Low Temperature Soldering: Thermal Cycling Reliability Performance

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Abstract
The technical and economic benefits derived from lowering the reflow temperatures have motivated the evaluation of new Sn-Bi low temperature alloys for soldering. Eutectic Sn-Bi alloy is usually described as having a brittle nature, not being able to sustain mechanical shock and thermal cycling stresses as well as Sn3Ag30.5Cu (SAC305) solder. A new non-eutectic Sn-Bi solder with 2 wt.% additives (generally called here as alloy A) is evaluated here and compared with other eutectic Sn-Bi alloys and SAC305. Tensile tests at -55°C, -25°C, +25°C, +75°C and +125°C were performed to provide insights on their relative mechanical properties. Mechanical drop shock tests of BGA84 and LGA84 were performed as per the JESD22-B111 standard, while thermal cycling tests were performed from -40°C (10 min) to +125°C (10 min) as per the IPC 9701 standard. The BGA84 was used for thermal cycling in situ monitoring, while BGA169, SOT223, QFP44 and 1206 chip resistors were also used for evaluating the effect of thermal cycling on IMC thickness, shear strength and tin whiskers. The results show that, for the aforementioned packages, assembly and testing conditions, alloy A is a viable replacement for SAC305. The joints formed with alloy A have the mechanical (drop) shock and thermal cycling performance as good as, or, in some cases, better than the same joints formed with SAC305.

Key words: lead-free, low temperature soldering, thermal cycling, mechanical drop shock, shear strength, tin whiskers.

Introduction
Eutectic Sn-Bi was extensively investigated as a potential replacement for eutectic Sn-Pb almost two decades ago [1-4]. Despite some positive results within mild environmental conditions [2-4], its poor mechanical reliability [5-6] and concerns regarding the formation of a low melting point phase [7-8] due to Pb contamination impeded its use at the time of Pb-free implementation. Since then, minor alloying additions have shown promising results in improving eutectic Sn-Bi mechanical and thermal fatigue properties [6, 9-12]. In recent years, progressive miniaturization of electronic assemblies and microprocessors led to challenges, such as dynamic warpage, that can be minimized when using reflow temperatures below 200°C [13-17]. Once more, low temperature solder alloys emerged as a possible solution, with the caveat that they will have to match the mechanical and thermal reliability of SAC305 solder alloy. Materials suppliers and industry consortia such as iNEMI have been extensively working on developing and testing new low temperature alloys to fulfill such requirements [18-21].

Perhaps one of the most interesting aspects of using low temperature Sn-Bi solder alloys is that they enable the soldering of packages with Sn-Ag-Cu balls at temperatures between 170 and 200°C, instead of the usual SAC reflow temperatures that are around 245°C. The use of real-time imaging to visualize the reflow of hybrid Sn-Bi/SAC solder joints provides additional insights on this process. Figure 1(a) shows the formation of a hybrid Sn-Bi/SAC305 solder joint, using a new non-eutectic Sn-Bi solder with 2 wt.% additives (generically called here as alloy A). The individual alloy particles in the solder paste are well-defined until just before the melting starts, at 139°C (+/-1°C), but the solder paste completely melts by 150°C (+/-1°C). Notably, there is a partial collapse of the SAC305 ball at around 188°C (+/-1°C) [22-23]. As a comparison, the homogeneous solder joint shown in Figure 1(b), in which the solder paste uses alloy A and the sphere alloy is eutectic Sn-Bi, confirms that the low temperature solder is mostly in a molten state by 142°C (+/-1°C). Cross-sectioning of hybrid alloy A/SAC305 solder joints confirms that the partial SAC305 ball collapse is due to inter-diffusion occurring between these two alloys, as showed in Figure 2, as discussed in Reference [12].

An adequate low temperature Sn-Bi solder alloy that can be used as a SAC305 drop-in replacement needs to fulfill multiple requirements. For example, its Bi content should be equal or higher than 40 wt.% for enabling reflow profiles with peak temperature lower than 200°C with moderate time above liquidus (TAL) that will not affect solderability and solder joint mechanical shock performance [23]. However, reduction in Bi alone is not enough to get a Sn-Bi alloy that can match both drop shock and thermal cycling performance of SAC305. In this work, this discussion is further extended to include the effect of temperature on bulk alloy mechanical properties, mechanical drop shock of hybrid Sn-Bi/SAC305 and homogeneous solder joints, in situ thermal cycling testing of hybrid solder joints, and the effect of thermal cycling on shear strength, intermetallic (IMC) thicknesses and tin whiskers. Throughout the testing, alloy A is compared to SAC305 or other commercially available alloys, such as eutectic Sn-Bi or 42Sn57.6Bi0.4Ag.
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**Figure 1** – Real-time images of (a) hybrid Alloy A/SAC305 solder joint during reflow and (b) SnBi/Alloy A solder joint during reflow [22].

