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# Pb-FREE ALLOY ALTERNATIVES: RELIABILITY INVESTIGATION

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## ABSTRACT

The paper compares different solder compositions and micro alloyed SAC solders in terms of assembly and mechanical / thermal fatigue properties. Solder materials under test were: SAC405, SAC305, SAC2704, SnAg(1.2-2.7)Cu(0.2-0.5), SAC105, SAC105Ni, SCNGe, SAC1302Ni0.05, SAC1305Ni0.05x

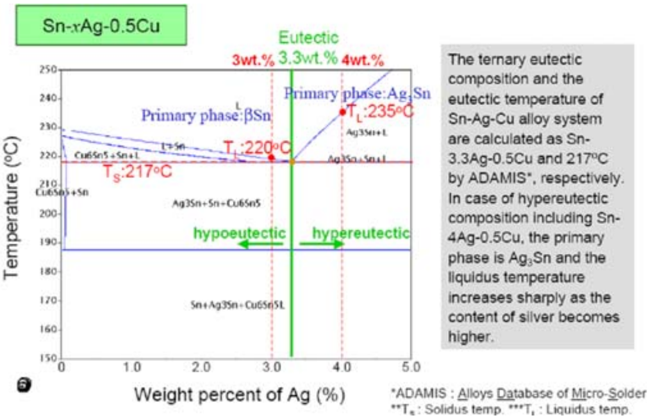
Assembly and reliability data of high Ag content alloys and low Ag content alloys will be presented and discussed in relation to the acceptance criteria for different applications. The acceptability of any alloy may vary from products and is dependent on the basic alloy data especially the long time behavior under test and / or field conditions. The influence of the assembly parameter will be discussed after visual inspection, X-ray and microsectioning at the initial state.

The test conditions used in the test procedure were temperature cycling with different parameters in terms of deltaT and hold and ramping times: 0/+80°C -20°C/+90°C (30'/10''/30'), -40°C/+125°C (30'/10''/30'), -40°C/+150°C (30'/10''/30'), 0°C/+80°C (30'/10''/30'),-40°C/+125°C (20′/10′′/15′/10′′), -40°C/+125°C (10'/20'/10'/20'), -40°C/+150°C (10'/20'/10'/20'), field simulation 0°C/+80°C (0'/60'/0'/360‘). Data are available for more than 2000 cycles.

A ranking list for reliable alloys will be presented for critical discussion and further requirements. Fatigue properties analyzed were shear and pull data, recrystallization, crack initiation and growth, electrical continuity. Based on the fatigue behavior the damage mechanism for different solders was analyzed and compared to characterize the possibility of the definition of the acceleration factor between alloys and / or TCT conditions. Acceptance criteria for lead-free solders will be discussed in relation to the modification of alloys and test conditions. A critical review is formulated for possibilities to transform test to field conditions and further demands to generate lifetime results.

## INTRODUCTION

Demands for more "ductility" of SAC and mechanical performance under field conditions led to the development of modified SAC compositions especially low Ag alloys to improve the mechanical behavior of solder joints (Figure 1).



The ternary eutectic composition and the eutectic temperature of Sn-Ag-Cu alloy system are calculated as Sn-3.3Ag-0.5Cu and 217°C by ADAMIS*, respectively. In case of hypereutectic composition including Sn-4Ag-0.5Cu, the primary phase is $Ag_3Sn$ and the liquidus temperature increases sharply as the content of silver becomes higher.

*ADAMIS : Alloys Database of Micro-Solder
**$T_s$ : Solidus temp. ***$T_l$ : Liquidus temp.

