Industrial Backward Solution for Lead-Free Exempted AHP* Electronic Products

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EXECUTIVE SUMMARY

Since July 1st 2006, the 2002/95/EC RoHS European directive has forced the electronic industry to switch from Tin-Lead to lead-free soldering alloys for components assembly.

Exemption domains have been defined for highly failure sensitive applications with long service lifetimes like military and aerospace because of the lack of knowledge on long term solder joint reliability in harsh environment. Furthermore, the physical properties of lead-free solder alloys (such as SAC) greatly differ from those of well known Tin-Lead so that well established accelerated tests can't be replicated for lead-free to forecast lifetime. These tests are not yet defined and moreover, the statistics of failure mechanisms and rates from the field are not sufficient to manage the reliability risk for many kinds of THALES products.
However, component manufacturers have changed their package finish to comply with the RoHS directive without taking into account AHP equipment makers due to their low share in volume. As a consequence, AHP companies have to face this difficult situation: either manage the obsolescence by component storage with the great difficulty to forecast the customer demands, or find a solution to use lead free package finishes with standard Tin-Lead alloy, particularly sensitive with all kinds of BGA.

Thales shared a cooperative and ambitious technological program with CELESTICA as a key partner in order to secure an industrial process solution called hereafter $SnPb^+$ (mixed metal assembly).

This paper describes microstructures and thermal cycling performance of lead-free ball grid array and leaded components assembled with Sn-Pb solder using conventional SnPb reflow and reflow with temperature higher than 217°C to melt the lead-free ball and insure a full mixing (the $SnPb^+$ process). The formation of uniform and non-uniform microstructures as a result of Sn-Ag-Cu (SAC) solder ball dissolution in a molten Sn-Pb solder using a conventional SnPb reflow or melting is studied. The difference in mechanisms and performance of uniform fully mixed and non-uniform partially mixed joints as a response on thermal cycling at -55°C to 125°C conditions is explored. Additional attention is paid to Sn-Bi finished QFPs and TSOPs. It is shown that Sn-Bi finish with 3 -5% Bi is not responsible for early failures if it is used with Sn-Pb solder.

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Part 2. Process Technology Fundamentals and Failure Analysis

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AHP : Aerospace & High Performance*

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Pb-Free component / SnPb Solder Joints in High Reliability Assemblies

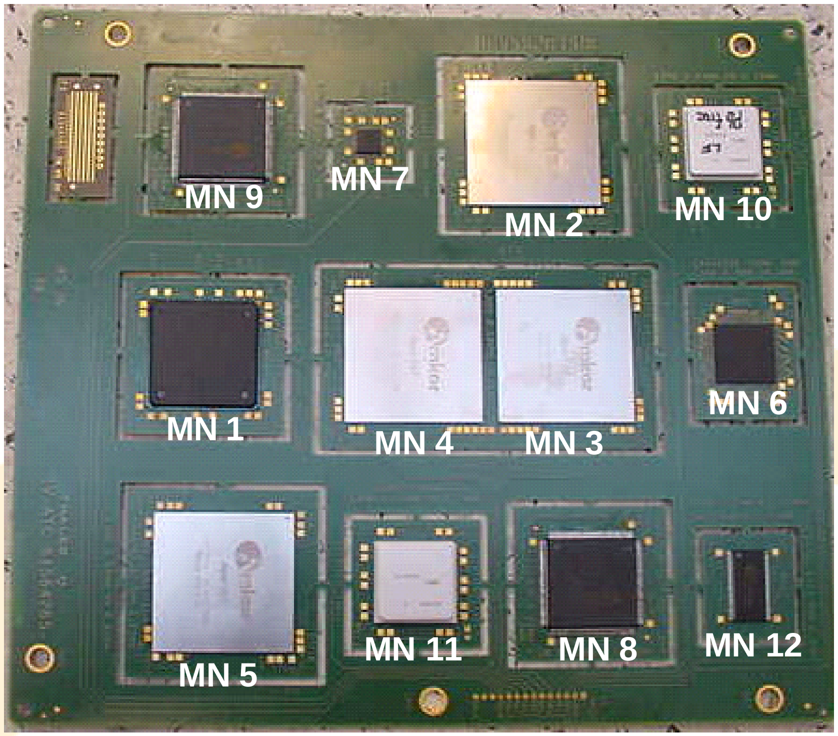
- **Impact of the transition to Pb-Free solder on the industries and companies that are exempted or excluded from the RoHS legislation**
  - Component manufacturers have switched to components with Pb-free finishes
  - The ability to find leaded components is getting harder and harder
  - The likelihood of lead-free parts inadvertently being assembled using SnPb solder is great
- **Two main scenarios can be considered:**
  - Design for reliable Pb-free / Sn-Pb assembly when the process parameters provide the best reliability for mixed assembly
  - Incorporation Pb-free components in a Sn-Pb assembly using conventional Sn-Pb process parameters

Content

- Thales - Celestica partnership in an industrial process solution
- Additional Celestica data

- Experimental
- Theory of SAC ball / SnPb paste mixing and solidification
- Reflow profile fundamentals
  - Conventional SnPb reflow
  - Design for mixed assembly $SnPb^+$
- ATC performance
- Microstructures and Failure analysis
- Conclusions

ATC Test Vehicle



- 12 layers
- 223mm x 233mm x 1.6 mm
- Laminate compatible and qualified for lead free soldering
- Surface finishes
  - ENIG
  - ImmSn
- Populated with 12 daisy chained packages
- Designed to allow
  - Easy removal of failed components
  - While maintaining capability to monitor electrical resistance on the daisy chains of the other devices.

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Component Description

Package	Ball or Finish	Dimensions, mm x mm	Pitch, mm	TV-ATC
CBGA 575	SAC 387	25 x 25	1.0	MN 10
	90Pb10Sn	25 x 25	1.0	MN 11
SBGA 560	SAC 405	42.5 x 42.5	1.27	MN 3 MN 4
	63Sn37Pb	42.5 x 42.5	1.27	MN 2 MN 5
PBGA 1156	SAC 405	35 x 35	1.0	MN 1
µBGA 288	SAC 405	19 x 19	0.8	MN 6
CSP 132	SAC 405	8 x 8	0.5	MN 7
QFP 208	97Sn3Bi	28 x 28	0.5	MN 9
	SnPb	28 x 28	0.5	MN 8
TSOP 54	97Sn3Bi	10.2 x 22.2	0.8	MN 12

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Profile Set-up

- Two reflow profiles
  - Conventional SnPb reflow
    - $T_{max} < 216°C$ to ensure that the SAC balls would not melt
    - Both fully and partially mixing is expected
  - Design for mixed assembly $SnPb^+$
    - Tmax > 217°C to ensure that the SAC balls are melted
    - $T_{SnPb} < T_{SnPb^+} > T_{SAC}$
    - All joints are fully mixed

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Profile Set-up (cont.)

- **Challenges for hot profile:**
  - Achieve full mixing of SAC solder ball and SnPb solder paste without overheating other components qualified to tin lead soldering process only.
  - Ensure that performance of traditional solder paste flux composition does not degrade (i.e. excessive voiding, poor solderability etc.)

