

## **New-Generation, Low-Temperature Lead-Free Solder for SMT Assembly**

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### **Abstract**

Sn3Ag0.5Cu (SAC305) is the major solder alloy after RoHS was adopted by the European Union. Since its melting temperature is relatively higher than eutectic SnPb alloy, the peak reflow temperature increases. This transformation in the assembly industry impacts the component requirement, where the deformation probability (warping) of a flat component is increased, which impacts the production yield. A lead-free, low-temperature SMT solder is needed to resolve this dilemma.

Low-temperature SMT assembly refers to the reflow process with a peak temperature less than 200°C. The new process provides a few advantages like reducing energy consumption, reducing BGA component warpage during reflow and diminishing non-wetting open (NWO) and head-on-pillow (HoP) defects. The SnBi alloy is one of the candidates used in low-temperature SMT assembly. However, the brittle mechanical property of conventional SnBi alloys will degrade the reliability of the assembly. The SnBi alloy properties can be altered via several means.

In this paper, the roles of additive and bismuth content will be discussed. Eutectic SnBi and three newly designed SnBi-based alloys (Sn57Bi1AgX, Sn48Bi1AgX and Sn40Bi1AgX, X represents <0.5wt.% of additive element) were experimented upon. Solder pastes that were blended with the aforementioned alloys and flux were used to assemble on the PCB with BGA components that have SAC305 solder spheres pre-mounted. The same reflow profile was used for all pastes. Cross-sectional analysis, shear testing, drop testing and thermal cycling testing were conducted to determine the microstructure, shear force, drop reliability and thermal reliability. The results show that the microstructure, especially the bismuth-rich phase, became finer and the shear force was elevated when the additive was added. On the other hand, the drop reliability improved with decreasing bismuth content, and the thermal reliability improved with increasing bismuth content.

### **Introduction**

Low-Temperature Solder (LTS) refers to a solder alloy with liquidus below eutectic Sn37Pb (183°C). The common LTS is eutectic Sn58Bi alloy, with a melting point of 139°C<sup>[1,2]</sup>. For the SMT process, the peak reflow temperature of the LTS paste should be below 200°C.

The main driving force for the LTS transition is increasing demand for ultra-thin packages. Reduction in package thickness increases its warpage, and this warpage generates production yield loss<sup>[3]</sup>. Also, the reflow temperature of SnAgCu series solder paste is much higher than the glass transition temperature ( $T_g$ ) of the substrate. This is another factor increasing substrate and PCB warpage. LTS paste can reduce the reflow temperature to below 200°C, hence decreasing both PCB and substrate deformation.

### **LTS Benefits and Drawbacks**

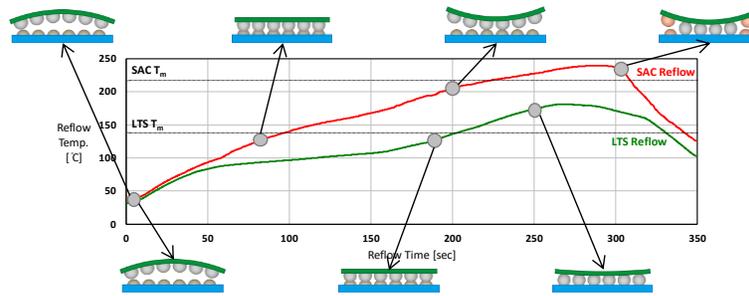
LTS provides numerous benefits. The four most notable are listed below.

#### Improved production yield

The reflow temperature of LTS is lower than SAC305. As a result, the deformation of PCBs and substrates is relatively small, and it subsequently improves the packaging yield of BGA components.

#### Reduced thermal stability requirement of PCBs and components

Because the reflow temperature is decreased, PCBs and components no longer need to withstand 240~250°C. Additionally, the product designer can choose components and PCBs with low thermal stability, thereby reducing product cost (Figure 1).



