

# Low Temperature SMT Solder Evaluation

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## ABSTRACT

The electronics industry could benefit greatly from using a reliable, manufacturable, reduced temperature, SMT solder material (alloy-composition) which is cost competitive with traditional Sn3Ag0.5Cu (SAC305) solder. The many possible advantages and some disadvantages / challenges are discussed.

Until recently, the use of Sn/Bi based materials has been investigated with negative consequences for high strain rate (drop-shock) applications and thus, these alloys have been avoided. Recent advances in alloy “doping” have opened the door to revisit Sn/Bi alloys as a possible alternative to SAC-305 for many applications.

We tested the manufacturability and reliability of three low-temperature and one SAC-305 (used as a control) solder paste materials. Two of these materials are doped Sn/Bi/Ag and one is just Sn/Bi/Ag1%.

We will discuss the tests and related results. And lastly, we will discuss the prospects, applications and possible implications (based on this evaluation) of these materials together with future actions.

Keywords: Bismuth, Tin, LTS, SMT, Paste, Low Temp Solder.

## INTRODUCTION

A typical SAC305 reflow profile will have peak temperatures in the 235C to 245C range. Tin/Bismuth or Tin/Bismuth/Silver solder alloys may use a peak temperature in the 165C to 195C range. This represents a peak temperature delta of more than 50C. Aside from the obvious energy cost savings there are many other benefits to using a low temperature solder (LTS) material and they will be discussed later in this paper. We also discuss some of the known and unknown risks as well.

Tin/Bismuth and Tin/Bismuth/Silver alloys are well known to the industry and have been used routinely in consumer products which are not likely to be subjected to shock, drop, vibration or high temperatures, such as TVs and some appliances. These alloys are more brittle than SAC-305 and more creep resistant. This makes them well suited for low strain rate stresses (temperature changes) but not well suited for high strain rate stresses (Shock, drop, vibration, bend etc....).

Some solder material suppliers have been working (for several years) to develop a version of this (low temperature) alloy which is comparable to SAC-305 in terms of higher strain rate reliability.

Historically they had come close, but only recently have they hit the mark using “secret” recipes which include trace amounts of ‘dopant’ materials to make the alloy more ductile and crack resistant. Other papers<sup>1</sup> discuss the dopant effects on lattice and grain structures by adding trace amounts of elements like Copper, Nickel, Manganese and Antimony so we will not go into that detail here, but the main point is that some suppliers seem to have found an appropriate recipe that maintains the bulk alloy (and hence low melting point) but alters its properties in a sufficiently beneficial way.

Another key factor in our consideration was that there had to be more than just one supplier of these types of materials before we performed any serious evaluations. We tended to avoid embracing proprietary processes or materials which are only available from a single source.

### Advantages

Some of the possible advantages of LTS include:

- Reduced Board and Component Warp
- Reduced Head in Pillow
- Lower residual Stress
- Reduced Pad Cratering
- Reduced CTE geometrical effects (scale factor)
  - Allows for smaller land pads / footprints
- Less expensive Materials

- PCBs
- Components
- Less thermal exposure
  - Thermally Sensitive Components
  - Semiconductors
- Lower Energy and Maintenance Costs
  - Estimated 20% to 25% lower energy cost depending on profile
  - Lower maintenance cost on oven moving parts
  - Possible Hybrid Assembly
    - SAC-305 on one side and Low Temp on the other
- Reduced Voiding
  - ~50% Void Reductions Observed

**Disadvantages**

As with any new material, there are unknown risks that may not come to light until the material is in use for some time. Some of the known risks include:

- Package Warp – Hot Tearing
  - Large BGA packages which were previously designed to flatten out at over 210C can cause “hot tearing” in the solder joint because the package never completely flattens and remains warped throughout the reflow cycle. One remedy for this is to use more solder paste to make up for the gap difference. The lower temp. alloys did not tend to wet as aggressively (discussed in more detail below) and therefore can allow more solder per unit area without bridging. If the industry moves towards accepting these alloys on a large scale, it is likely the packaging vendors will adjust accordingly and may offer “LTS” versions of these packages.
- Rework
  - Solder Wire: Very limited (only 1 known source and it is not commercially available yet) and it is brittle.
  - Cracked Solder Pots: Bismuth expands when it cools so it can cause some solder pots (wave solder) to crack.
- Wide Liquidus / Solidus Range
  - We observed that a very rapid cooling was necessary in order to guarantee that the assembly was below 138C exiting the conveyor reflow oven.
- Flux Residue
  - We observed a considerable amount of flux residue after reflow. In time, these solder pastes may evolve to improve this.
- More Slump and Less Wetting
  - Our tests indicate a bit more slump (hot and cold) than our controlled material but this is, again, more likely to do with the maturity of the paste. The alloy itself however does not wet as aggressively as SAC-305 and this can be an issue in certain circumstances although, we still found it to be acceptable. In some cases, less wetting can be an advantage as well such as for paste in hole.

**EXPERIMENTAL AND RESULTS**

**Materials Tested.**

The materials tested are shown in Figure 1.

Material	Basic Composition - Descriptions
A - Control	SAC305 (96.5% tin, 3% silver, and 0.5% copper)
B	Sn + 47% to 51% Bi +2% other “dopants” including Ag
C	57Bi 42Sn 1Ag - No dopants
D	48% Bi, 50% Sn, 2% Ag with some dopants

**Figure 1. Materials tested.**

Material “A” is the control Material. Materials B and D are the “doped” alloys and material C has no dopants added.