**Figure 1: Hypo- and hypereutectic SAC alloys, Hitachi June 2003**

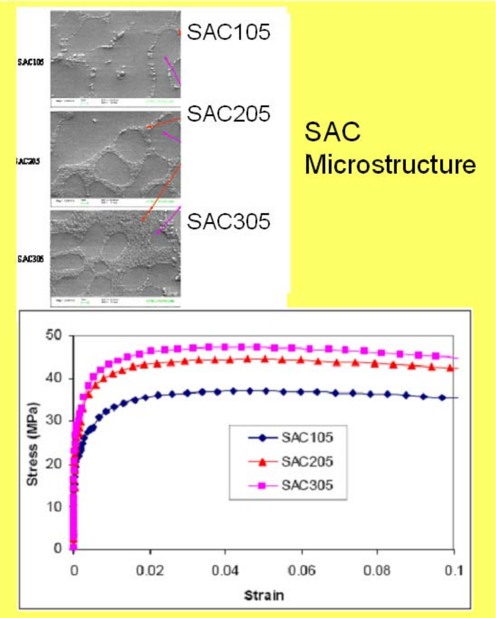
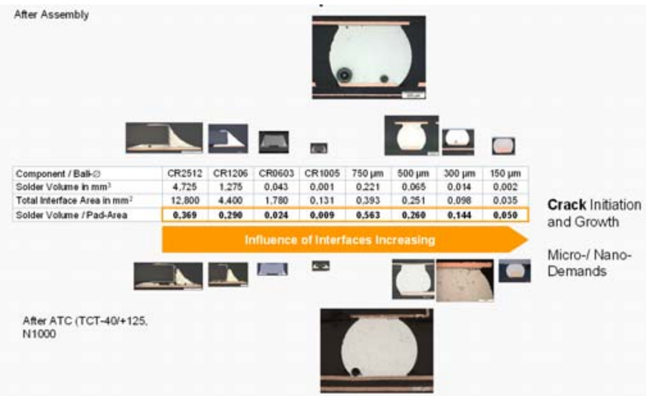


**Figure 2: Microstruture and mechanical properties of different SAC compositions /6, 16/**

The stress-strain characteristic of SAC solders with different Ag contents between 1 wt.-% and 3 wt.-% is listed in Figure 2. Many processability and reliability data are available for compositions like SAC305 and SAC405, but to understand metallurgical driven mechanisms describing the differences in terms of reliability needs more investigations.

Solder paste qualifications based on modified compositions are already introduced. To understand pro / cons compared to near-eutectic alloys lot of board level investigations were started to understand metallurgical driven differences in terms of fatigue properties.

Further activities were initiated to study the dissolution behavior of commonly used finishes at component and PCB side, the influence related to the SAC microstructure and the description of interfaces. Consequences from the dissolution behavior are linked to the miniaturization of components and therefore on metallurgical gradients at interfaces (see Figure 3). Independent from the size and complexity of packages it is to guarantee that the reliability of all interconnects is uniform for the whole product.



| Component / Ball-∅ | CR2512 | CR1206 | CR0603 | CR1005 | 750 µm | 500 µm | 300 µm | 150 µm |
|---|---|---|---|---|---|---|---|---|
| Solder Volume in mm³ | 4,725 | 1,275 | 0,043 | 0,001 | 0,221 | 0,065 | 0,014 | 0,002 |
| Total Interface Area in mm² | 12,800 | 4,400 | 1,780 | 0,131 | 0,393 | 0,251 | 0,098 | 0,035 |
| Solder Volume / Pad-Area | **0,369** | **0,290** | **0,024** | **0,009** | **0,563** | **0,260** | **0,144** | **0,050** |

**Figure 3: Microsections of different solder interconnects of passive and Area Array devices (solder volume vs interface area) after assembly and ACT**

To answer the question of the damage characteristics in the solder volume and in interfaces the destructive evaluation is performed to collect irreversible damage properties, like cracks. Whether the damage behavior is influenced by the original SAC constitution w/o minor impurities (micro alloying or dissolved elements) will be analyzed. The ratio of solder volume and interface area (Figure 4) must be considered not only for metallurgical reasons. Figure 4 gives some relations for miniaturized packages / interconnects, coming from a conventional BGA through to interconnect of the next generation of microsystems. The red market dots in the BGA, LFBGA, FlipChip ball solder joints are the solder volume of the expected bump diameters for highly miniaturized packages. Totally the interface performance has an increasing influence. iNEMI is also addressing the number of interfacial driven questions in terms of the miniaturization, responsible for the board level reliability /1/. The increasing package complexity will be a driver for advanced materials.

