

# HIGH THERMO-MECHANICAL FATIGUE AND DROP SHOCK RESISTANT ALLOYS FOR BALL-GRID ARRAY PACKAGE APPLICATIONS

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## ABSTRACT

High-Ag, low-Ag, high-Ag plus additives: Which alloy fits best certain application? Here we present a comprehensive report on the thermal and mechanical reliability of alloys ranging from 0.3 to 3.8% Ag, with and without presence of additives such as Bi, Ni and Sb. CTBGA packages with 84 I/Os were assembled using SAC105, SACX Plus 0307, SAC125N, SAC305, Innolot and Maxrel Plus spheres. Test vehicle assembly used SAC305 solder paste for all alloys, except for Maxrel Plus BGAs, which were evaluated with both SAC305 and Maxrel Plus solder pastes. Single ball shear, drop shock and thermal cycling were used to evaluate these alloys performance for BGA packages applications. Our results expand the perspective over the usual belief that high-Ag Sn-Ag-Cu alloys result in better thermal cycling and lower drop shock performance than when using low-Ag alloys.

Alloying additions can be used to improve single ball shear, drop shock and thermal cycling properties. In order to obtain maximum performance and cost benefit, solder alloys need to be paired to the correct application. Based on the results shown, we recommend: i) SACX Plus 0307 for applications that require maximum drop shock and reasonable thermal cycling performance. ii) SAC305 for applications requiring good drop shock and thermal cycling properties. iii) Maxrel Plus for applications that require higher shear strength, drop shock and thermal cycling, including automotive under the hood, high efficiency LEDs and semiconductor packaging.

Key words: Ball-grid array packages, lead-free, solder alloys, thermal cycling, drop shock.

## INTRODUCTION

Lead-free alloys SAC305 and SAC405 are popular choices that have been commonly used since the electronics industry transitioned to lead-free solders [1-3]. They are particularly known to have thermal cycling properties superior to eutectic Sn-Pb [4-5]. Unfortunately, these high silver Sn-Ag-Cu alloys do not reproduce Sn-Pb mechanical reliability performance. As devices complexity increased and they became smaller and more portable, there was a need to improve mechanical reliability of Sn-Ag-Cu alloys. One of the solutions was to reduce silver content in Sn-Ag-Cu alloys, generally resulting in improved drop shock resistance [6-7]. Alloys with silver content below 1 wt.% became popular choices as they were better suited for portable electronics. In addition to that, lowering silver content reduces exposure to its market price oscillations, resulting in more stable soldering materials costs.

However, certain applications still required alloys with higher thermal reliability than SAC305/SAC405 alloys [8]. Therefore, high silver Sn-Ag-Cu alloys with performance additives such as Sb, Bi and Ni were introduced and, especially recommended, for automotive and energy technology applications [9-12]. In the case of semiconductors applications, there is limited information on how these various alloys fare against each other. In addition to that, practical reasons could lead electronics manufacturers to continue using SAC305 solder paste, despite switching the solder alloy in the components.

In the work presented here, for the first time we present a comprehensive investigation of thermo-mechanical

reliability of mixed lead-free Sn-Ag-Cu solder alloys. The six alloys evaluated for ball-grid array (BGA) applications include alloys with Ag content from 0.3 to 3.8%, and other alloying additions including Ni, Bi and Sb. In order to obtain maximum performance and cost benefit, solder alloys need to be paired to the correct application. Here we evaluate these alloys single ball shear, high temperature storage, thermal cycling, and drop performance, and conclude on their suitability for various thermo-mechanical reliability requirements.