**Assembly Conditions**

All test boards were baked, inspected and labeled prior to solder screen print. SPI (solder paste inspection) was performed as well as SMT assembly and reflow.

**Reflow Profile for LTS**

Although peak temperatures as low as 165C can be used (and should be used when appropriate) a higher temperature of 190C was used to drive mixing on the SAC-305 BGAs. The solder paste and BGA ball interface experiences a sufficient phase change at these temperatures to drive diffusion and hence mixing of the BGA ball with the solder paste.

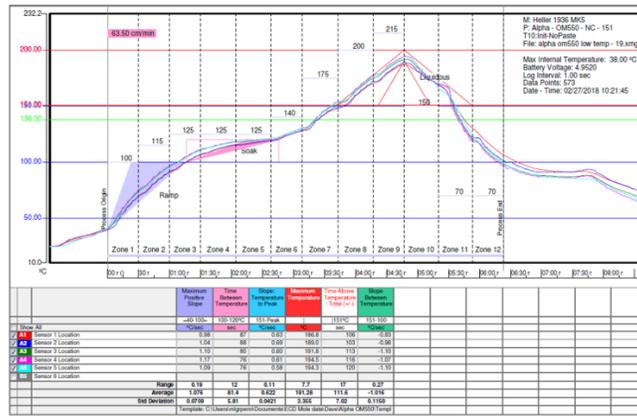


Figure 2. Reflow Profile for the LTS

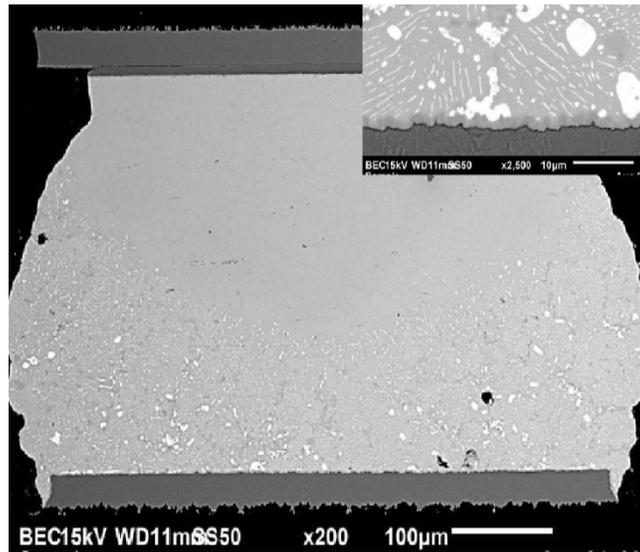


Figure 3. Cross-section of a BGA ball after 1800 Temp Cycles.

Mixing of the BGA with the SnBi paste shown in Figure 3 was approximately 50%. This is comparable to Time 0 as well as characteristic of all the solder joints we observed which fell into the 40% to 60% mixing range.

Testing Methodology

Two types of testing were performed. Manufacturability and Reliability.

Manufacturability:

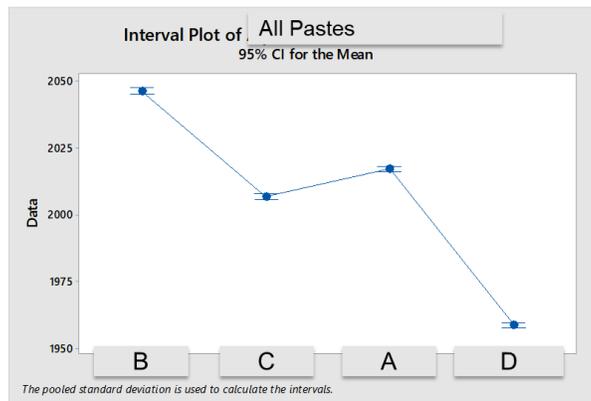
- Solder Paste Volume
- Missing Print
- Hot Slump – Cold Slump
- Solder Ball and Two Wetting Tests
- X-Ray and Visual Inspection

Reliability:

- Accelerated Temp Cycle (0-100C) - JEDEC 9701
- 4 Point Monotonic Bend Test - JEDEC 9702

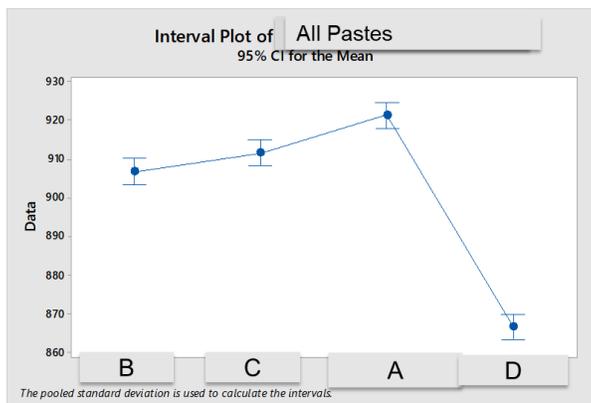
Manufacturability - Solder Paste Volume

We measured and analyzed the solder paste volume across six different aperture ratios ranging from 0.4 up to 1.1. The apertures ranged from 8 to 22 mils (0.20mm to 0.56mm) using a 5 mil(0.13mm) thick stencil.