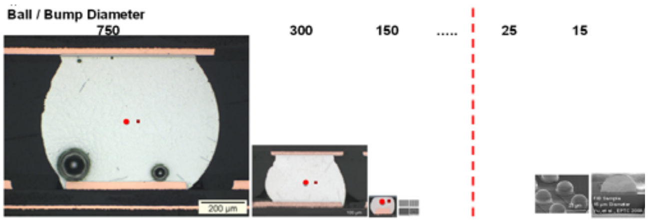
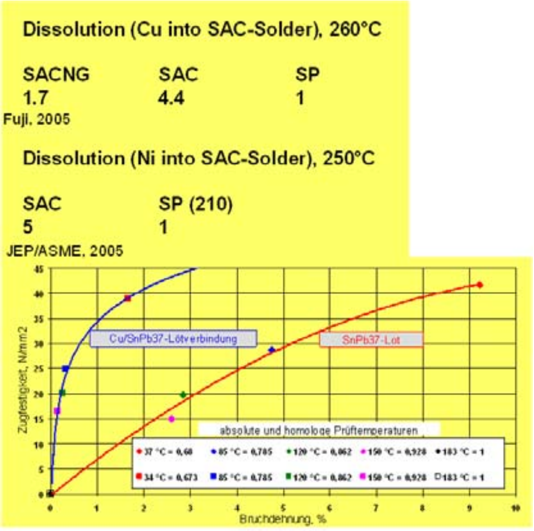


**Figure 4: Left: BGA/FlipChip interconnects; Middle: micro-bumps 25 µm /2/ Right side 15 µm bumps /3/**

Results describing the ratio between solder balls and intermetallics formed at the interface were published /4, 5/. The primary formation of intermetallics in the reflowed solder joints is influenced by the composition of SAC (w/o microalloying elements) and will be further influenced by the dissolved quantity of finishes from the package and PCB terminations. In Figure 5 and /4/ any results are collected for extended temperatures to compare different solder materials in relative manner. It can be expected that micro alloying will influence significantly the microstructure and therefore the fatigue behavior under accelerated test conditions.


Dissolution (Cu into SAC-Solder), 260°C

| SACNG | SAC | SP |
|---|---|---|
| 1.7 | 4.4 | 1 |

Fuji, 2005

Dissolution (Ni into SAC-Solder), 250°C

| SAC | SP (210) |
|---|---|
| 5 | 1 |

JEP/ASME, 2005

Souce: K. Wittke u. a.: Long term behavior of Solder- and Glue-Interconnects
IZM Berlin, 1999

**Figure 5: Dissolution data of Cu and Ni into SAC solders (SAC SnAgCu; SP SnPb) and the expected metallurgical modification in terms of reflow processes**

## EXPERIMENTAL

In addition to testboard based SAC3807 reliability investigations, the number of lead-free alloys varies further in terms of the Ag and Cu content, mainly driven by fracture and fatigue properties for different applications and cost factors. Further investigations are needed to improve SAC alloys in order to overcome critical concerns. The alloys tested in this study were: SAC105, SAC2704, SAC305(9), SAC405(9), SnAg(1.2-2.7)Cu(0.2-0.5), SAC105Ni, SCNGe, SAC1302Ni0.05, SAC1305Ni0.05x, SnAgCuBiSbNi (InnoLot). Sn-3.0Ag-0.5Cu (SAC305) and Sn-4.0Ag- 0.5Cu (SCA405) are most popular choices for the application demanding long-term reliability (fatigue life) and Sn-1.0Ag- 0.5Cu (SAC105) alloy becomes one of the choice for mobile application where drop performance is of primary importance.