### EXPERIMENTAL DETAILS

Total of seven sphere-solder paste combinations were chosen for this study, as shown in Table 1. These include three low silver (SACX Plus 0307, SAC105 and SAC125N) and three high silver (SAC305, Innolot and Maxrel Plus) alloys. SAC125N has 0.05 wt.% Ni, whereas ALPHA® SACX Plus® is a Sn-0.3Ag-0.7Cu-Bi alloy that contains proprietary additives to enhance its mechanical reliability. Innolot, or ALPHA® Maxrel™ (Sn-3.8Ag-0.7Cu-Sb-Bi alloy with alloying additions) is known to have improved thermal cycling performance. ALPHA® Maxrel® Plus (Sn-3.8Ag-0.8Cu-Bi with additives) is a recently introduced ultra-high reliability alloy. Solder pastes were prepared using ALPHA® CVP390 paste flux. CTBGA84 with Ni-Au finish 0.225 mm pad size were assembled using 12 mil spheres of each of the alloys.

**Table 1.** Test matrix of sphere-solder paste alloy combinations

Sphere	Solder Paste
SAC105	SAC305
SACX Plus 0307	SAC305
SAC125N	SAC305
SAC305	SAC305
Innolot	SAC305
Maxrel Plus	SAC305
Maxrel Plus	Maxrel Plus

### Single Ball Shear

Single ball shear test was conducted in a Condor Sigma bond tester (Figure 1). From the two outermost rows of the CTBGA84 (Figure 1 inset), each sphere is sheared at 700  $\mu\text{m/s}$  test speed. A total of five BGAs were tested and the average single ball shear strength of each alloy was computed.

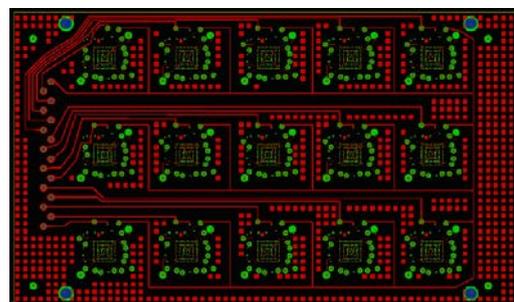


**Figure 1.** Condor Sigma bond tester. CTBGA84 (inset)

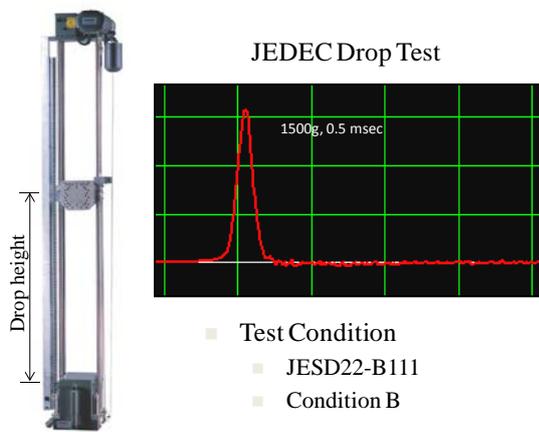
### Drop Shock

The same test vehicle was used for thermal cycling and drop shock evaluation (Figure 2). This test vehicle is a copper OSP, 77 x 132 mm, non-solder mask defined PCB, with 15 CTBGA84 components per board. A Lansmont M23 shock machine, shown in Figure 3 (left), is used for performing the drop tests of our customized test vehicle. By adjusting the drop height and the strike surface it is possible to achieve JEDEC's recommended service condition B (1500Gs, 0.5 msec duration and half-sine pulse), which is monitored as shown in Figure 3 (right).

The electrical continuity of each component is monitored during each drop using an Analysis Tech STD event detector. Each of the CTBGA84 units on the drop shock test vehicle was tested till failure as per JESD22-B111 standard. Failures were recorded once a first discontinuity is followed by three others, within five subsequent drops. Weibull curves were built for evaluating the probability distribution of the failures over a period of time.