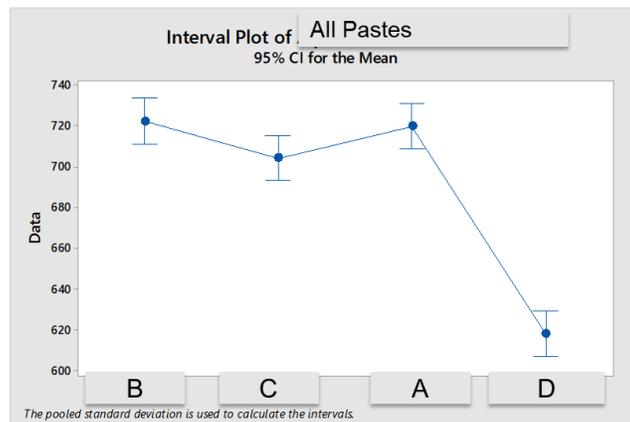
**Figure 4. Solder volume box plots for the 22 mil (0.56mm) aperture with an area ratio of 1.1. Material A is the control.**

From Figure 4, Material D has somewhat less (although sufficient) volume consistently. All materials passed our internal company specifications.



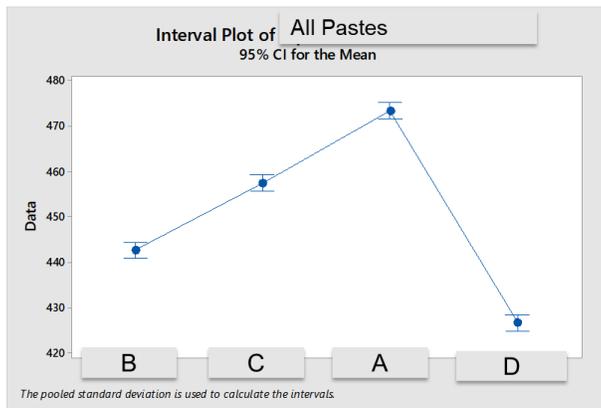
**Figure 5. Solder volume box plots for the 16 mil (0.40mm) aperture with an area ratio of 0.8. Material A is the control.**

From Figure 5, Material D has somewhat less (although sufficient) volume consistently. All materials passed our internal specifications.



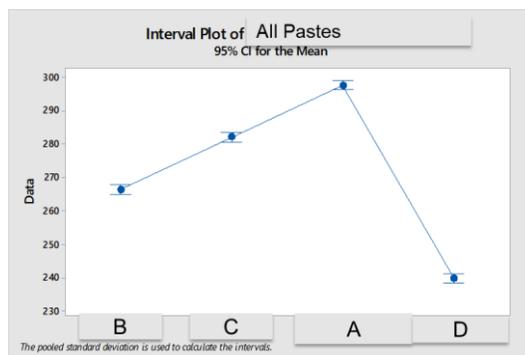
**Figure 6. Solder volume box plots for the 14 mil (0.36mm) aperture with an area ratio of 0.7. Material A is the control.**

From Figure 6, Material D has somewhat less (although sufficient) volume consistently. All materials passed our internal specifications.



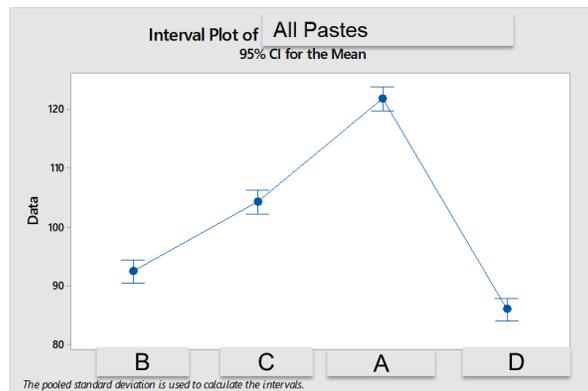
**Figure 7. Solder volume box plots for the 12 mil (0.30mm) aperture with an area ratio of 1.1. Material A is the control.**

From Figure 7, Material D has somewhat less (although sufficient) volume consistently. All materials passed our internal specifications.



**Figure 8. Solder volume box plots for the 10 mil (0.25mm) aperture with an area ratio of 0.5. Material A is the control.**

From Figure 8, Material D has somewhat less (although sufficient) volume consistently. All materials passed our internal specifications.



**Figure 9. Solder volume box plots for the 8 mil (0.20mm) aperture with an area ratio of 0.4. Material A is the control.**

From Figure 9, Material D has somewhat less (although sufficient) volume consistently. All materials passed our internal specifications.

#### Manufacturability Testing- Missing Print

In this test circular apertures 6 to 16 mils (0.15mm to 0.40mm) diameter are printed in 3 locations on the test board and inspected for missing print locations. The number of missing prints for each aperture are counted. We do not expect the 6 mil (0.15mm) apertures to print at all. There were no missing prints on any of the apertures from 8 mils (0.20mm) to 16 mils (0.40mm), so all materials pass.