Based on experimental analysis of different lead-free solder materials for conventional and advanced components the quality of Pb-free interconnections, specially the interface characteristic will be discussed followed by reliability results. The ternary eutectic is close to SnAg3.8Cu0.7 with a melting temperature of 217°C. The near eutectic, commercially available alloys are SnAg3.8Cu0.7 and SnAg4.0Cu0.5 compositions, furthermore SnAg3.0Cu0.5 as a under-eutectic material (Figure 1). By further modifications of the basic SAC composition and the addition of one or more elements into the SAC the microstructure and the performance should be optimized.

Elements for microalloying in pretests were: Bi, Zn, Nd, La, Co, Ni, Fe, Mn, Ti, P, Ge. Expected are influencies related to the crystallization, re-crystallization, IMC formation, more element IMC, dendrite growth, cohesive properties, strain / stress behavior, creep resistance.
Additions of Co, Fe, Ni will decrease the dissolution quantity of Cu into SAC. Co, Ni, Pt, Sb, Zn will reduce the intermetallic formation /7, 8, 9, 10, 15/.

In relation to the miniaturization of solder interconnects negative impacts of lower joint height (Figure 3 and 4) on solder joint reliability may create opportunities for new interconnect technologies and materials. New materials mean SAC optimization with a decreased impact to the intermetallic formation. The ratio between reflowed solder and IMC (volume fraction) will influence the thermo-mechanical and mechanical fatigue properties /5/.
The level of the microalloying addition is typically 0.1% or lower (except InnoLot). Thus, in parallel with the evolution of SAC alloys to lower levels of Ag /14/, the impact of microalloying additions to the properties of SnAgCu eutectic has been explored for TCT- /11, 12, 13, 18/, Drop- /17, 18/ and electro-migration (EM) properties /15/.

One area of particular interest to OEMs is solder joint reliability under temperature cycling. A substantial body of knowledge exists regarding the performance of the eutectic SnPb alloy in this area, including analyses of the impact of various different pad surface finishes (e.g., NiAu, imm. Sn, OSP, etc.) upon joint integrity. Similarly, due to the popularity of the SAC alloys as Pb-free alternatives, much data have been generated to characterize their performance under similar test conditions. However, it has been found by several investigations that the SAC alloys exhibit increased sensitivity to high strain rate failure (i.e., drop test), as well as the propensity, under certain temperature and time conditions, to develop Kirkendall void-induced joint failures /5, 19/.

In the tests done the following parameters were taken into account:

- Conventional, lead-free finished components (passives 01005 to 2512, QFP, TSOP, QFN, BGA)
- Testboards
- Solders listed above
- Different reflow profiles in terms of peak temperature and time above liquidus

Accelerated cycle test conditions are
- HHT
- HTS
- TCT -20°C/+90°C (30'/10"/30'), -40°C/+125°C (30'/10"/30'), -40°C/+150°C (30'/10"/30'), 0°C/+80°C (30'/10"/30'),-40°C/+125°C (20´/10´´/15´/10´´), -40°C/+125°C (10'/20'/10'/20'), -40°C/+150°C (10'/20'/10'/20'), field simulation 0°C/+80°C (0'/60'/0'/360‘)
- Combined ACT tests (HTS + shock, TCT + vibration)

In addition to the above, the following characterization activities took place at various stages of the assembly and testing:
- Thermal Moire interferometry (BGA, testboard)
- X-ray analysis of soldered assemblies (void identification)
- Dye-and-pry testing of mounted and cycled components (first damage information before microsectioning)
- Cross-sectional analyses of representative solder joints at the initial state and after defined readouts
- SEM analysis of solder joint interfaces
- EBSD analysis (re-crystallisation behavior)