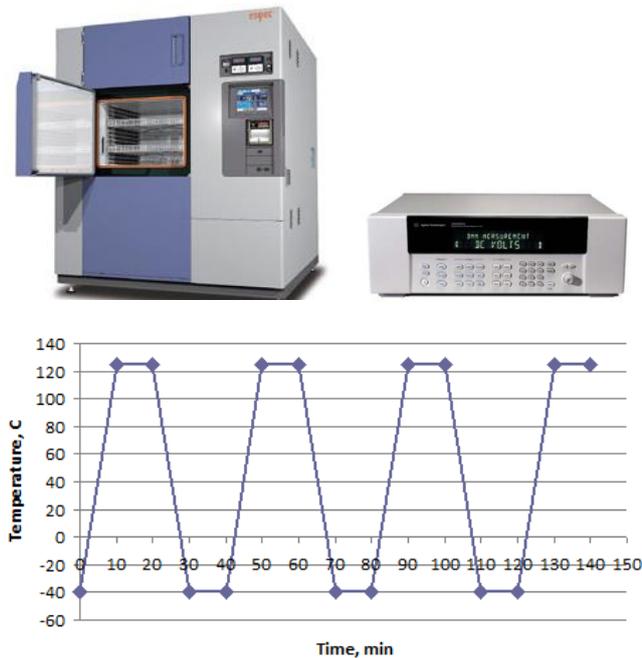
**Figure 2.** Test vehicle used for thermal cycling and drop shock tests



**Figure 3.** Lansmont drop shock testing machine (left) and half-sine shock pulse curve (right)

### Thermal Cycling

Thermal cycling tests were carried out in an air-to-air Espec chamber (model TSA-101S), Figure 4 (top). Thermal cycling profile followed condition G of the JEDEC JESD22-A104 standard, from  $-40^{\circ}\text{C}$  to  $125^{\circ}\text{C}$ , with 10 min dwell at the extreme temperatures, as shown in Figure 4 (bottom). The components were electrically monitored for discontinuities/increase in contact resistance for a total of 4,000 thermal cycles using a data logger.



**Figure 4.** Equipment (top) and thermal profile (bottom) used in the thermal cycling test

### High Temperature Storage

The effect of high temperature storage on the alloy microstructure and intermetallics were also evaluated. Test vehicles were assembled with CTBGA84 as per sphere-solder paste combinations shown in Table 1. Samples were uniformly maintained at  $150^{\circ}\text{C}$  for up to

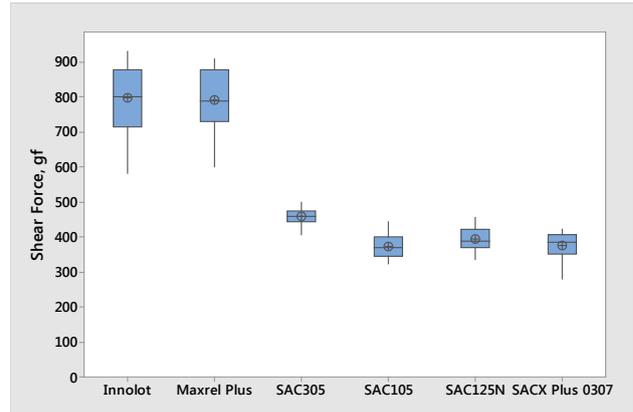
1000 hours. Sampling was done at 250, 500, 750 and 1000 hours intervals.

### Intermetallics Analysis

The effect of thermal cycling and high temperature storage on the solder joints of the new alloys was also evaluated. Cross-sections of each assembly were investigated using a scanning electron microscope (SEM) in order to assess the solder joint integrity of the respective sphere-solder paste combinations. In addition to that, the interfacial intermetallics thickness was measured, on both PCB and component sides.