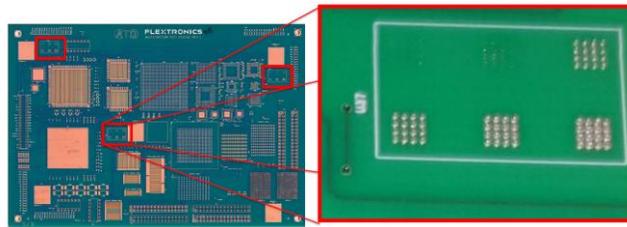


Figure 10. Missing print test pattern.

Ratio	C			B			A			D		
	U302	U301	U37									
6 Mils	4	0	7	1	41	14	21	0	0	9	0	0
8 Mils	0	0	0	0	0	0	0	0	0	0	0	0
10 Mils	0	0	0	0	0	0	0	0	0	0	0	0
12 Mils	0	0	0	0	0	0	0	0	0	0	0	0
14 Mils	0	0	0	0	0	0	0	0	0	0	0	0
16 Mils	0	0	0	0	0	0	0	0	0	0	0	0
Location Totals	4	0	7	1	41	14	21	0	0	9	0	0
Grand Total	11			56			21			9		
Rank	2			4			3			1		

Figure 11. Missing print test data and rank. All materials passed.

### Manufacturability - Wetting Test 1

In this test, we printed a circle of paste on an oversized Cu pad and measured the diameter after reflow. There is no specific pass/fail criteria for this test in terms of diameter. It is used, as with the test below (Wetting Test 2) to gauge the wetting properties of the material. The lower temperature solders do not wet as well as the control material. This can be an advantage in Paste in Hole (PIH) applications.

- Wetting Test 1
  - Print solder paste and measure solder spread after reflow.



Figure 12. Wetting Test 1 sample.

Material	C	B	D	A
Min	6.35	6.52	5.88	6.51
Max	6.53	6.58	6.59	6.58
Std Dev	0.03	0.02	0.27	0.02
Average	6.48	6.54	6.26	6.55
Rank	3	2	4	1

Figure 13. Wetting Test 1 results.

### Manufacturability - Wetting Test 2

In this test we deposited paste on rectangular pads at 5% intervals from 90% to 120% of the pad length. We then looked for the smallest percentage to completely cover the pad.

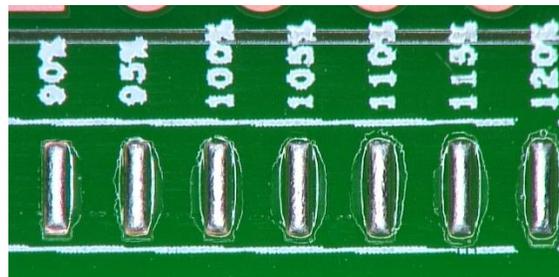


Figure 14. Wetting Test 2 sample. In this sample case the result is 105%.

Ranking				
Wetting Test - 2A				
Wetting %	C	B	D	A
Count of 105%	1	9	11	15
Count of 110%	9	15	16	14
Count of 115%	13	5	3	0
Count of 120%	7	0	0	0
Ranking	4	3	2	1

Figure 15. Results of Wetting Test 2.

As expected in Figure 15, the low temperature materials do not wet as well as the Sn3Ag0.5Cu control paste material.

#### Manufacturability –Cold Slump

In this test, we printed multiple lines spaced from 0.075mm (3 mils) to 0.300mm (12 mils) and counted the bridged lines at each spacing. The paste all performed similarly but the low temp. materials did slump a little more. The overall ranking is as follows:

- Rank 1 – Material D (120 Avg. bridges 3 Boards)
- Rank 2 – Material A (125 Avg. bridges 3 Boards)
- Rank 3 – Material B (185 Avg. bridges 3 Boards)
- Rank 4 – Material C (196 Avg. bridges 3 Boards)



Figure 16. Cold Slump Test Sample

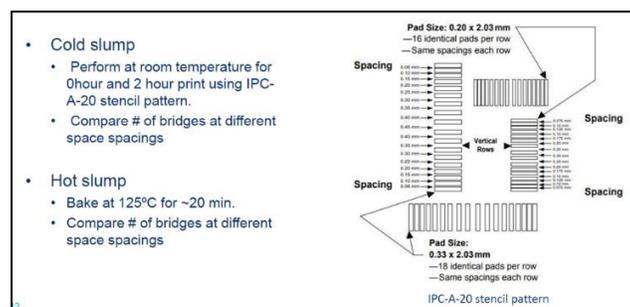
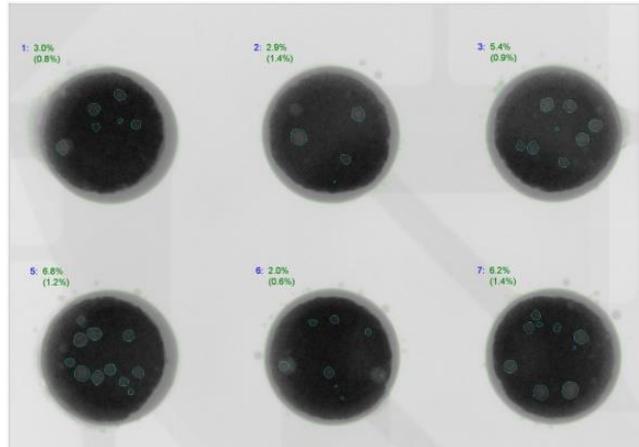


Figure 17. Description of both the hot and cold slump test.