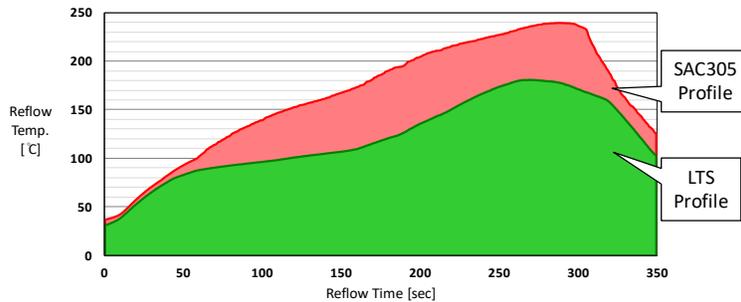
**Figure 1. Benefits of using LTS assembly**

### Energy conservation

Since the reflow temperature is decreased, the reflow oven's energy consumption also is reduced. However, the actual benefit is related to the thermal storage ability of the oven, product type, production quantity, etc.

### Green production

The green issue becomes critical in electronics production as can be seen in Figure 2. Because the energy consumption of the LTS process is decreased, the carbon footprint can be reduced as well.



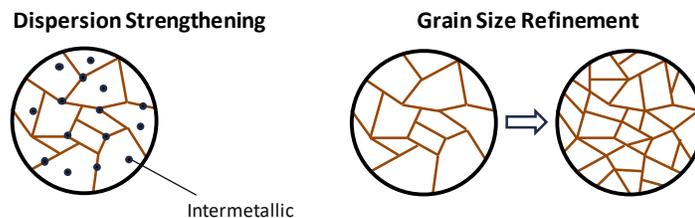
**Figure 2. A benefit of LTS is that its reduced energy consumption results in a smaller carbon footprint.**

However, the SnBi alloy, especially the Bi-rich phase within its microstructure, is prone to brittle fractures under high strain rate. In general, the ductility of the SnBi alloy is worse than the SnAgCu alloy. Therefore, the SnBi solder joints show worse performance in drop test and mechanical shock test.

### **Ductility Improving Method**

The addition of elements as shown in Figure 3 can improve the ductility of SnBi solder by modifying its microstructure:

- Additive elements form new phases or react with the Sn matrix to form intermetallic compounds (IMC)
- Additive elements to SnBi solder can suppress the coarsening of Bi-rich phase



**Figure 3. Adding elements can help improve the ductility of SnBi solder by forming IMCs and suppressing the coarsening of the Bi-rich phase.**

### **Experimental Procedure**

Four types of SnBi alloys were investigated in this study: eutectic Sn58Bi and three newly designed SnBi-based alloys (Sn57Bi1AgX, Sn48Bi1AgX and Sn40Bi1AgX). Each of the solders was tested using the following experiments:

### DSC

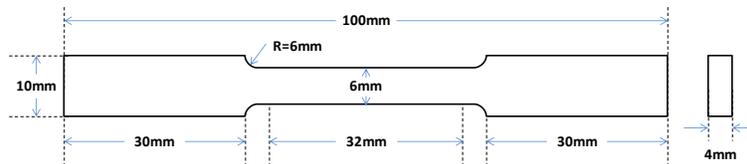
The differential scanning calorimetry (DSC) measurement was conducted at a heating rate of 10°C/min from 50°C-250°C. Onset temperature of melting is defined as solidus in this study. The DSC measurement results clarified the solidus as well as the endset temperature of melting of eutectic Sn58Bi and the three newly designed SnBi-based alloys.

### Microstructures

Eutectic Sn58Bi and the three newly designed SnBi-based alloy specimens were cross-sectioned, ground with SiC paper, and polished with 0.1 µm diamond paste. The microstructure was observed via scanning electron microscopy (SEM), and chemical compositions were analyzed using an energy-dispersive X-ray spectrometer (EDX) installed in the SEM. An operating voltage of 20 KeV was used to characterize the microstructures and phases formed in these specimens.

### Tensile Properties

Tensile tests were conducted using production tensile tester equipment. Flat samples were prepared per ASTM E8, as shown in Figure 4. These tests were performed at a constant strain rate of 6 mm/min, stress-strain curves of five samples of each alloys were recorded at room temperature. The average of the yield strength and elongation were reported in this study.