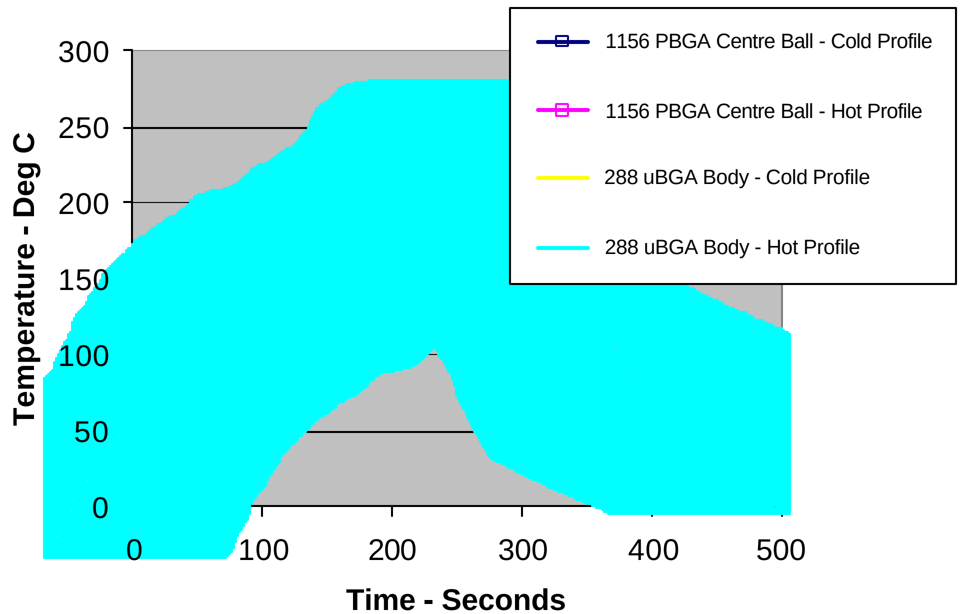
- **Theoretical process window:**
  - Solder joint minimum peak temperature 217°C
  - Component body maximum peak temp 235°C - J-STD-020

- **Practical target process window (Allowing for repeatability/tolerances):**
  - SnPb Profile
    - T_{max} at solder joint between 205°C and 215°C.
  - $SnPb^{+}$ Profile
    - T_{min} at solder joint = 220°C
    - T_{max} package body = 233°C

Profile Results

- **Optimised profile results using 10 heating zone convection oven:**
  - –Profile targets achieved for conventional SnPb
  - –For SnPb$^+$ target parameters could not be met in full, but it still meets the requirements of J-STD-020
    - –Coldest solder joint measured at 221°C at center of 1156 PBGA.
    - –Hottest package measured at 239°C on CSP and µBGA288.

Ref	Component Description	Thermocouple Position	Peak Temp (°C) SnPb Profile	Peak Temp(°C) SnPb$^+$ Profile
MN1	PBGA1156 SAC	Central Ball	206	221
MN3	SBGA560 SnPb	Central Ball	209	230
MN4	SBGA560 SnPb	Central Ball	209	230
MN6	uBGA288 SAC	Central Ball	215	237
		Outer Ball	215	237
		Body	218	239
MN7	CSP132 SAC	Central Ball	215	239
		Body	215	239
MN8	QFP208 SnBi	Lead	211	231
		Body	207	226
MN10	CBGA575 SAC	Central Ball	207	225
MN11	CBGA575 SnPb	Central Ball	206	226
MN12	TSOP54 SnBi	Lead	216	236



ATC Testing

- –55°C to +125°C
  – the most severe test conditions of the IPC-9701A specification, TC4
- 60 minutes a total cycle duration
  – Dwell times at lower and upper temperatures - 15 minutes
  – Ramp-up and ramp-down rates of 12°C/min
- The testing duration - more than 4000 ATC cycles
- 4-probe electrical testing before FA

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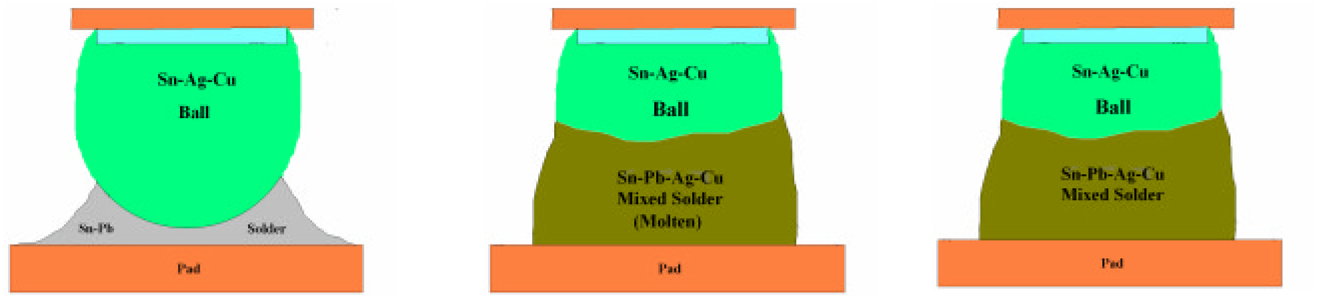
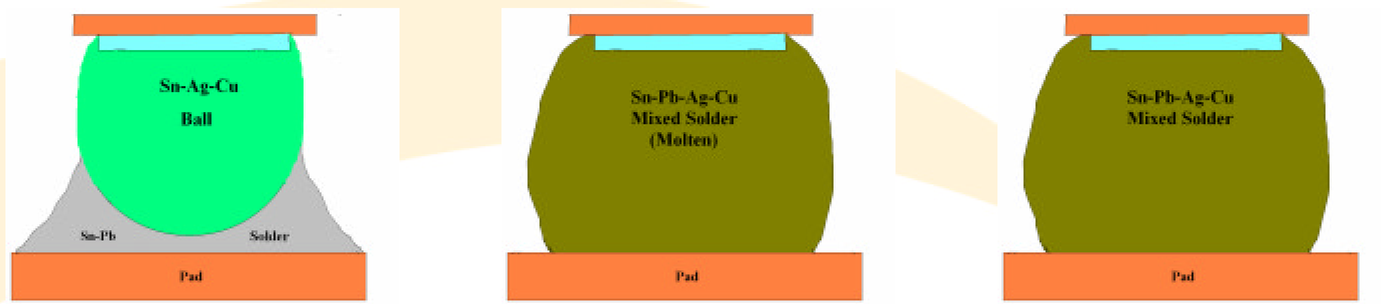
Theory of Mixing

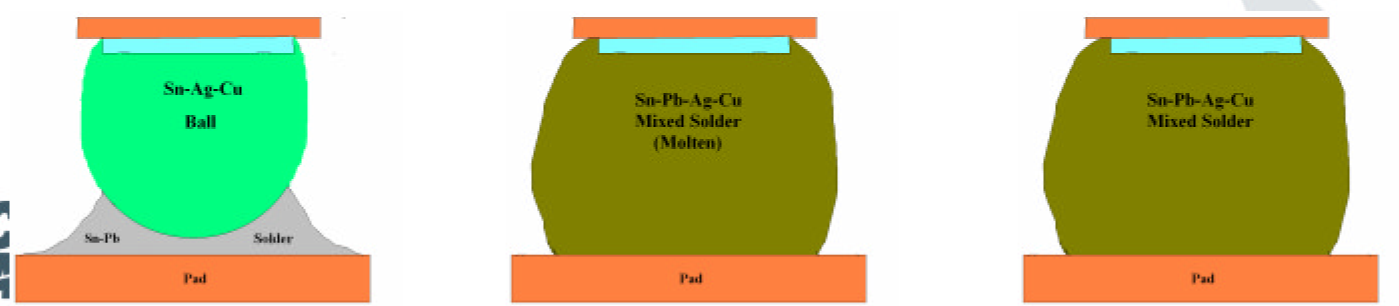
Tmax < 217°C, Partial Mixture



Tmax < 217°C, Full Mixture



Tmax > 217°C, Full Mixture



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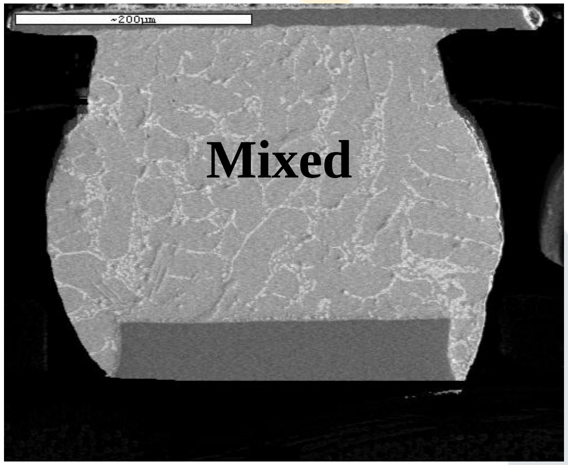
Theory of Mixing (Cont.)