### Manufacturability –BGA Voids

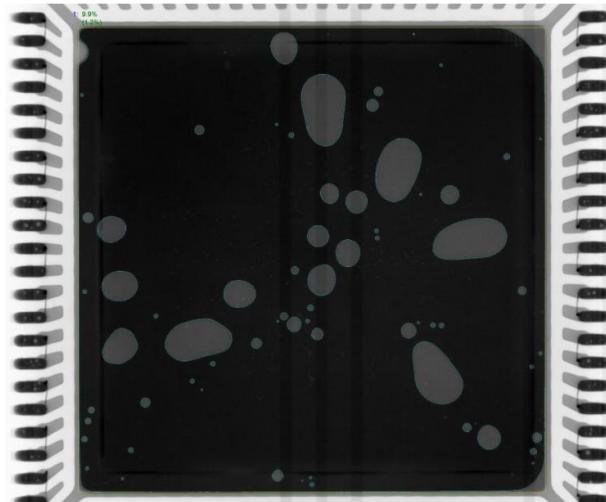
We observed approximately between 1% and 10% voiding on the BGA balls across all solder pastes tested with no significant performance difference between materials. Since we are not fully melting the BGA ball, we are not significantly altering the “as received” condition.



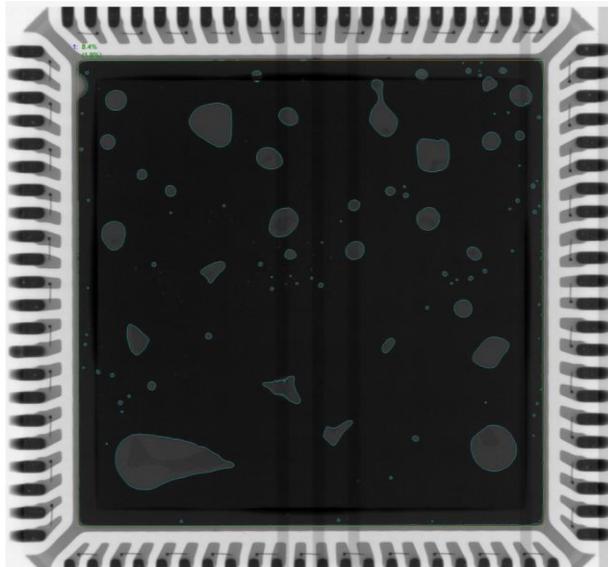
**Figure 18. A typical X-Ray inspection result of the 35x35 BGA with SAC305 balls.**

### Manufacturability –QFN Voids

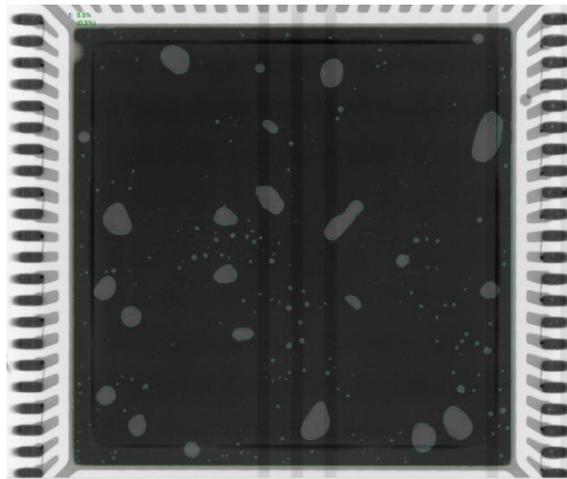
One surprising result was how well the lower temperature paste materials performed under the QFN/BTC component. While voiding in our control SAC305 paste materials averaged 9.9%, the lower temperature materials averaged between 1.8% for paste “C”, 5.9% for paste “B” and 8.4% for paste “D”. These results are shown in Figures 19 to 22.



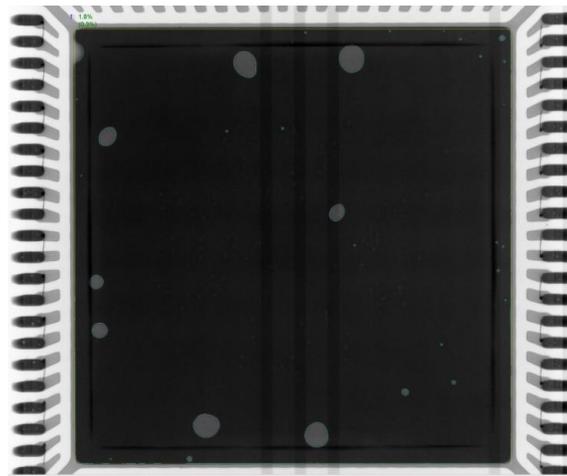
**Figure 19. Typical QFN voiding for Sn3Ag0.5Cu paste “A”**



**Figure 20. Typical QFN voiding for paste “D”**



**Figure 21. Typical QFN voiding for paste “B”**



**Figure 22. Typical QFN voiding for paste “C”**

#### Reliability–Four-point Monotonic Bend Test

We followed JEDEC 9702 recommended procedures to perform four-point monotonic bend testing on four boards of each paste type. We mounted a single 35x35 daisy-chained BGA to each 4 Layer test board with a thickness of 62 mils (1.6mm).