**Figure 2** – Cross-section of SAC305/Alloy A hybrid solder joint assembled at 190°C. The highlighted area shows the inter-diffusion zone between the two alloys.

**Experimental Methodology**
For the bulk alloy analysis, the alloy was cast and machined into appropriate specimens, as described below. The various solder joint evaluations used test vehicles assembled using dummy packages such as BGA84, BGA169, LGA84, QFP44, SOT223 and 1206 chip resistors. These test vehicles were assembled using a reflow profile with 190°C peak temperature and 90s of time above liquidus (TAL) [23].

**Bulk Alloy Testing**
A universal testing machine with an environmental chamber is used for performing tensile tests at -55, -25, +25, +75 and +125°C. Rounded specimens were prepared as per ASTM E8 tensile test standard [24], using a 16 mm gauge length and 4 mm diameter, as shown in Figure 3. The stress-strain curves of at least five specimens were recorded, using 10^{-3} s^{-1} strain rate, and average values of ultimate tensile strength, yield strength and elongation are computed.
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**Drop shock Test**
The drop shock characteristic life (63.2% of cumulative failures calculated from Weibull plots) of the alloy was obtained from board level testing, as described in the JEDEC standard JESD22-B111 [25]. Each Cu-OSP finished test vehicle was assembled with a total of 15 CTBGA84 components, which have 12 mil SAC305 solder spheres in an array with 0.5 mm pitch. JEDEC’s service condition B was obtained by adjusting the drop height and striking surface till the shock pulse had 1500 Gs, 0.5 msec duration and half-sine shape. Each component was tested until its complete failure, similar to the procedure described in the IPC/JEDEC-9706 standard for Mechanical Shock In-situ Electrical Metrology Test [26]. A high-speed data acquisition system was used to monitor failures when there was a drop of 1V or more in the applied potential for a duration of 0.5msec or more.

**Thermal Cycling Test**
Thermal cycle testing was performed as per the IPC 9701 standard, using a profile from -40°C to +125°C, with a 10 min dwell at each of the extreme temperatures. The data reported here comes from two experiments, performed under the same conditions and using the same thermal cycling chamber. As comparative examples, 42Sn-57.6Bi-0.4Ag and SAC305 solder paste were tested in both experiments, whereas only SAC305 was used as a reference in the second experiment. The electrical resistance of the solder joints was monitored continuously using a data logger for the complete duration of the test. The test vehicle used for the testing also had 15 CTBGA84 components. Another test vehicle with Cu-OSP finish was used for evaluating the effect of thermal cycling on the shear strength of 1206 chip resistors (CR), on the IMC thickness growth (BGA169, QFP44, SOT223 and CR 1206) and tin whiskers (QFP44, SOT223 and CR 1206).

**Solder Joint Evaluation**
The effect of thermal cycling on the solder joints was evaluated through microscopic analysis and shear strength testing. The testing boards were removed from the thermal cycling chamber at regular intervals. Their corresponding cross-sections were investigated using a scanning electron microscope (SEM) for assessing solder joint integrity and growth of intermetallic thicknesses on BGA169, QFP44, SOT223 and 1206 CRs. The shear strength values of the 1206 CRs were measured using a bond tester, as described in the JIS Z3198-7:2003 standard. From each test condition, 20 to 25 chip resistors were evaluated, using a 700 µm/s shear speed and 20 µm shear height.

The test method used for evaluation of tin whiskers follows as close as possible the JEDEC standard JESD22-A121A “Test Method for Measuring Whisker Growth on Tin and Tin Alloy Surface Finishes” (July 2008, reaffirmed May 2014). At least five testing boards were evaluated and their surface was inspected for presence of whiskers on QFP44, SOT223 and 1206 CRs. The length of the detected whiskers was measured by tracing a straight line from the whisker termination at the solder surface to its most distant point.