**Figure 4. Tensile test sample**

### SAC Ball/SnBi Paste Hybrid Joint Shear Test

The eutectic Sn58Bi and the three newly designed SnBi-based solder powders were manufactured. Powder size is type 4 based on IPC J-STD-005A. These powders were blended with a zero halogen flux to make solder paste. The SAC305 solder spheres used in this study had a diameter of 0.45 mm. The board pad finish was Cu-OSP with a 0.4 mm diameter, solder mask-defined type opening. The eutectic Sn58Bi and the three newly designed SnBi-based solder pastes were printed onto the board pads using a 100 µm-thick stainless-steel stencil. The SAC305 solder spheres were placed onto the printed solder paste. SAC solder balls were hybrid bonded with LTS paste on the PCB in a 12-zone reflow oven with the following profile: preheat between 100~120°C for 120 seconds, peak reflow temperature was 190°C, and time above liquidus was 100 seconds. The shear test for each alloy specimen was tested after reflow. The production shear tester used a shear speed of 500 µm/s.

### On-board Reliability Test

A PCBA with 15 CABGA192 with 192 I/O with 0.8 mm pitch and 0.45 mm diameter SAC305 solder balls was chosen as the test vehicle. The surface finish at the component side was Ni/Au, and at the PCB side was Cu-OSP. The pad diameter was 0.4 mm. The assemblies were bonded in a 12-zone reflow oven with the following profile: preheat between 100~120°C for 120 seconds, peak reflow temperature was 190°C, and time above liquidus was 100 seconds. The assembly is shown in Figure 5. Drop testing was performed with 1500Gs impact, 0.5 millisecond duration and half-sine pulse. Thermal cycling test was performed from -40°C to 100°C, with 10 minutes dwell time on each side and 10°C/min ramp rate. The thermal cycling test was performed for 1000 cycles.



**Figure 5. Reliability test board**

## Results and Discussion

### DSC

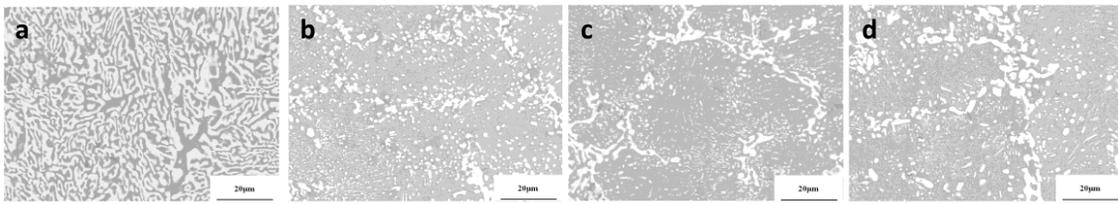
The DSC results of four alloys are shown in Table 1. The solidus of eutectic Sn58Bi is 139.2°C and the melting finished at 141.1°C, with a melting range of 1.9°C. The solidus of Sn57Bi1AgX was 138.6°C and the melting finished at 141.3°C. The melting behavior of Sn57Bi1AgX was the closest to the eutectic Sn58Bi among the three newly designed alloys. As bismuth content decreased, the solidus had no significant change. The solidus of the eutectic Sn48Bi1AgX was 138.5°C and the melting finished at 153.8°C, with a melting range of 15.3°C. The solidus of eutectic Sn40Bi1AgX was 138.7°C and the melting finished at 168.2°C, with a melting range of 29.5°C. The solidus and end set temperature of melting affected the peak temperature during the reflow process. Higher end set temperatures of melting need higher peak temperatures.