Tmax < 217°C

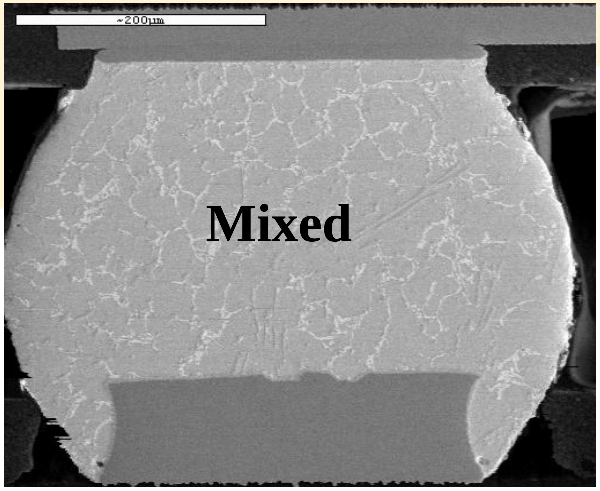
- Sn-Pb solder melts at 183°C, the Sn-Ag-Cu, solder ball begins to dissolve in the molten solder
- The dissolution continues until the liquid attains a saturation composition
- The saturation level increases with rising temperature
- The higher the temperature, the larger the portion of the SAC solder ball that is consumed by the molten Sn-Pb solder
- The time above liquidus should be sufficient
- The degree of mixing depends on SAC ball / Sn-Pb solder ratio
- For a certain SAC ball / Sn-Pb solder ratio, full dissolution is possible below the melting temperature of 217°C for Sn-Ag-Cu solders
- The mixed Sn-Pb-Ag-Cu liquid solder solidifies during cooling stage of the reflow.

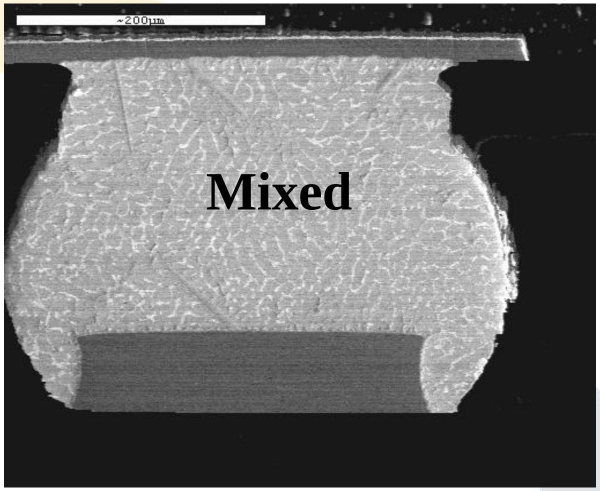


Theory of Mixing (Cont.)

Tmax > 217°C

- The Sn-Ag-Cu solder ball starts melting at 217°C and mixing with molten SnPb solder
- Full mixing can be achieved for all components independent of solder joint size or SAC ball / Sn-Pb paste ratio
- The mixed Sn-Pb-Ag-Cu liquid solder solidifies during cooling stage of the reflow.





Voiding Characterization

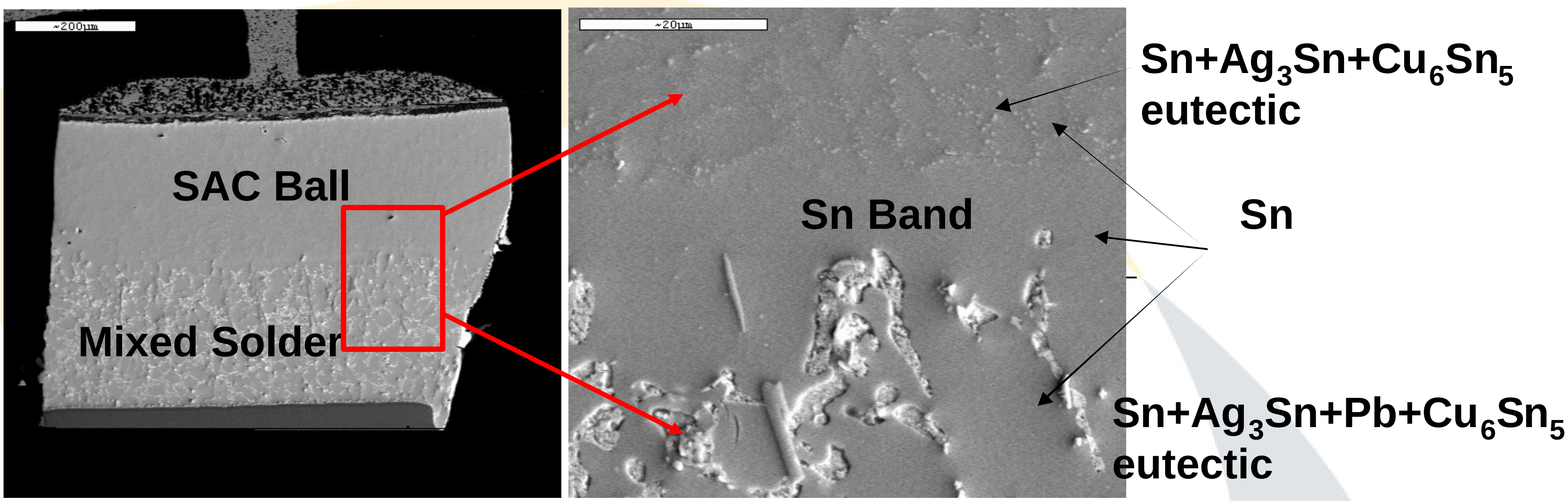
- In general, voiding was within acceptable levels - IPC-A-610D
  - Greater in devices with SAC balls than with SnPb balls
  - Slightly greater in the components soldered with the $SnPb^{+}$ profile
  - No difference between ENIG and ImmSn

Component Type	Surface Finish	Profile	Voids, %					
			20	19-17	16-12	11-8	7-4	3-0
CSP132	ENIG	$SnPb^{+}$	+ (20.1%)	+	+	+	+	+
CSP132	ENIG	SnPb			+	+	+	+
CSP132	ImmSn	SnPb		+	+	+	+	+
µBGA288	ENIG	$SnPb^{+}$			+	+	+	+
µBGA288	ENIG	SnPb				+	+	+
µBGA288	ImmSn	SnPb					+	+

Microstructure Formation

SnPb Profile, Large Components

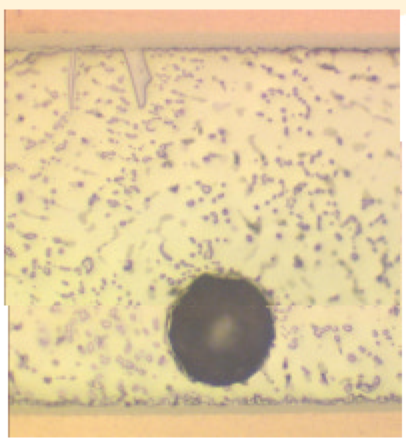
- Significant portions of the initial SAC balls
  - PBGA1156 – 30 - 50%
  - SBGA560 – 35 – 45%
- The corner joints were exposed to higher temperatures and had better mixing
- No difference in the degree of mixing for ENIG and ImmSn



Microstructure Formation
SnPb Profile, Small Components

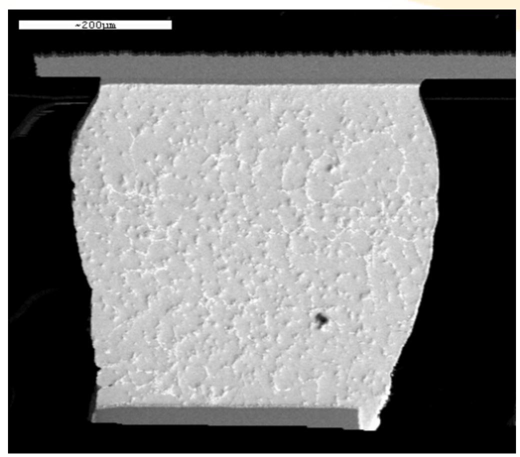
- May be completely or partially mixed
  - CSP132 – 100% mixing
  - µBGA288 100% at the corner and outer layers and 70% in inner rows
  - The microstructure is not uniform across the joint
    - Sn dendrite arms larger at the component side
    - More eutectic at the board side