### RESULTS AND DISCUSSION

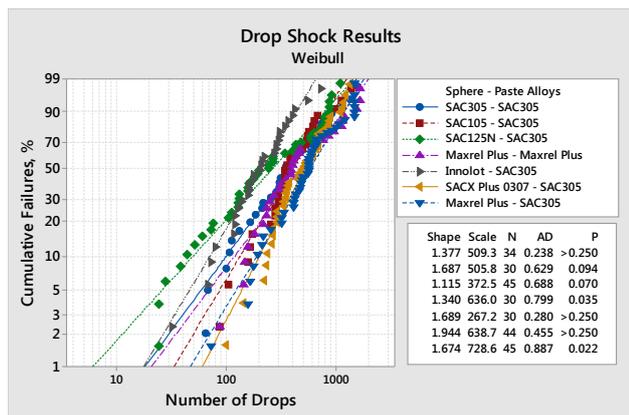
Results of single ball shear strength are shown in Figure 5. Innolot and Maxrel Plus average shear strength is 73% higher than SAC305 and 100-114% higher than the low-Ag alloys. Innolot and Maxrel Plus have a little higher Ag content than SAC305, so Ag addition alone is not responsible for their higher shear strength. Both Innolot and Maxrel Plus have Bi addition, which increases the alloy strength through solid solution. In the case of Innolot, Sb addition also contributes to its solid solution strengthening. Maxrel Plus has other additives that bring its strength to the same level of Innolot, despite being a Sb-free alloy. There is very little difference in shear strength between the alloys from 0.3 to 1.25 wt.% Ag. Therefore, it is fair to conclude that Ag addition has only a minor effect on the single ball shear strength of these alloys.



**Figure 5.** Single ball shear strength

Single ball shear strength was found to be a poor indication of drop shock performance of these alloys, which is shown in Figure 6. For example, Innolot and SAC125N BGAs resulted in the worst drop shock characteristic life. SAC105 and SAC305 have similar drop shock performance, but use of Maxrel Plus spheres increases drop shock characteristic life in 43%. SACX Plus 0307 and Maxrel Plus showed the best drop shock performance among the alloys tested. The superior performance of SACX Plus 0307 and Maxrel Plus does not come as a surprise given the fact that these alloys were specifically developed for maximized thermo-mechanical performance. Both of these alloys have additives that control atomic diffusion during interfacial intermetallics

formation. Although Maxrel Plus is a high-Ag alloy, its additives confine Ag<sub>3</sub>Sn mostly to within the eutectic phase.



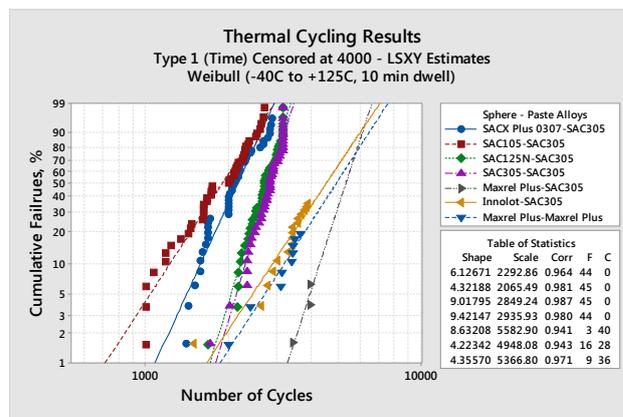
**Figure 6.** Drop shock performance of sphere-solder paste combinations

Thermal cycling results are summarized in Table 2. SAC105 has the poorest thermal cycling performance, with 100% BGA electrical failures before 3000 cycles. By 3500 thermal cycles, SACX Plus 0307, SAC125N and SAC305 BGAs also have also showed 100% failures. At the end of the test completion (4000 cycles), 9-20% Maxrel Plus BGAs had failed, whereas 37.8% of Innolot BGAs failed. The Weibull curves representing these results are shown in Figure 7.

SACX Plus 0307 thermal cycling characteristic life is 11% higher than SAC105. Thus, despite its lower Ag content, SACX thermal cycling is higher than what is expected due to its alloying additions. SAC125N, which has four times more Ag than SACX is 24% higher. Perhaps the most surprising results is that SAC305 thermal cycling was just 3% higher than SAC125N. Innolot, which is known for its high thermal fatigue properties, showed 68% higher performance than SAC305. Both sets using Maxrel Plus spheres showed excellent thermal cycling performance, with considerably less cumulative failures than Innolot. However, due to the small number of failures, their Weibull curves are less accurate in describing their behaviour.