**Table 1. Melting behavior**

Alloy	Composition (wt.%)				Solidus (°C)	Endset Temperature of Melting (°C)	Melting Range (°C)
	Sn	Bi	Ag	X			
Sn58Bi	REM.	58	-	-	139.2	141.1	1.9
Sn57Bi1AgX	REM.	57	1	✓	138.6	141.3	2.7
Sn48Bi1AgX	REM.	48	1	✓	138.5	153.8	15.3
Sn40Bi1AgX	REM.	40	1	✓	138.7	168.2	29.5

### Bulk Microstructures

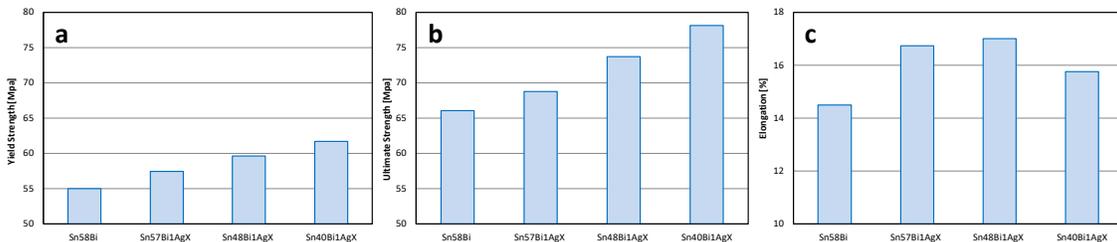
Backscattered electron images of eutectic Sn58Bi and the three newly designed SnBi-based alloys are shown in Figure 6. The dark region is the Sn phase and the white region represents the Bi phase. The typical eutectic structure is shown in eutectic Sn58Bi alloy. The non-continuous and needle-like Bi phase was observed in the three newly designed alloys. This indicated that the Bi phase morphology had been changed by Ag and the X element addition. However, the Bi content variation in the alloy had no effect on the Bi phase morphology.



**Figure 6. As-casted microstructure: (a)Sn58Bi, (b)Sn57Bi1AgX, (c) Sn48Bi1AgX, (d) Sn40Bi1AgX**

### Tensile Test

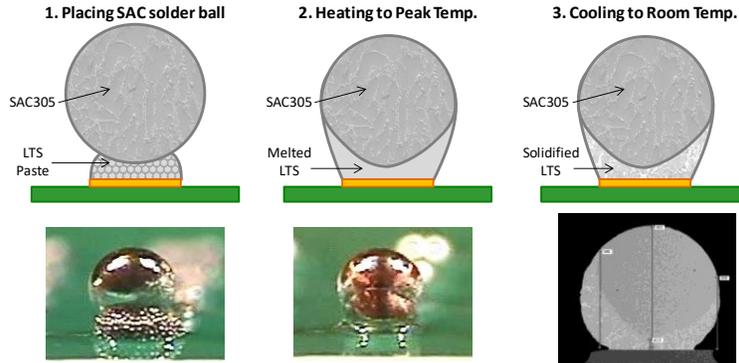
The tensile result of eutectic Sn58Bi and the three newly designed SnBi-based alloys is shown in Figure 7. This indicated that the ultimate tensile strength and yield strength have been elevated by the Ag and X element addition. Meanwhile, as bismuth content decreases, the ultimate tensile strength and yield strength have been elevated. The ultimate tensile strength and yield strength of Sn40Bi1AgX has been elevated by 18.4% and 12.1% respectively. When compared to eutectic Sn58Bi, it is the highest ultimate tensile strength and yield strength among the four alloys. Sn48Bi1AgX had the best elongation with 17.3% when compared to eutectic Sn58Bi.



**Figure 7. Tensile properties (test rate: 6 mm/min), (a) Yield Strength, (b) Ultimate Strength, (c) Elongation**

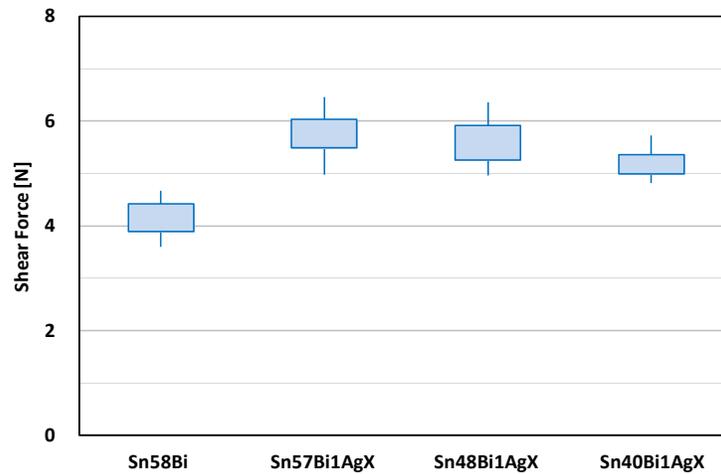
### SAC Ball/LTS Paste Hybrid Joint Shear Test