The strain rates were driven at a constant target head speed of 4mm/second which resulted in a strain response of between 5k  $\mu\epsilon$ /sec (micro strains per second) and 8k  $\mu\epsilon$ /sec.

One material (material “D”) had a couple of anomalous readings where the daisy chain went open ahead of the bulk material failure. This is likely a weakened or compromised solder joint on the periphery of the package. This small sample set was to get an early first level approximation.

Subsequent testing is currently underway. We will be testing 8 boards at 3x the strain rate (15K  $\mu\epsilon$ /sec). In addition, we will be doing drop testing on all materials as well. The differences between the pastes were less than the differences within the pastes but we were still able to rank the performance. The doped material “B” slightly outperformed the Sn3Ag05Cu Control and the other materials were comparable or slightly lower than the control. Material D had the widest range.

In the following stress and continuity response curves the solid lines are the strain measurement (inverse because the sensors were placed on the bottom) and the dotted lines (colors commensurate with each board) are the daisy chains. The dotted lines (daisy chains) rapidly go “open” when the circuit fails. Signal sampling is at 4x the specified rate of 500 per second (measured at 2K per second).

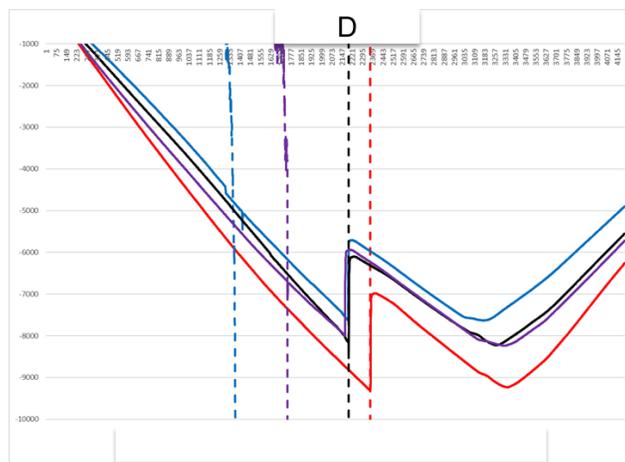


Figure 23. Strain and Daisy-Chain response for four sample “D” boards.

From Figure 23, two of the 4 boards tested failed prior to the bulk material. This material had the highest as well as the lowest response range (9311 $\mu\epsilon$  and 7313 $\mu\epsilon$  respectively). Further evaluation would be needed to understand the early failures.

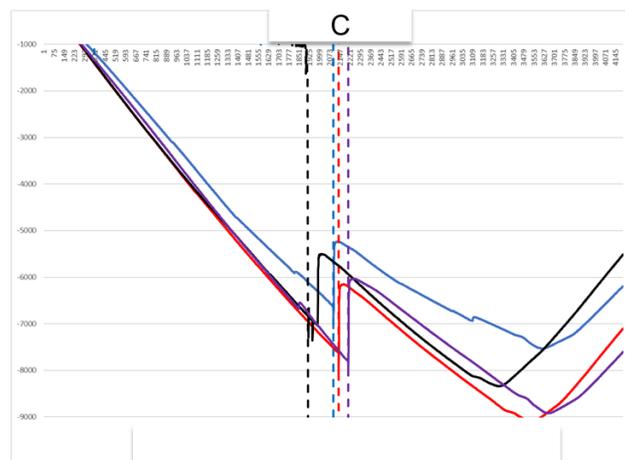
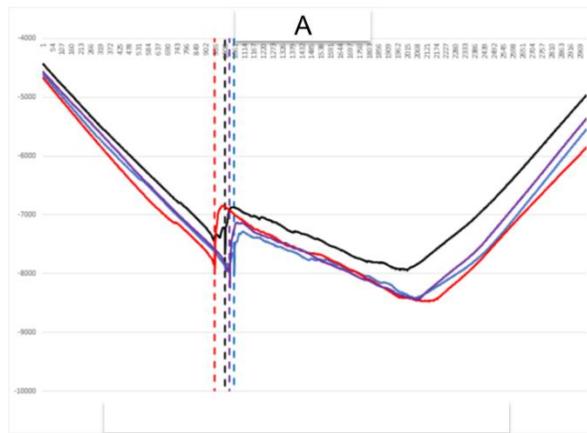


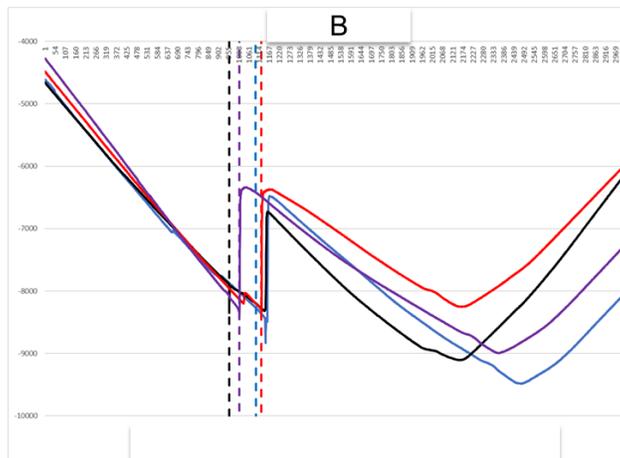
Figure 24. Strain and Daisy-Chain response for four sample “C” boards.