**Results and Discussion**
From the stress-strain curves obtained in the tensile test at various temperatures, it is observed as a general trend that ultimate tensile strength and yield strength are higher at temperatures below zero and lower as the testing temperature approaches their
melting point. These are expected trends, as they depend on the movement of dislocations, which is impeded at lower temperatures and favoured at higher temperatures, depending on the atomic vibrations. Figure 4 shows results of ultimate tensile strength, yield strength and elongation at -55, -25, +25, +75 and +125°C. SAC305 ultimate tensile strength is highest at -55°C and lowest at +125°C, but for the low temperature alloys 42Sn57.6Bi0.4Ag and alloy A, tensile strength at -25°C is a little higher than at -55°C. SAC305 generally has lower tensile strength than the low temperature alloys, except at +75°C, when all three alloys exhibit the same tensile strength. Above 75°C, SAC305 tensile strength is expected to be higher than 42Sn57.6Bi0.4Ag and alloy A, as observed at +125°C. The yield strength follows a similar trend, in which it is highest at -55°C and lowest at +125°C. It is also higher in the low temperature alloys than in SAC305 at testing temperatures below +75°C, equal at +75°C, and lower at +125°C. It is important to note that there were challenges in testing the low temperature alloys at the extreme temperatures. This was more evident in the 42Sn57.6Bi0.4Ag alloy, as in some of the testing conditions most samples deformed and the elongation data could not be collected. Little variation was observed in SAC305 elongation with the testing temperature. As such plots reflect the results obtained in the tensile tests, it is important to also highlight the shape of the corresponding stress-strain curves. Stress-strain curves for the low temperature alloys 42Sn57.6Bi0.4Ag and alloy A at -55°C are typical examples of brittle materials, whereas at -25°C the stress-strain curves show regions of plastic deformation, characteristic of ductile materials.

![Ultimate Tensile Strength (UTS), Yield Strength (YS) and Elongation of SAC305, 42Sn-57.6Bi0.4Ag and Alloy A at -55°C, -25°C, +25°C, +75°C and +125°C](image)

Such mechanical tests are useful for providing insights into the general behaviour of these alloys in a solder joint, but do not provide enough information to predict their performance in actual devices. Instead, proxy tests such as mechanical drop shock and thermal cycling are often used to predict thermal and mechanical reliability of solder joints. Figure 5 shows Weibull plots of the drop shock results of alloy A and SAC305, using BGA84 and LGA84. SAC305 balls are used on the BGA84s, resulting in hybrid alloy A/SAC305 solder joints, as exemplified in Figure 2. For the LGA84s, only the solder paste is applied, resulting in
in homogeneous solder joints. From these plots, the drop shock characteristic life (i.e., 63.2% cumulative failures) of alloy A/SAC305 hybrid solder joints is 82% of SAC305 homogeneous solder joints in the same package, with 1.41 and 1.27 respective shape parameters, and overlapping within the 95% confidence interval. In LGA84, alloy A and SAC305 homogeneous solder joints have the same drop shock performance, with 1.27 and 1.73 shape parameter.

As mentioned earlier, poor thermal cycling has been recognized as one of the key drawbacks from using eutectic Sn-Bi alloy. Small additions of Ag resulted in improved mechanical properties [9], but were not enough to match SAC305 thermal cycling performance [6,11]. Table 1 shows the cumulative failures from thermal cycling in situ monitoring of BGA84 hybrid Sn-Bi/SAC and homogeneous SAC305 solder joints. After 2,000 cycles, eutectic Sn-Bi alloy has six times more failures than SAC305. Alloy A solder composition has been optimized for combining the strength from Sn-Bi alloy with improved thermal reliability obtained from minor alloying additions, so at 2,000 cycles, alloy A has only 13% cumulative failures. Figure 6 shows the same data in a Weibull plot. Whereas all components assembled using eutectic Sn-Bi failed before 2,300 cycles, less than a third failed for alloy A and SAC305, so the data is censored at 2,300 cycles. The thermal cycling characteristic life of alloy A and SAC305 are basically identical, overlapping within 95% confidence level. Eutectic Sn-Bi has clearly lower thermal cycling performance, which is about 28% lower than SAC305. Indeed, these differences could be even higher if the experiment was kept for a longer time. The cross-sections of BGA84 solder joints after thermal cycling reflected these same findings (Figure 7), in which eutectic Sn-Bi alloy performance was much lower than SAC305 and alloy A. The degradation at such thermal cycling profiles start as early as 500 cycles for eutectic Sn-Bi/SAC305 hybrid solder joints. On the other hand, alloy A does not undergo such degradation even at 1,500 cycles when its first cracks are observed. Comparatively, only small cracks are observed in SAC305 at 1,500 cycles.

<table>
<thead>
<tr>
<th>Alloy / Component</th>
<th>Weibull</th>
<th>Mechanical (Drop) Shock Results</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Alloy A T4 BGA</td>
<td>Alloy A T4 LGA</td>
</tr>
<tr>
<td>Shape Ch.Life N AD P</td>
<td>1.409 677.8 49 0.660 0.082</td>
<td>1.273 803.2 21 0.349 &gt;0.250</td>
</tr>
</tbody>
</table>

![Figure 5 – Drop shock results](image)