In this study, SAC305 solder spheres were placed onto the printed SnBi based solder paste. During the reflow process, SnBi-based solder paste was melted first, and the melted solder wetted and surrounded the SAC305 solder sphere, subsequently with solder/liquid diffusion reaction. The SAC/SnBi hybrid joints were formed after cooling, as shown in Figure 8. The shear test was performed on the hybrid joints.



**Figure 8. SnAgCu ball/LTS paste hybrid soldering process**

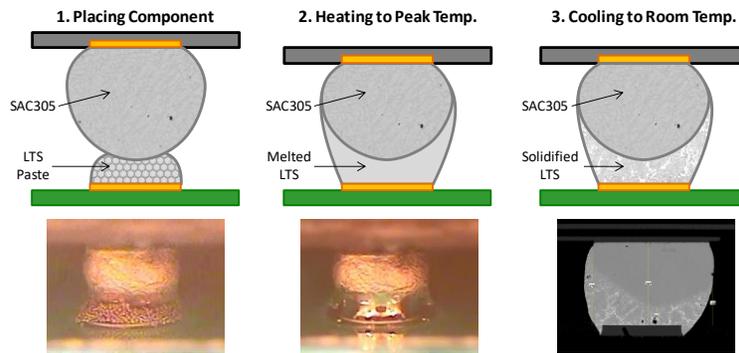
The result of the SAC ball/LTS paste hybrid joints shear test is shown in Figure 9. By comparing Sn57Bi1AgX with the Sn58Bi hybrid joint result it is evident that shear strength was elevated through Ag and the X element addition. On the other hand, when the same additives were present in SnBiAgX alloys, the hybrid joints' shear strength gradually decreased with decreasing bismuth content.



**Figure 9. Ball shear result**

On-board Reliability Test

During the reflow process, the SnBi-based solder paste was melted first, and the melted solder wetted and surrounded the SAC305 solder sphere, subsequently with the solder/liquid diffusion reaction. The SAC/SnBi hybrid joints were formed after cooling. Figure 10 shows the schematic diagram of the SAC BGA component/LTS paste hybrid soldering process as well as the solder joint cross-section image after assembly. The drop test and TCT test were performed on the test boards separately.



**Figure 10. SAC BGA component/LTS paste hybrid soldering process**

#### On-board Reliability Test – Drop Test

The BGA component on the PCBA for drop testing had added corner glue (CG), and each test board had 15 BGA components. As shown in Table 2, for the Sn58Bi+CG test group, the first fail occurred at the 82<sup>nd</sup> drop. Four BGA components failed after 100 drops. For the Sn57Bi1AgX+CG test group, the first fail occurred at the 92<sup>nd</sup> drop. One BGA component failed after 100 drops. The Sn48Bi1AgX+CG and Sn40Bi1AgX+CG test groups had no fails after the one hundred 1500Gs accelerated drop condition. This indicated that the drop performance was improved by Ag and X element addition with drop performance elevated further with decreased Bi content.

**Table 2. Drop test result**

Test Sample	First Fail (Drop No.)	Survival Rate after 100 drop
Sn58Bi+ Corner Glue	82	11/15, 73%
Sn57Bi1AgX+ Corner Glue	92	14/15, 93%
Sn48Bi1AgX+ Corner Glue	<b>No fail after 100<sup>th</sup> drop</b>	
Sn40Bi1AgX+ Corner Glue	<b>No fail after 100<sup>th</sup> drop</b>	