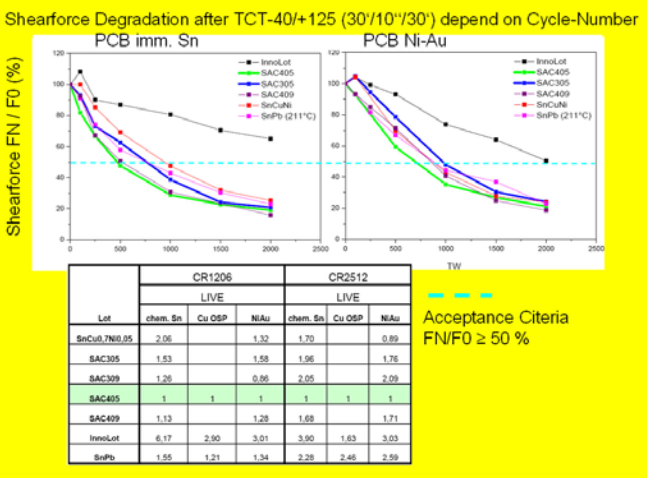
The main question was, how should SAC solder joints be tested during the qualification phase so that they will meet the desired reliability expectation in the field? Compared to Sn-Pb solder joints, the understanding of the fatigue of SnAgCu solder joints is far from complete.

To analyze and predict solder joint reliability in the field, various standards for accelerated temperature cycling (ATC) tests (SnPb) have been proposed and implemented, with the question: Can the commonly used procedure apply for SnAgCu as well? /20 /. Currently, however, there are very few experimentally validated material parameters for SnAgCu alloys. Such ATC orientations on temperature test ranges and suggested cycle numbers for SAC solder joints to pass are under evaluation. Damage-equivalent TCT conditions (SnPb vs SAC) are required, to minimize the risk later on the product level. For all accelerated analyses it is necessary to know the mission profile, consisting of the min. / max. tempera-ture ranges during the operation of the component in a system, and the required cycles in the field.

Furthermore existing (SnPb) or laed-free based acceptance criteria must be agreed for the qualification phase. Acceptance criteria are R(D), F(shear, pull), crack length, functional test described as follows:

RN > 1,5 R0
F(shear, pull)N ≥ 50 % F(shear, pull)0
Crack < 50 % of wetted length
Microstructure (re-crystallization)

Mostly the mission profiles are different from the ACT test applied, therefore we have to work for transformation solutions between the test and the field. This is accomplished by first determining the amount of solder damage that is expected to accumulate in the field over a specified period of time from temperature and power cycles (on/off cycles under defined operating conditions), and then designing TCT tests to generate the equivalent kind and amount of damage. In the evaluation phase we need products from the field, to compare that directly, but long-time SAC products from the field are not available yet. For the TCT-40/125°C the shear force degradation behavior of passive components is summarized in Figure 6. To discuss the ability to fit the acceptance criteria, the crack growth after all accelerated tests was measured after microsectioning. Data directly linked to the shear force are collected in Figure 7, depending on the solder material. The primary interest is focused to the understanding of the different damage mechanisms of solders applied in the test. In relation to the shear force, the acceptance criterion is marked to compare directly the solder composition dependent properties. The alloy SnAgCuSbBiNi fits completely such kind of criteria. But what solder composition is the preferred one: The alloy with the highest strength or the solder with the highest ductility? That must be answered after the evaluation of the level of the ΔT in test and the ramping parameters in the test.


Shearforce Degradation after TCT-40/+125 (30'/10''/30') depend on Cycle-Number

PCB imm. Sn

PCB Ni-Au

| Lot | CR1206 |  |  | CR2512 |  |  |
|---|---|---|---|---|---|---|
|  | LIVE |  |  | LIVE |  |  |
|  | chem. Sn | Cu OSP | NiAu | chem. Sn | Cu OSP | NiAu |
| SnCu0,7Ni0,05 | 2,06 |  | 1,32 | 1,70 |  | 0,89 |
| SAC305 | 1,53 |  | 1,58 | 1,96 |  | 1,76 |
| SAC309 | 1,26 |  | 0,86 | 2,05 |  | 2,09 |
| SAC405 | 1 | 1 | 1 | 1 | 1 | 1 |
| SAC409 | 1,13 |  | 1,28 | 1,68 |  | 1,71 |
| InnoLot | 6,17 | 2,90 | 3,01 | 3,90 | 1,63 | 3,03 |
| SnPb | 1,55 | 1,21 | 1,34 | 2,28 | 2,46 | 2,59 |