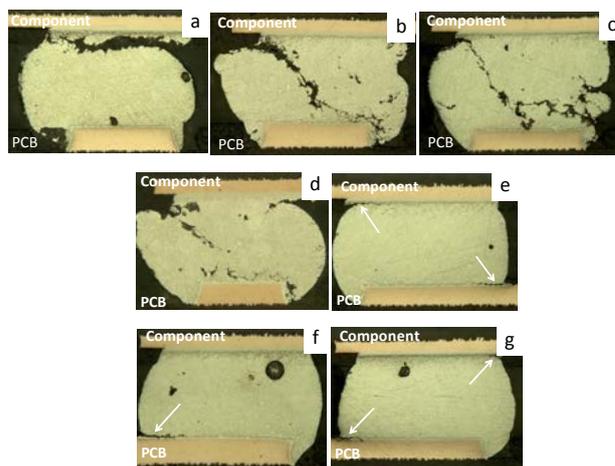
**Table 2.** Cumulative failures after thermal cycling test

Sphere Alloy	Paste Alloy	Cumulative Failures (%)							
		0- 500 TC	0- 1000 TC	0- 1500 TC	0- 2000 TC	0-2500 TC	0- 3000 TC	0- 3500 TC	0-4000 TC
SAC105	SAC305	0	0	24.4	51.1	86.7	100	100	100
SACX Plus 0307	SAC305	0	0	4.5	40.1	79.5	97.7	100	100
SAC125N	SAC305	0	0	0	2.2	26.7	75.6	100	100
SAC305	SAC305	0	0	0	2.2	20	68.9	100	100
Innolot	SAC305	0	0	0	2.2	2.2	11.1	24.4	37.8
MaxRel™ Plus	MaxRel Plus	0	0	0	0	2.2	4.4	17.8	20
MaxRel™ Plus	SAC305	0	0	0	0	0	0	4.5	9



**Figure 7.** Weibull curves of thermal cycling test results

Various solder joints were analysed through cross-sections after 4000 cycles. This analysis confirmed the electrical failures and depict the solder joint performance after such extensive thermal cycling test. Images representing typical failure modes of these solder joints are shown in Figure 8. The low-Ag spheres showed extensive cracks (Figure 8 a-c), which sometimes run across between PCB and component, whereas SAC305 showed less extensive cracks (Figure 8 d). Unlike these alloys, the combination of high-Ag and additives of Innolot (Figure 8 e) and Maxrel Plus (Figure f-g) resulted in only minor cracks after 4000 thermal cycles.



**Figure 8.** Cross-sections after 4,000 thermal cycles. a) SAC105, b) SAC125N, c) SACX Plus 0307, d) SAC305, e) Innolot, f) Maxrel Plus (SAC305 paste), and g) Maxrel Plus (Maxrel Plus paste)

The effect of high temperature storage on intermetallics thickness was evaluated on both component and PCB sides. Table 3 shows the intermetallics thickness on the component-solder interface, i.e., solder on Ni-Au finish, whereas Table 4 shows the intermetallics thickness on solder-PCB interface, i.e., solder on OSP finish. Figure 9 show the initial intermetallics and microstructure appearance on both interfaces.

Initial intermetallics thickness on the component-solder interface is between 2.25 and 2.48 μm, except for Innolot,

which was 1.65  $\mu\text{m}$ . After 1000 hrs, SAC305 and Innolot showed thinner thickness, around 2.80  $\mu\text{m}$ . The intermetallics of the other alloys was between 3.43 and 4.08  $\mu\text{m}$ . SAC305 showed the lowest growth in intermetallics thickness due to high temperature storage (21%), whereas Innolot had the highest growth (73%).