CSP132

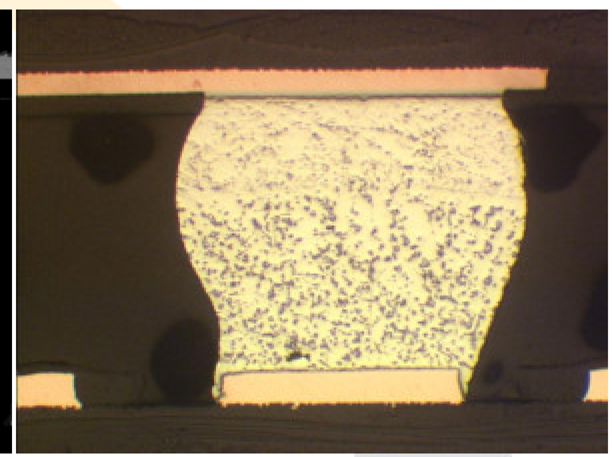


400x

µBGA288



SEM, 130x



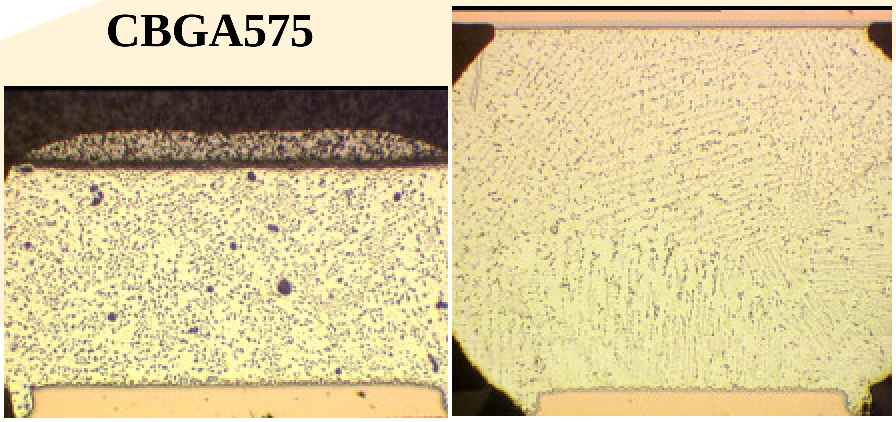
100x

Microstructure Formation
SnPb$^+$ Profile

- SAC solder balls melt and mix completely with SnPb solder paste
- Uniform microstructure
- The SnPb$^+$ reflow microstructure is finer than after SnPb profile
  - The Sn dendrite arms 3.5 times smaller

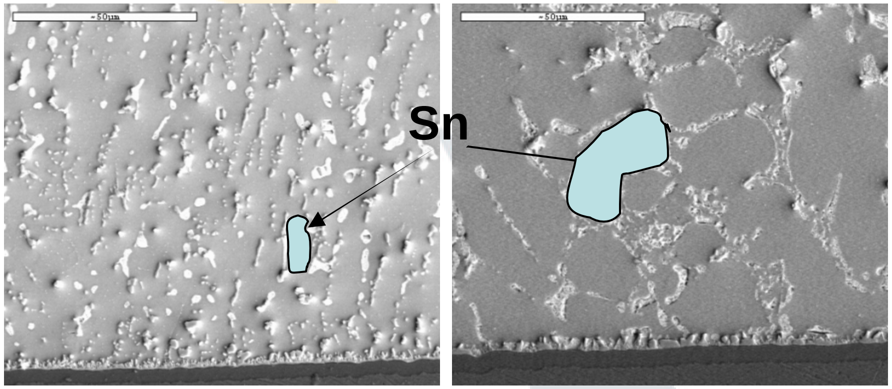
SBGA560

CBGA575



100x

SnPb$^+$ Profile **SnPb Profile**



SEM, 1000x

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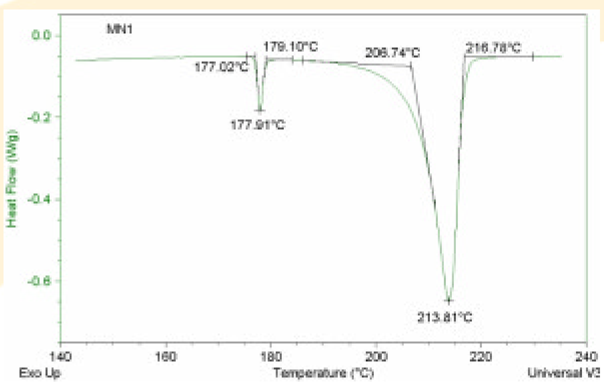
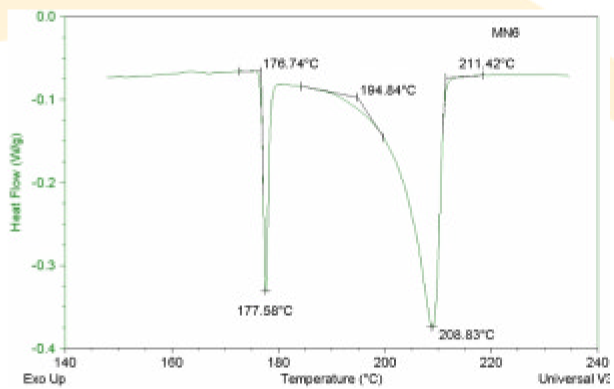
Microstructure Formation
Melting

- The resulting Sn-Pb-Ag-Cu compositions have large pasty ranges
  - PBGA1156 – 40°C
  - µBGA288 – 34°C
  - CSP132 – 28°C

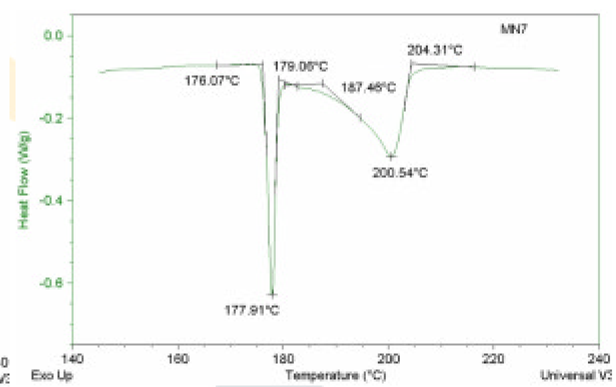
PBGA1156



µBGA288



CSP132



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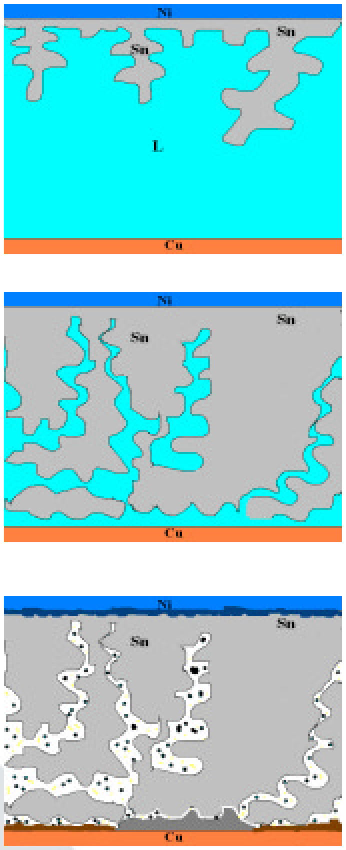
Microstructure Formation
Solidification

- Solidification occurs over a wide temperature range
  - Sn dendrites
  - Eutectic
    - Sn+Pb binry
    - Sn+Pb+Ag_3Sn ternary and /or Sn+Pb+Ag_3Sn quaternary
- The Sn dendrites originate
  - From existing Sn in the remaining SAC ball
  - From the Sn clusters in the liquid after SAC ball dissolution
- The solidification proceeds towards the board side forming a zonal microstructure
- The last portion of liquid that contains more eutectic, solidifies at the board side – Pb-rich zone
- The SnPb+ profile
  - Eliminate Sn nucleation sites
  - Homogenizes the liquid solder and
  - Provides conditions for a uniform solidified microstructure