From Figure 24, one board (shown in Black) had a slightly early failure (before the bulk failure). These may be compromised solder joints. They may also indicate slight variance in the solder composition. More information would be needed to determine the reason for the slightly early failure.



**Figure 25. Strain and Daisy-Chain response for four sample “A” (control) boards.**

From Figure 25, the continuity failures corresponded directly with the bulk failures for all boards tested. Interestingly, although these boards mostly failed at the board land pad to board interface, this material did not have the strongest response.



**Figure 26. Strain and Daisy-Chain response for four sample “B” boards.**

From Figure 26, sample “B” boards had similar behavior to the Control material but one (blue) board had an open very slightly ahead of the bulk solder failure.

4 Point Bend 35mm BGA 4.5 mm/Sec head speed - Monotonic Bend to Failure Sample Freq: 2K/Sec			
Material	Average Microstrains Over 4 Measurements	Maximum Microstrains Over 4 Measurements	Minimum Microstrains Over 4 Measurements
A-Control	7703	7963	7306
B	8172	8334	7890
C	7235	7811	6644
D	7313	9311	5031

**Figure 27. Summary of Strain and Daisy-Chain response ranges for the four paste sample boards.**

From Figure 27, the differences between the materials is less than the differences within each material. This indicates that there is little or no statistical difference. The slope and range of material “D” needs to be studied further to determine if this is typical or an anomaly. Additional testing is under way.

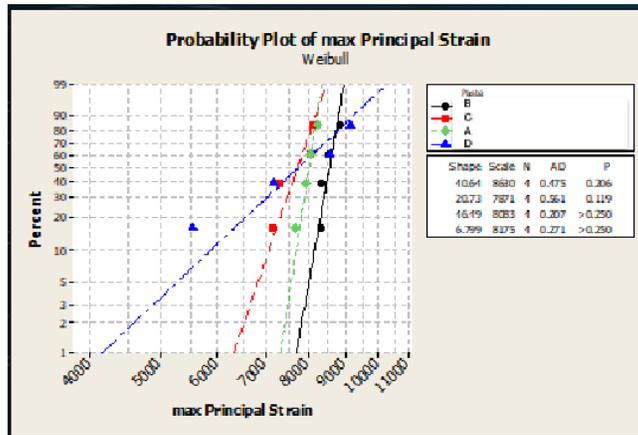


Figure 28. Results after bending 4 boards of each paste type to failure.

From Figure 28, Material “B” performed the best while material “D” the worst.

The failure modes were analyzed after dye and pry and cross sectioning and there were two primary failure modes. The control Sn3Ag0.5Cu material mostly failed below the board land pad (shown as type “5” failure mode in Figure 29) and many pulled some board material (similar to pad cratering) while the low temperature materials tended to break through the IMC (intermetallic) boundary in the bulk of the solder joint on the board side, (shown as “type 4” failure mode in Figure 29).

Interestingly the strongest point has historically been the bond between the board land pad and the board. In this (limited) test the control material did not have the strongest response. This may indicate that the higher process temperatures of the SAC-305 reflow profile has an effect on the pad to board strength.

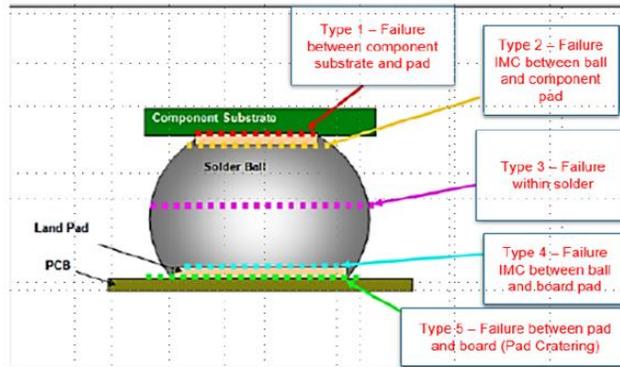


Figure 29. Failure mode descriptions. A type 5 failure mode is between the boardland pad and the board while a type 4 failure is in the IMC on the board side.

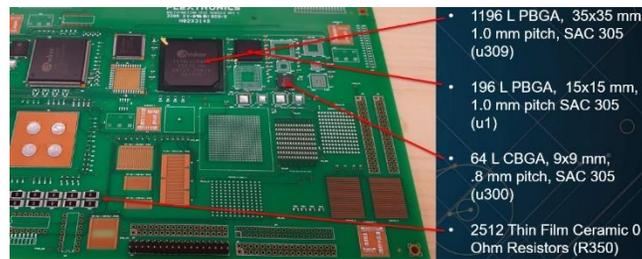
Board ID	Type 2	Type 4	Type 5	No solder joint failure
A-Control	0	0	~65%	~35%
	0	0	~60%	~40%
C	0	~75%	0	~25%
	0	~75%	0	~25%
B	~15%	~45%	~5%	~35%
	0	~60%	0	~40%
D	~15%	~45%	~10%	~30%
	0	~60%	0	~40%

Figure 30. Results of the dye and pry and cross-section post-strain (solder joint) fracture failure mode analysis. The control paste mostly failed between the pad and the board while the other materials mostly failed at the IMC.