#### On-board Reliability Test – Thermal Cycle Test

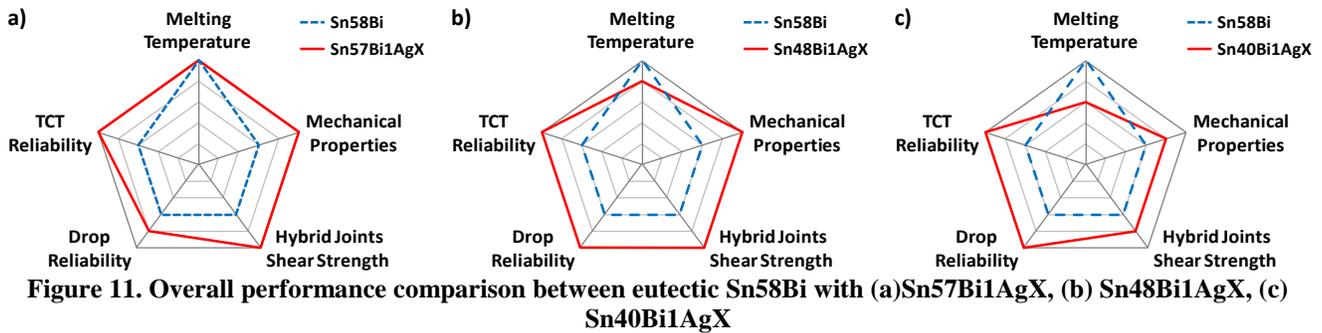
The thermal cycle test results are shown in Table 3. Each test group had five BGA components on-board. Only one BGA component failed in eutectic Sn58Bi test cell. The three newly designed alloys had no fails after the thermal cycle test of 1,000 cycles, indicating that the thermal cycle performance was improved by Ag and X element additions.

**Table 3. Thermal cycle test result**

Test Sample	First Fail	Survival Rate
Sn58Bi	719 cycle	4/5, 80%
Sn57Bi1AgX	-	<b>5/5, 100%</b>
Sn48Bi1AgX	-	<b>5/5, 100%</b>
Sn40Bi1AgX	-	<b>5/5, 100%</b>

#### Overall Performance

Figure 11 shows the overall performance comparison between Sn58Bi with the three new alloys, the performance is compared in five aspects:



**Figure 11. Overall performance comparison between eutectic Sn58Bi with (a) Sn57Bi1AgX, (b) Sn48Bi1AgX, (c) Sn40Bi1AgX**

### Melting Point

A lower final melting temperature could lower the reflow peak temperature, and hence reduce thermal damage on the PCB and components. According to the DSC results, the eutectic Sn58Bi and Sn57Bi1AgX had the lowest final melting temperature among the four alloys.

### Mechanical Properties

Higher ductility provides better toughness performance. In this study, Sn57Bi1AgX and Sn48Bi1AgX show the highest ductility among all the alloys.

### Hybrid Ball Shear Test

The compatibility of SnBi-based alloys with SAC305 has been tested. The result showed that Sn57Bi1AgX and Sn48Bi1AgX have the best hybrid ball shear.

### Drop Reliability

The drop test results showed that, after 100 times of a 1500Gs accelerated drop, Sn48Bi1AgX+CG and Sn40Bi1AgX+CG had no fails.

### TCT Reliability

Three newly designed Ag and X element added alloys had no fails after 1,000 thermal cycle testing, indicating that the three alloys have better performance than the eutectic Sn58Bi.

### **Conclusions**

The result of this study showed that the Bi phase became finer with Ag and X element additions in the SnBi-based alloy, and hence altered the mechanical performance and reliability of the SnBi-based alloy. It was also found that the three newly designed alloys have the following features:

1. The solidus and final melting temperature of Sn57Bi1AgX is close to the eutectic SnBi alloy. The Bi phase becomes non-continuous and needle-like with Ag and X element additions, significantly improving mechanical properties and thermal cycle reliability.
2. Sn48Bi1AgX has less bismuth content than the eutectic SnBi, hence the final melting temperature is 12°C greater than the eutectic SnBi. The thermal cycle performance and drop reliability are better with Ag and X element additions.
3. Sn40Bi1AgX has better performance in the thermal cycle and drop tests than the eutectic SnBi; however, the final melting temperature is 30°C greater than the eutectic SnBi, showing that a higher peak temperature is needed.

### References

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