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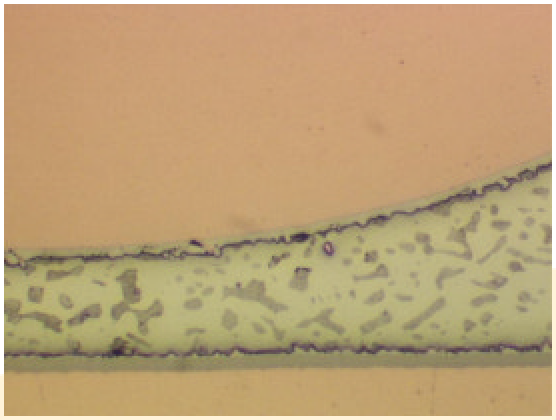
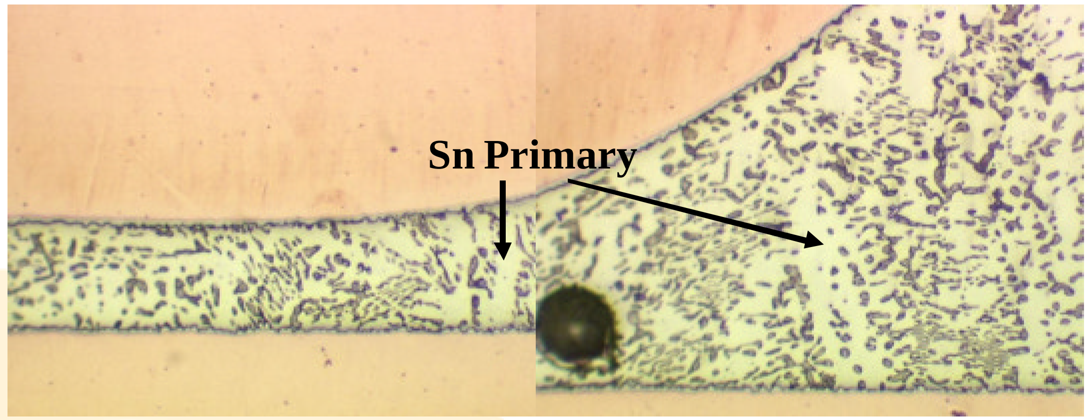
Microstructure Formation: Leaded Components

QFP 208



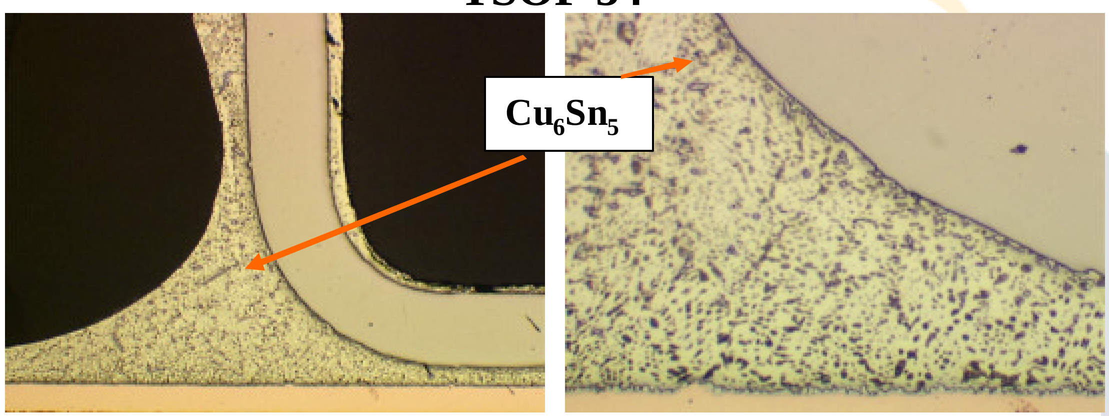
Sn-Pb finish



Sn-Bi finish

400x

TSOP 54



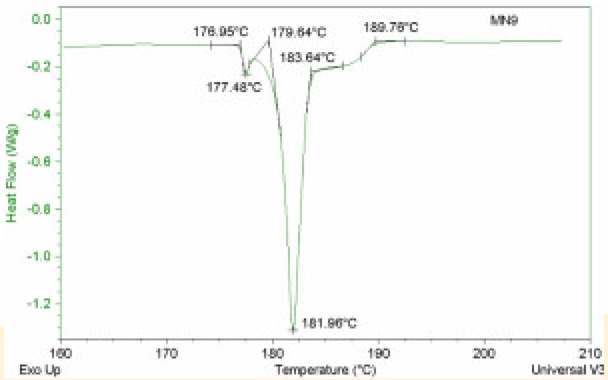
100x

400x

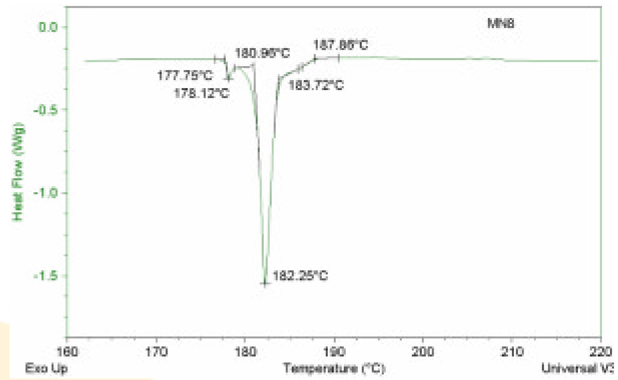
TSOP 54 microstructure containing Cu6Sn5 particles: a – 100x; b – 400x