Table 1 - In situ cumulative thermal cycling failures on CTBGA84

<table>
<thead>
<tr>
<th>Alloy</th>
<th>% Failures</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>0-1000 TC</td>
</tr>
<tr>
<td>Eutectic Sn-Bi</td>
<td>0 7 67</td>
</tr>
<tr>
<td>Alloy A</td>
<td>0 0 13</td>
</tr>
<tr>
<td>SAC305</td>
<td>0 0 11</td>
</tr>
</tbody>
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The cross-sections of homogeneous solder joints show a different trend than in the hybrid solder joints, as showed in Figure 8. In the case of the 1206 chip resistors, the first cracks are observed in SAC305 before 1,000 cycles. These cracks initiate on the solder joint surface and propagate through the bulk alloy. For the eutectic Sn-Bi, larger cracks are observed by 2,000 cycles. Such cracks originate and propagate mostly through the package/solder IMC interface. Alloy A shows the best thermal cycling resistance, as no cracks were visible even after 2,000 thermal cycles. The shear test post-thermal cycling confirms the superior
performance of alloy A, as shown in Figure 9. Eutectic Sn-Bi, alloy A and SAC305 have similar (within standard deviation) initial shear strength, 10.6, 11.2 and 10.1 kgf, respectively. At 500 cycles, both eutectic Sn-Bi and alloy A have similar ability to retain shear strength after thermal cycling, whereas SAC305 loss in shear strength is eight times higher. After 1,000 cycles, eutectic Sn-Bi reduction in shear strength is four times higher than alloy A, whereas SAC305 loss is eight times higher. At the end of 2,000 cycles, alloy A shear strength is only 24% lower than its initial value, while eutectic Sn-Bi post-thermal cycling shear strength is 68.4% lower and SAC305 is 81.1% lower.

Further analysis of the total IMC thickness was performed on BGA169, QFP44 and SOT223, for alloy A, using SAC305 as reference, as shown in Figure 10. On the BGA169, the IMC growth rate of the hybrid alloy A/SAC305 solder joint, is the same as in homogeneous SAC305. Although, the IMC growth of homogeneous alloy A solder joints is faster (QFP44, SOT223 and CR1206), its final value after 1,500 thermal cycles is the same as in SAC305, or within the standard deviation of +/-0.3 µm. The same samples were analysed to evaluate tin whiskers growth during the thermal cycling test. A few of these examples, for alloy A and SAC305 are shown in Figure 11. There is no difference in the whiskers’ morphology of these two alloys and most.
of the whiskers observed are sized between 10 and 20 µm. As showed in the figure, the largest tin whiskers observed in alloy A measured 15.9, 25.4 and 18.4 µm, for chip resistors, QFP and SOT, respectively. For SAC305, the largest tin whiskers observed measured 16, 25.4, 21.4 µm, for chip resistors, QFP and SOT, respectively.

![Figure 10–Effect of thermal cycling on the average intermetallic thicknesses](image)

![Figure 11 - Whisker analysis after thermal cycling of 1206 chip resistors, QFP44 and SOT223, using Alloy A (top) and SAC305 (bottom).](image)

**Summary/Conclusions**

For the packages and experimental conditions discussed in this work, the results are summarized as follows:

- Stress-strain curves obtained in the tensile test at various temperatures, show that strength decreases with the increase in temperature. Low temperature alloy A has higher ultimate tensile strength and yield strength than SAC305 at -55, -25, +25°C, equal at +75°C, and lower than SAC305 as the testing temperature approaches their melting point.
- Drop shock characteristic life of alloy A/SAC305 hybrid solder joints is 82% of SAC305 BGA84 solder joints, whereas homogeneous alloy A and SAC305 LGA solder joints have the same drop shock performance.
- Weibull curves using data from in situ monitoring of the BGA84 during thermal cycling show that alloy A and SAC305 have almost identical characteristic lives.
• After 2,000 cycles, alloy A shear strength is only 24% lower than its initial value, while eutectic Sn-Bi is 68.4% lower and SAC305 is 81.1% lower. Chip resistor cross-sections confirmed these results, as alloy A solder joints do not have cracks at 2,000 thermal cycles, showing much higher performance than SAC305.

• IMC thickness post-thermal cycling in hybrid solder joints alloy A/SAC305 is the same as in homogeneous SAC305 solder joints. Although IMC growth in homogeneous alloy A solder joints are a bit faster, its final IMC thickness (QFP44, SOT223 and 1206CR) is equal to SAC305.

• After thermal cycling, tin whiskers in SAC305 and alloy A solder joints have similar morphology and length.

It is possible to replace SAC305 alloy by a low temperature Sn-Bi alloy with micro-additives (alloy A) in the packages evaluated, while maintaining or improving SAC305 mechanical (drop) shock and thermal cycling performances. However, further investigation is necessary for using low temperature solders, including alloy A at temperatures below -40°C as these show brittle behaviour at -55°C.

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References
[1] Ferrer, E. and Holder, H., “57Bi-42Sn-1Ag: A Lead Free, Low Temperature Solder for the Electronic Industry”.


