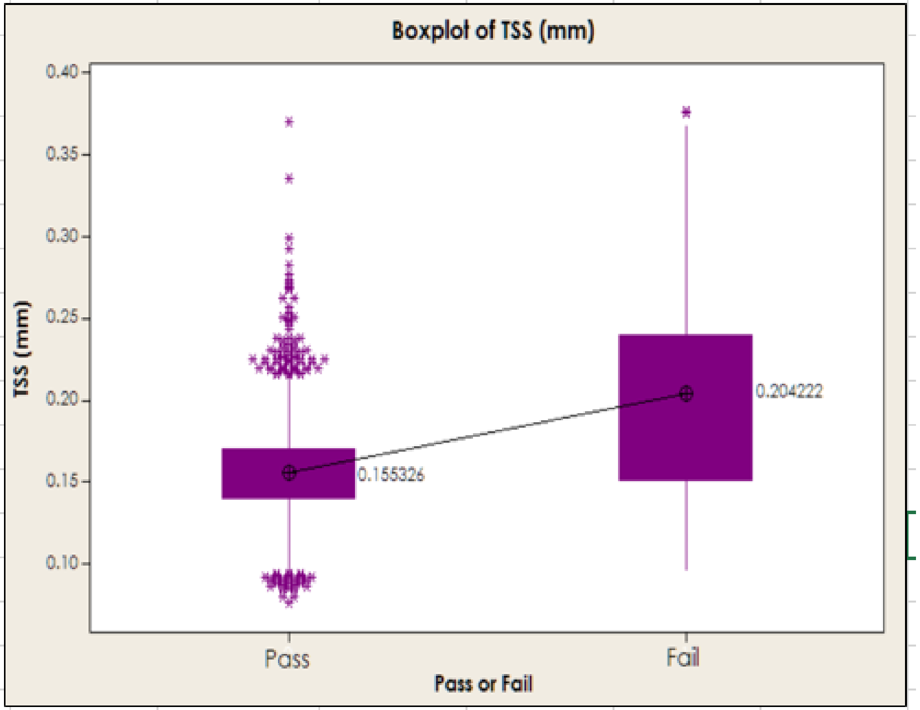
PHASE 2: PCB Materials and Construction DoE

Passing boards had a smaller average and standard deviation.

They also had a significant number of points outside the box.

This makes it difficult to point to a specific coplanarity as needed to produce a passing result.

Pass or fail	Sample size	Average (mm)	Std. Dev. (mm)	Minimum (mm)	Maximum (mm)
Fail	36	0.2042	0.074	0.096	0.377
Pass	3192	0.15533	0.02734	0.076	0.37



PHASE 2: PCB Materials and Construction DoE

- Pass/fail between suppliers

Supplier Contingency Table

		Pass (0)	Fail (1)	Total
Supplier 1	Row count	1779	21	1800
	Row percent	98.83	1.17	100
Supplier 2	Row count	1413	15	1428
	Row percent	98.95	1.05	100
Total	Row count	3192	36	3228
	Row percent	98.88	1.12	100

Pearson Chi-Square = 0.098, DF = 1, P-Value = 0.755

Likelihood Ratio Chi-Square = 0.098, DF = 1, P-Value = 0.754

- Pass/fail between laminate types

Laminate Contingency Table

		Pass (0)	Fail (1)	Total
Existing Material	Row count	1605	15	1620
	Row percent	99.07	0.93	100
Existing Material BT Hybrid	Row count	891	9	900
	Row percent	99	1	100
Alternate Material	Row count	696	12	708
	Row percent	98.31	1.69	100
Total	Row count	3192	36	3228
	Row percent	98.88	1.12	100

Pearson Chi-Square = 2.792, DF = 2, P-Value = 0.248

Likelihood Ratio Chi-Square = 2.532, DF = 2, P-Value = 0.282

Changing suppliers or laminate types made no statistical improvement

PHASE 2: PCB Materials and Construction DoE

- Pass/fail between Original copper and rebalanced design

Copper Balanace Contingency Table

		Pass (0)	Fail (1)	Total
Balanced Copper	Row count	297	3	300
	Row percent	99	1	100
Current Copper	Row count	2180	28	2208
	Row percent	98.73	1.27	100
Reduced Copper	Row count	715	5	720
	Row percent	99.31	0.69	100
Total	Row count	3192	36	3228
	Row percent	98.88	1.12	100

Pearson Chi-Square = 1.660, DF = 2, P-Value = 0.436

Likelihood Ratio Chi-Square = 1.821, DF = 2, P-Value = 0.402

Changing the copper balance in the module or the rails made no statistical improvement

PHASE 2: PCB Materials and Construction DoE

- Pass/fail between current corner tabs and extra tabs in corner

Break Tab Contingency Table

		Pass (0)	Fail (1)	Total
Current tabs	Row count	2586	36	2622
	Row percent	98.63	1.37	100
Extra tabs	Row count	606	0	606
	Row percent	100	0	100
Total	Row count	3192	36	3228
	Row percent	98.88	1.12	100

Pearson Chi-Square = 8.414, DF = 1, P-Value = 0.004

Likelihood Ratio Chi-Square = 15.064, DF = 1, P-Value = 0.000

- Pass/fail between corner boards –vs – non corner boards

Working Panel Position Contingency Table

		Pass (0)	Fail (1)	Total
Corner boards	Row count	512	16	528
	Row percent	96.97	3.03	100
Non corner boards	Row count	2680	20	2700
	Row percent	99.26	0.74	100
Total	Row count	3192	36	3228
	Row percent	98.88	1.12	100

Pearson Chi-Square = 20.993, DF = 1, P-Value = 0.000

Likelihood Ratio Chi-Square = 15.855, DF = 1, P-Value = 0.000

Key findings: (1) additional tabs between modules in the pallet improved performance; (2) pallets from the corner locations of the suppliers' working panels worsened performance

PHASE 2: PCB Materials and Construction DoE

RESULTS

Key variables evaluated

1. Copper balance layer-to-layer
2. Laminate type
3. Palletization tabs between modules
4. Breakoff rail copper
5. Supplier-to-supplier variation
6. Pallet location in supplier working panel

Only these factors were found to have statistically significant effect on attachment yield

Conclusions

- **PHASE 1 - Incoming PCB warpage directly affects module-carrier attachment yields**
  - The “flatter” the pallets as-received, the better probability of successful attachment
  - Warpage of pallets tends to worsen during reflow

- **PHASE 2 – DoE was conducted to understand the factors that influence PCB warpage**
  - A more “rigid” palletization, with additional tabs separating individual modules in the assembly pallet, greatly improved warpage performance
  - The location of the pallet in the suppliers’ working panel is significant; pallets that came from corner locations were worse

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