DSC Heating Curves, Cold Profile

QFP 208

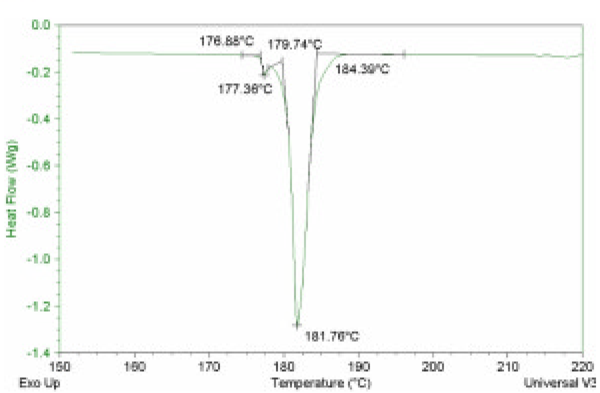


Sn-Bi finish, ImmSn

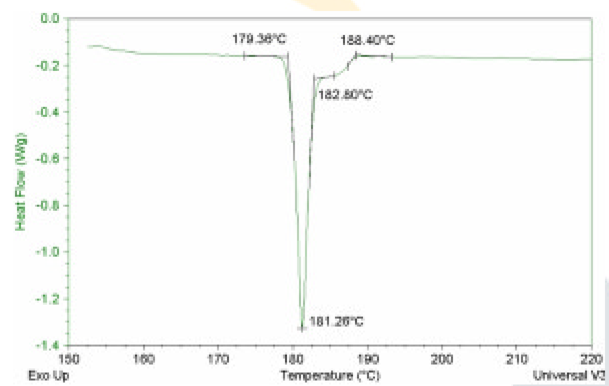


Sn-Pb finish, ImmSn

TSOP 54



Sn-Bi finish, ImmSn



Sn-Bi finish, ENIG

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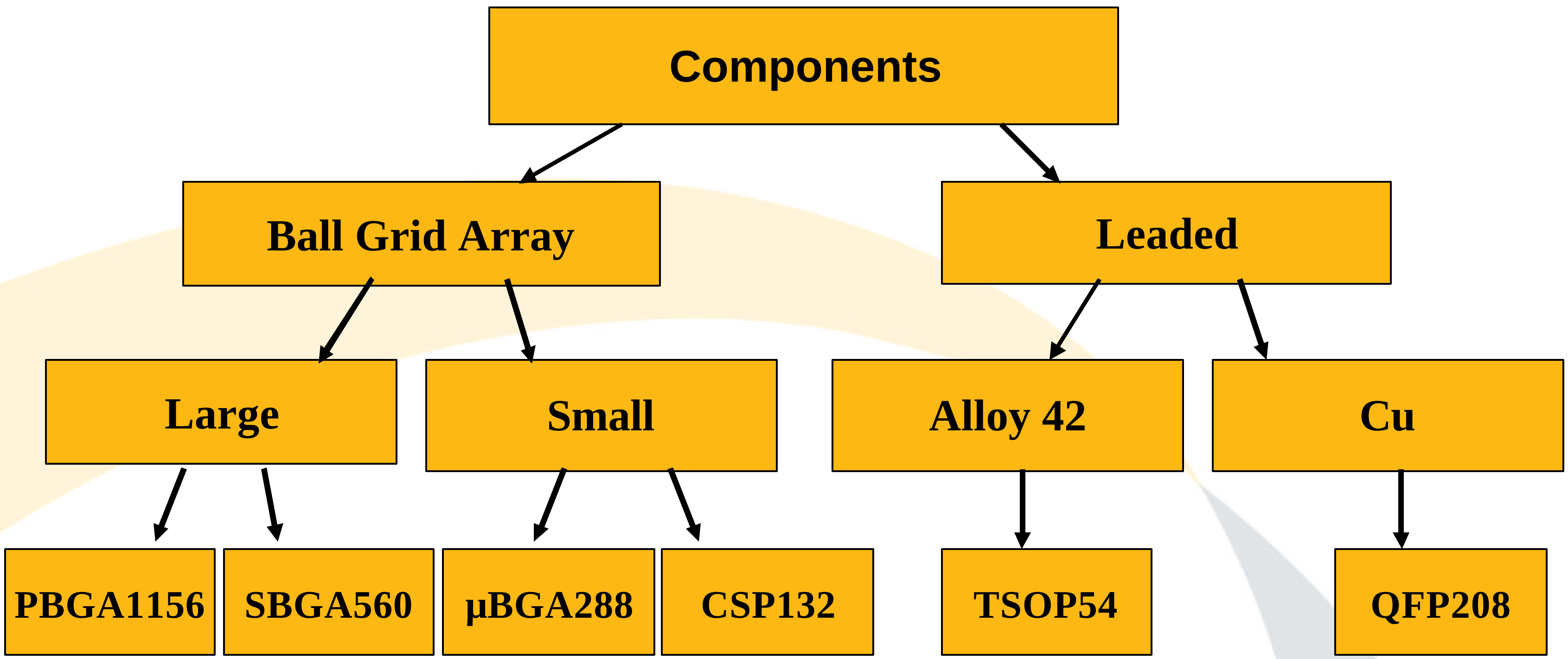
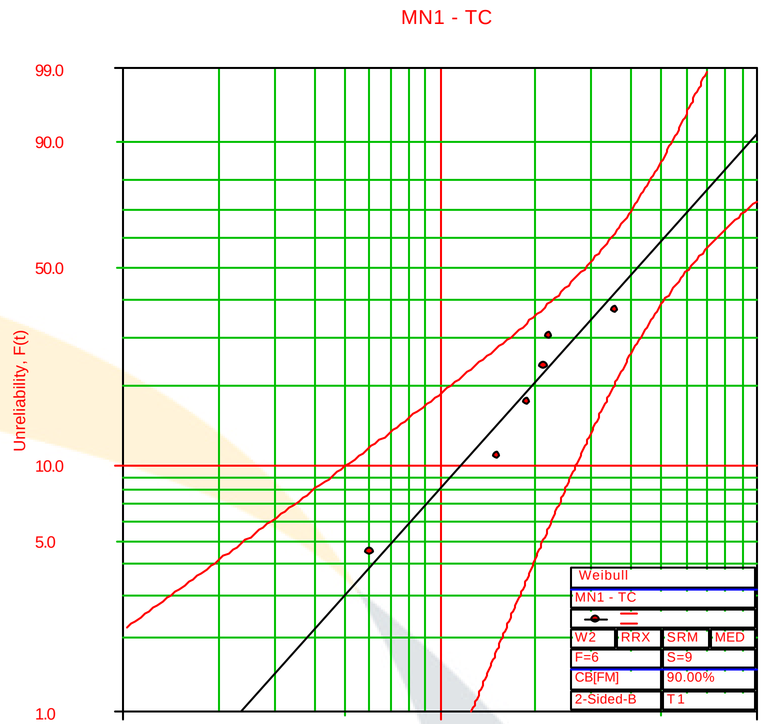
Component Grouping for ATC Reliability Discussion



ATC Results for SAC405/SnPb PBGA1156

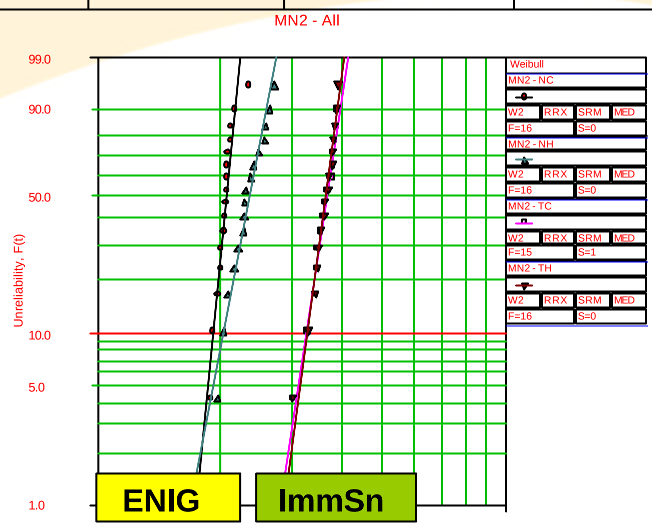
Number of Failures	Cycles to failure			
	SnPb, ENIG	SnPb+, ENIG	SnPb, ImmSn	SnPb+, ImmSn
1		3011	601	
2		4160	1506	
3			1885	
4			2130	
5			2210	
6			3553	



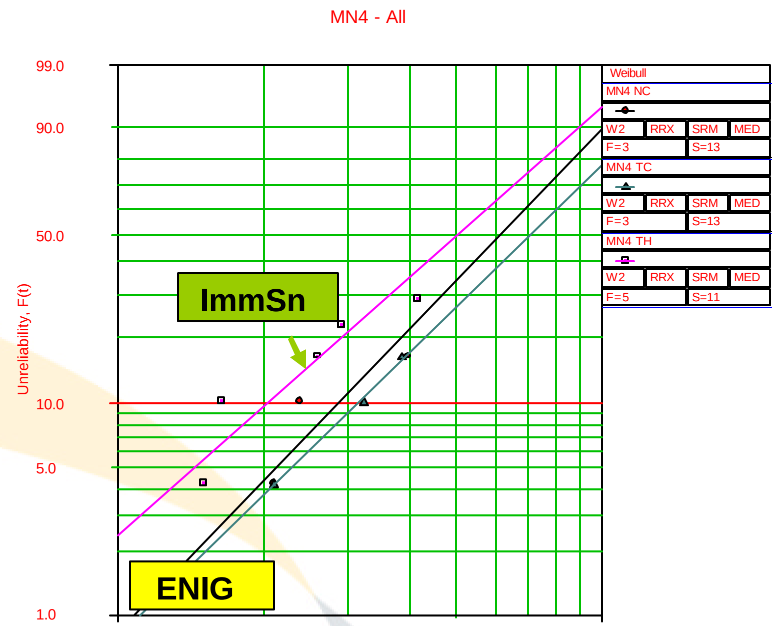
SAC405/SnPn PBGA1156, ImmSn, SnPb Profile

ATC Results for SAC405/SnPb SBGA560

Number of Failures	Cycles to failure			
	SnPb, ENIG	SnPb^{+}, ENIG	SnPb, ImmSn	SnPb^{+}, ImmSn
1	1819	2070	2724	2803
2	3808			