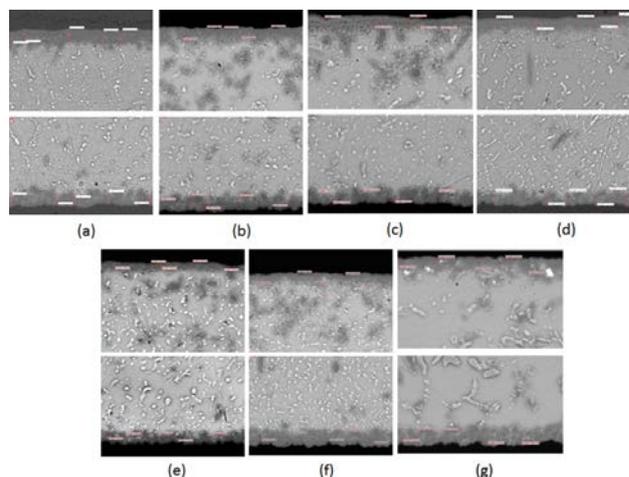
On the solder-PCB interface, Innolot initial intermetallics thickness was also the thinnest (1.61  $\mu\text{m}$ ), followed by SACX Plus 0307 (1.77  $\mu\text{m}$ ). Other alloys were between 2.19 and 2.59  $\mu\text{m}$ . Innolot, Maxrel Plus-SAC305, and SACX Plus 0307 intermetallics thickness more than double after 1000 hrs, whereas SAC305, SAC125N and Maxrel Plus-Maxrel Plus showed lower growth (45-65%).

**Table 3.** Intermetallics thickness after high temperature storage (in hours) measured on component-solder interface

Alloy	0	100	250	500	1000
SACX Plus 0307	2.29	2.28	2.48	2.79	3.46
SAC105	2.48	2.71	3.14	3.38	4.08
SAC125N	2.37	2.28	2.58	2.94	3.50
SAC305	2.31	2.56	2.56	2.63	2.80
Innolot	1.65	2.04	2.16	2.32	2.85
Maxrel Plus (SAC305)	2.25	2.35	3.07	3.47	3.75
Maxrel Plus (MP)	2.28	2.35	2.54	2.86	3.43

**Table 4.** Intermetallics thickness after high temperature storage (in hours) measured on solder-PCB interface

Alloy	0	100	250	500	1000
SACX Plus 0307	1.77	2.05	2.91	3.38	3.99
SAC105	2.19	2.21	2.83	3.28	4.04
SAC125N	2.30	2.18	2.75	3.09	3.40
SAC305	2.48	2.57	2.84	3.26	3.59
Innolot	1.61	2.10	2.60	2.72	3.49
Maxrel Plus (SAC305)	2.17	2.45	3.65	4.07	4.93
Maxrel Plus (MP)	2.59	2.47	3.09	3.59	4.28



**Figure 9.** Intermetallics and microstructure for: a) SAC105, b) SAC125N, c) SACX Plus 0307, d) SAC305, e) Innolot, f) Maxrel Plus (SAC305 paste), and g) Maxrel Plus (Maxrel™ Plus paste). PCB at the bottom.

## CONCLUSIONS

We have shown here a little broader perspective over the usual belief that higher drop shock performance is achieved using lower-Ag SAC alloys, whereas high thermal cycling results from higher-Ag content. By performing a very comprehensive study of six alloys with various degrees of Ag content and additives, we were able to draw the following conclusions:

Given these results, we conclude that: i) Bi, Sb and other alloying additions can significantly increase single ball shear strength, ii) SACX Plus 0307 and Maxrel Plus presented the highest drop shock performance, which is attributed to additives that control atomic diffusion at the substrate interface and in the bulk solder, iii) Increasing Ag in the solder alloy (e.g., SAC305) improves thermal cycling, but its performance can be further improved by combining higher-Ag content and performance additives as shown for Innolot and Maxrel Plus alloys.

In order to obtain maximum performance and cost benefit, solder alloys need to be paired to the correct application. Among the low-Ag alloys, SACX Plus 0307 provides the best drop shock and thermal cycling performance. SAC305 provides good drop shock and thermal cycling properties. For applications that require higher thermal reliability performance, including shear strength and thermal cycling, Innolot and Maxrel Plus are recommended. In addition to that, Maxrel Plus also delivers excellent drop shock (and vibration) performance, and is particularly recommended for applications such as automotive under the hood, high efficiency LEDs and semiconductor packaging.

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