## Reliability–Accelerated Temp Cycle Testing

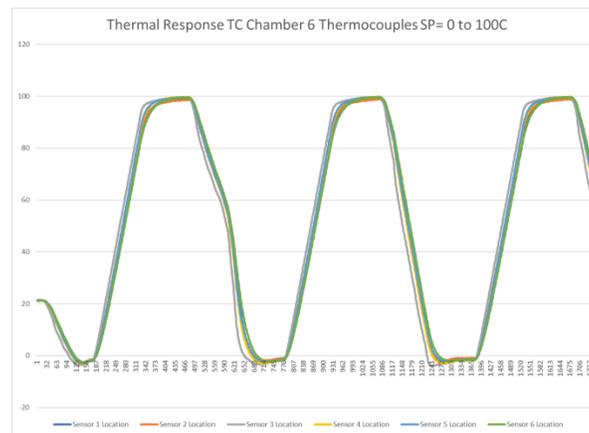
We followed JEDEC 9701 recommended procedures to perform accelerated temperature cycle testing. We mounted multiple daisy chained and 0 Ohm components to a 4 Layer PCB. The board was 62 mils (1.6mm) thick with 18 to 20 boards used for each solder material. The boards were subjected to 0 to 100C 40-minute temperature cycles with 10 minute ramps and dwells. We measured electrical continuity at 200 cycle intervals for the following four components:

- 1196 PBGA, 35x35 mm, 1.0 mm pitch, SAC 305 (u309)
- 196 PBGA, 15x15 mm, 1.0 mm pitch SAC 305 (u1)
- 64 CBGA, 9x9 mm, 0.8 mm pitch, SAC 305 (u300)
- 2512 Thin Film Ceramic Zero Ohm Resistors (R350)

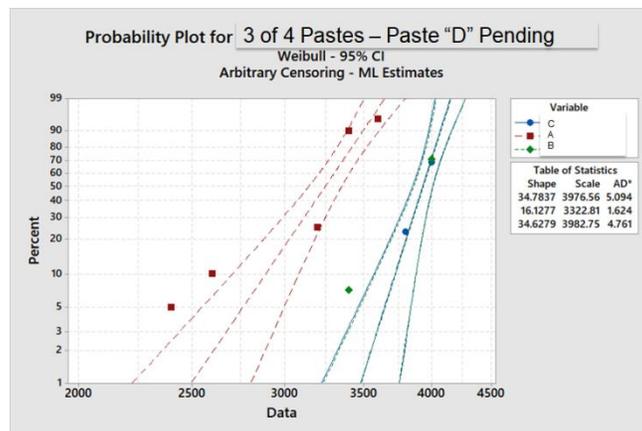


**Figure 31. Test vehicle arrangement and the locations of the four monitored components.**

As of the time of this paper, we had reached 4200 cycles with very few failures on any components other than the (expected) 2512 Thin Film Ceramic Zero Ohm Resistors. Solder Paste “D” boards were not assembled at the same time as the other paste boards so it had only completed 1000 temperature cycles as of the time of this paper without any failures.



**Figure 32. Temperature cycle chamber characterization response. 0 to 100C, 10-minute ramps and dwells.**

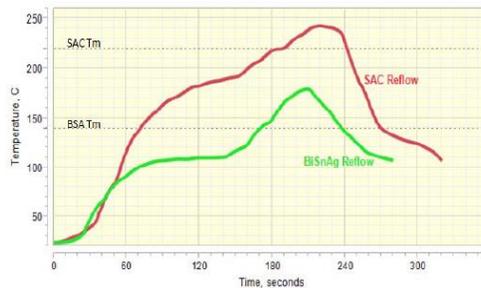


**Figure 33. Weibull failure plots for the three materials (Paste A, B, C) on the 2512 Capacitors.**

As expected in Figure 33, the low temperature (Bismuth containing) alloys slightly outperformed the control material “A” during this relatively low strain rate testing.

#### Environmental Impact and Potential Cost Savings

With a greater than fifty degree peak temperature delta and a lower temperature profile overall it should be clear that the energy consumption is significantly reduced during the reflow process. These low temperature solders are estimated to save 20% to 25% in (reflow) energy cost over SAC-305.



**Figure 34. Comparison of the typical reflow profiles for both SAC-305 (red) and the low temperature solder (green).<sup>1</sup>**

It is also estimated that using these low temperature solders would also reduce the CO<sub>2</sub> emissions by 1.1 metric tons per week<sup>1</sup>. This is roughly equivalent to 10 average gasoline vehicles (driven in the U.S.) per year.

#### CONCLUSIONS

Preliminary results investigating the low temperature paste alloys against the Sn3Ag0.5Cu paste alloy look promising. Limited internal testing to date, combined with limited external testing data, indicates that these newer, doped, lower temperature solders perform as well or better than Sn3AgCu(SAC305).

Further testing and evaluation is needed and is underway. We are proceeding with drop/shock and higher strain rate monotonic bend testing which is where we expect to see differentiation between the doped and non-doped solders under investigation.

#### Future Work

If the materials continue to make it past the tests previously mentioned, additional qualification testing will include SIR, cleanliness and application specific scenarios such as Large BGA assembly, high mix assembly, paste in hole assembly and rework.

Finally, in order to fully understand the manufacturing process window for reflow, a DOE will be conducted to define the range of peak temperatures and their effect on mixed alloy reliability across a multitude of alloys (i.e., when used to attach SAC-305 or low silver containing SAC125 BGAs).

#### REFERENCES

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