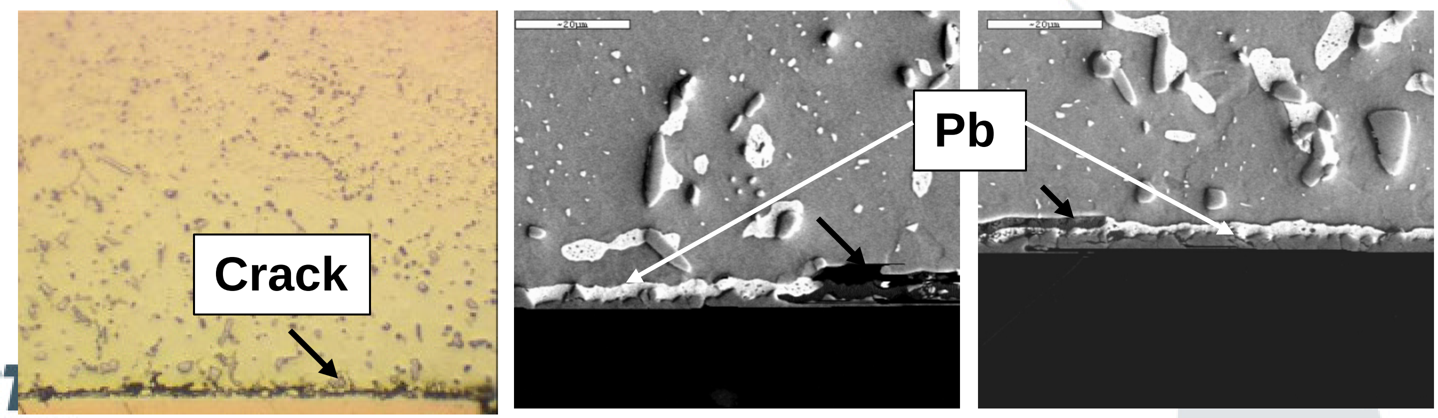
Pure SnPn SBGA560



SAC405/SnPn SBGA560, Rework

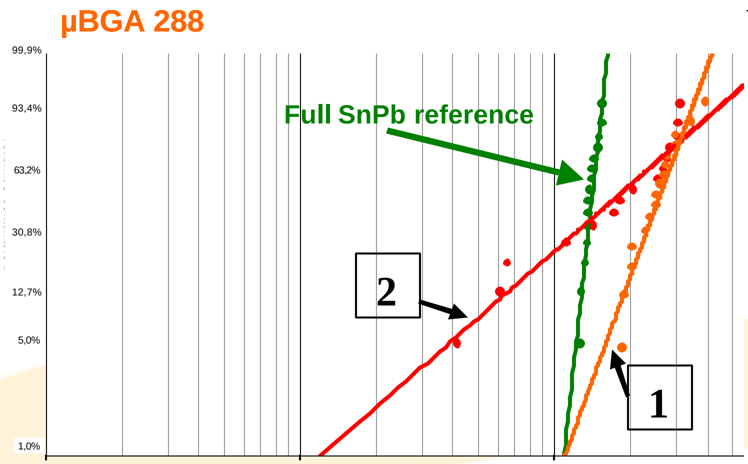
ATC Results and Failure Analysis

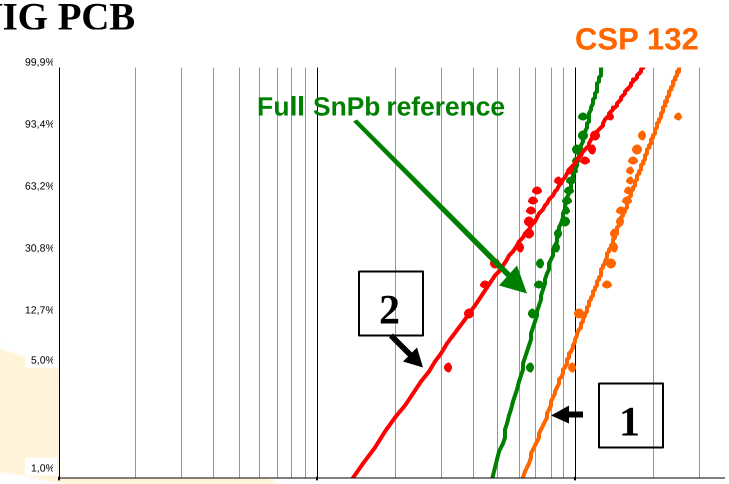
- Large BGA1156 and SBGA560 with extended reliability:
  - $SnPb^+$ profile
    - Completely mixed
    - Excellent performance at harsh environment cycling
  - SnPb profile
    - Partially mixed
    - May have acceptable reliability – failure at the component side
    - Risk of eutectic with high Pb-content and defect accumulation at the board side
      - Interfacial cracks
      - Early failure - low ß slope



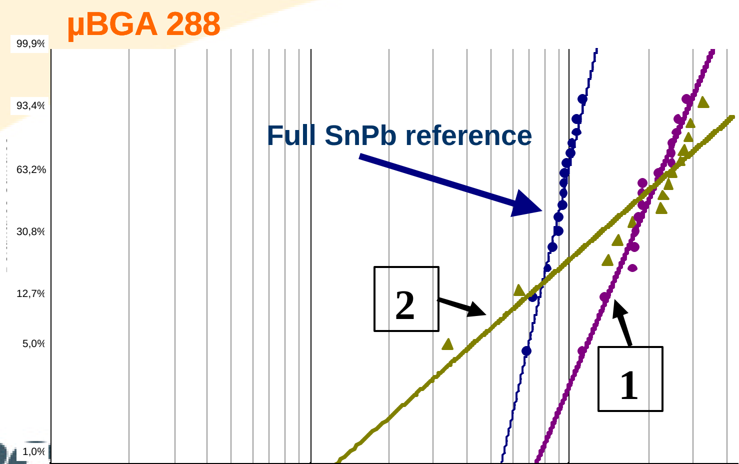
ATC Results for SAC405/SnPb µBGA288 and CSP132

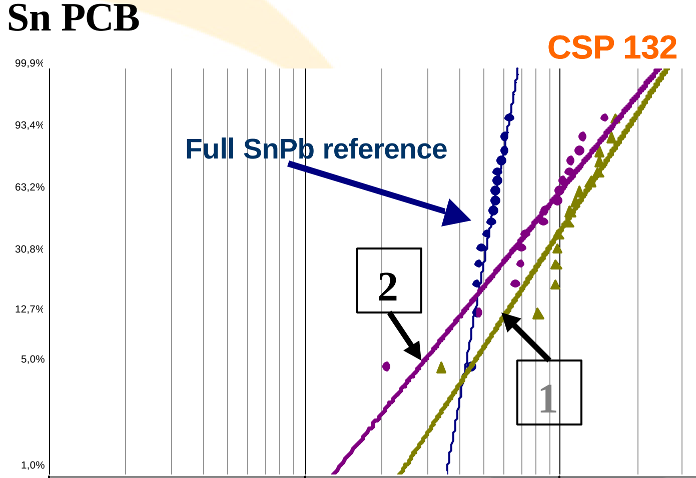
ENIG PCB





Imm. Sn PCB

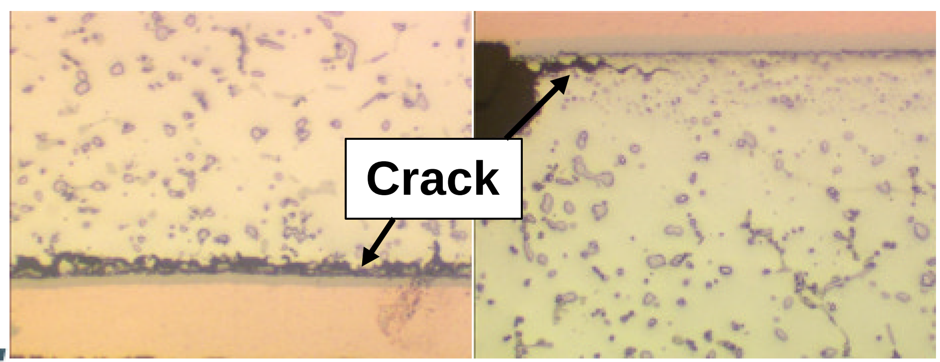




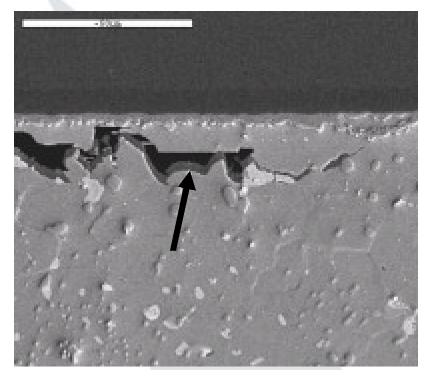
ATC Results and Failure Analysis

- Small with limited reliability: µBGA288
  - SnPb$^+$ profile
    - Completely mixed
    - Acceptable performance at harsh environment cycling
  - SnPb profile
    - Partially mixed
    - Non-unuform microstructure
    - Interfacial cracks
    - Early failure - low ß slope

SnPb Profile



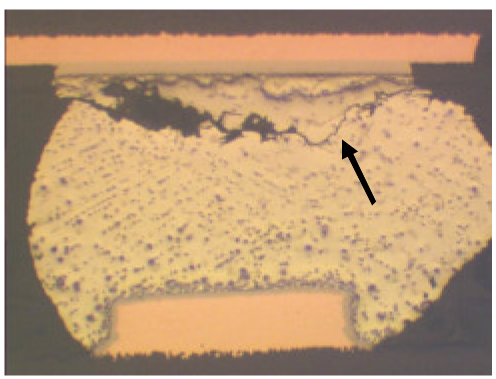
SnPb$^+$ Profile



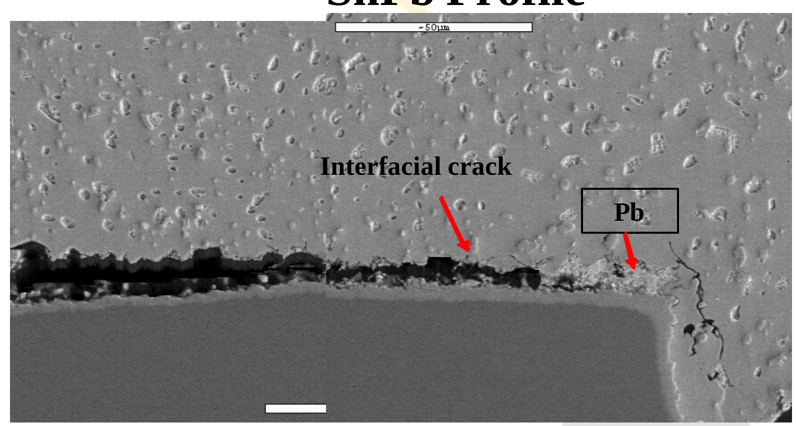
ATC Results and Failure analysis (cont.)

- Small with limited reliability: CSP132
  - $SnPb^+$ and SnPb profiles
    - Completely mixed
      - ImmSn
        - » uniform microstructure, no statistically significant difference in reliability between $SnPb^+$ and SnPb profiles
      - ENIG
        - » non-uniform phase distribution after SnPb profile – interfacial failure
        - » Good performance after $SnPb^+$ profile

$SnPb^+$ Profile



SnPb Profile



ATC Results for Leaded Components

- The Cu based QFP 208 joints showed excellent performance in harsh environment cycling
- No difference in behavior was detected between Sn-Bi and Sn-Pb finished components

QFP finish	Cycles to failure			
	SnPb, ENIG	$SnPb^{+}$, ENIG	SnPb, ImmSn	$SnPb^{+}$, ImmSn
Sn-Pb		2360	2042	2250
Sn-Bi	2408	3081		3249

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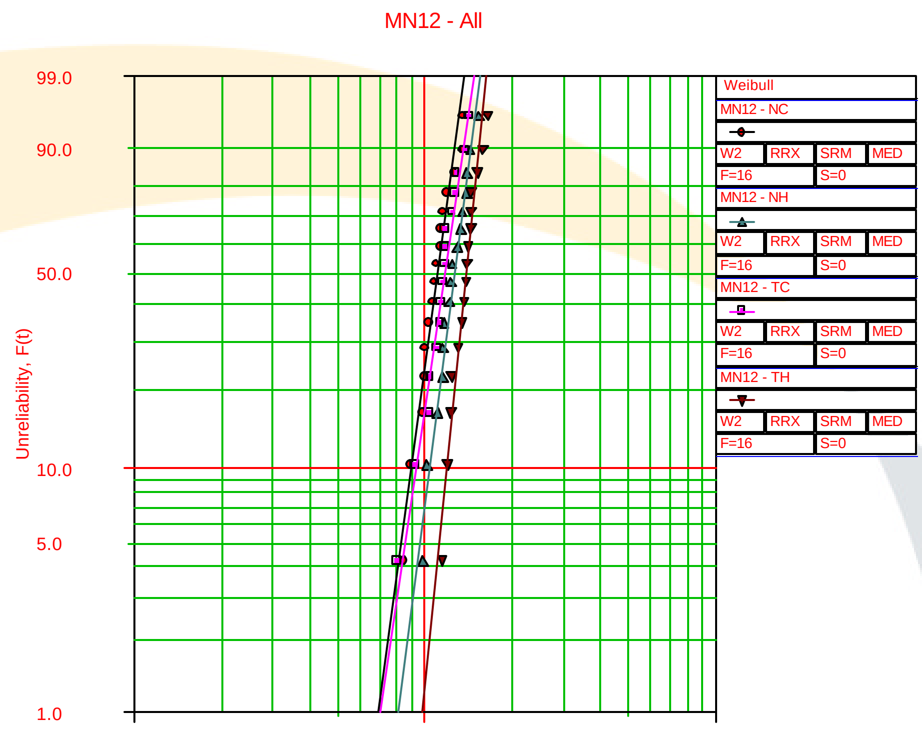
ATC Results for Leaded Components

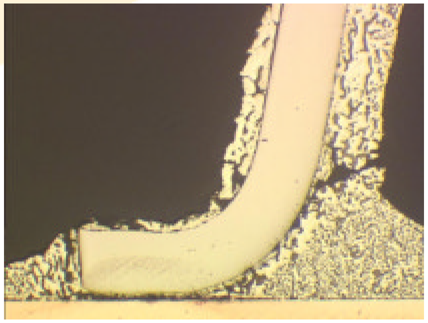
- TSOP 54 with the Alloy 42 lead frame material and Sn-Bi finish had much poorer performance than the QFP
  - Attributed to a higher CTE mismatch due to the Alloy42.
- The ATC results are similar to those reported in industry for Sn-Pb finished TSOPs
- No anomalies in failure mode were detected



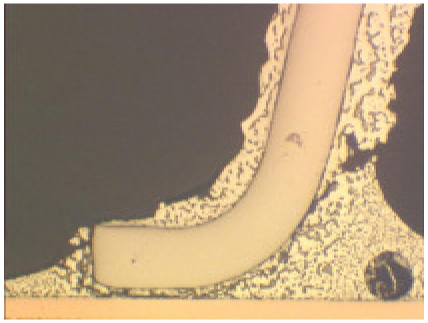
ATC Results for Leaded Components

TSOP finish	Cycles to failure									
	SnPb, ENIG		SnPb+, ENIG		SnPb, ImmSn		SnPb+, ImmSn		Data from [15]	
	First Failure	Mean Life	First Failure	Mean Life	First Failure	Mean Life	First Failure	Mean Life	First Failure	Mean Life
Sn-Pb									1125	1381
Sn-Bi	850	1158	982	1313	802	1220	1148	1448	945	1172

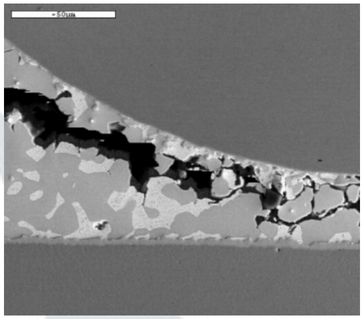
TSOP 54



SnPb profile, 1044 cycles
100x



SnPb+ profile, 1155 cycles
100x



SnPb+ profile, 1155 cycles
SEM,700x

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Conclusions

- SnPb+ reflow with the min temperature 220°C
  - Allows to melt SAC balls and mix it with SnPb solder and
  - Provide proper conditions for uniform solidified microstructure
  - Demonstrate good reliability at harsh environment cycling - -55°C to 125°C
- SnPb reflow with the max temperature below 217°C
  - Allows SAC ball dissolve in molten SnPb solder and form partially or complete mixed joints
  - Do not provide conditions for uniform microstructure formation - risk of zonal solidification that causes early failures
  - May demonstrate acceptable and poor reliability depending on reflow conditions, component type, and surface finish.

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Conclusions (cont.)

- Although the $SnPb^+$ process solution is much superior than standard SnPb reflow profile
  - the $SnPb^+$ process window is much more reduced and critical than a standard full SnPb process
  - the voiding susceptibility is increased even if compliance with the IPC-A-610 class 3 requirements
- Reliability test under vibration and shock stresses are now on going before to release this backward solution for products subjected to severe mechanical conditions.

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