Acceptance Citeria
FN/F0 ≥ 50 %

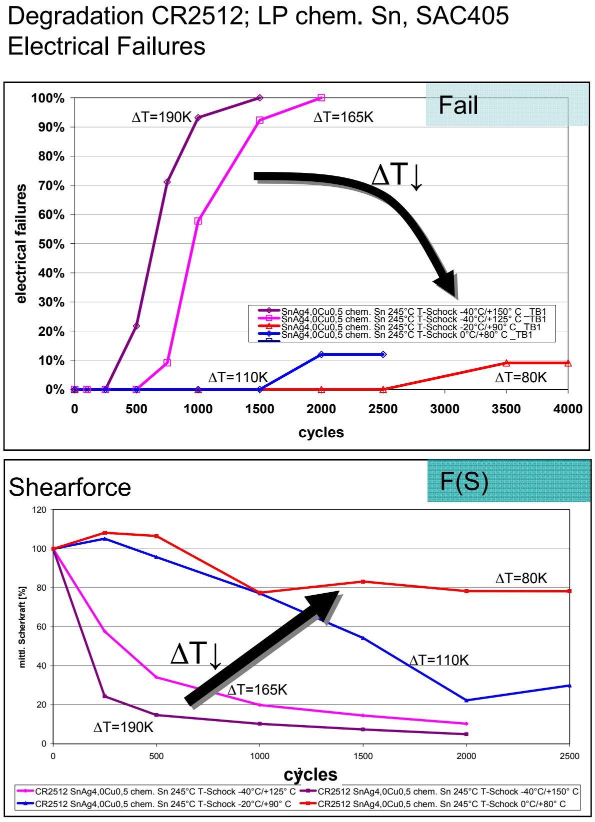
**Figure 6: Shear force degradation after accelerated test for CR 1206** /24/

Compared to Figure 6, the 6-element-alloy shows the lowest level of irreversible defects after ACT. The mechanism behind must be clarified. Figure 11 and 12 demonstrate the solder joint structure after the TCT and delivers first indicator for structure dependency. Further important questions come from the slow/fast ramping and the comparison (better simulation) to the field conditions.

| CR1206 | TS -40/125, imm. Sn. |  | TS -40/125, NiAu |  |
|---|---|---|---|---|
|  | Crack length after 1000 TW [%] | Crack length after 1000 TW [%] | Crack length after 1000 TW [%] | Crack length after 1000 TW [%] |
| SnPb | 29,00 | 60,00 | 19,00 | 59,00 |
| SAC305 |  |  |  |  |
| SAC405 | 65,00 | 78,00 | 58,00 | 75,00 |
| InnoLot | 26,00 | 44,00 | 32,00 | 46,00 |
|  |  |  |  |  |
| CR0201 | TS -40/125, imm. Sn. |  | TS -40/125, NiAu |  |
|  | Crack length after 1000 TW [%] | Crack length after 1000 TW [%] | Crack length after 1000 TW [%] | Crack length after 1000 TW [%] |
| SnPb | 5,00 | 19,00 | 11,00 | 35,00 |
| SAC305 |  |  |  |  |
| SAC405 | 27,00 | 48,00 | 8,00 | 18,00 |
| InnoLot | 6,00 | 18,00 | 9,00 | 18,00 |

**Figure 7: Crack length in CR0201 and 1206 interconnects after TCT (thermal shock) depending on solder composition**

The failure behavior depends on TCT conditions in terms of the electrical and mechanical criteria, as can be taken for SAC405 from Figure 8. Note, the highly accelerated tests with ΔT of 190K and 165K in comparison to ΔT of 110K and 80K, which are much closer to the field conditions


Degradation CR2512; LP chem. Sn, SAC405
Electrical Failures

Shearforce

**Figure 8: Comparison of different TCT related ΔT values for CR2512 / PCB imm. Sn in terms of acceleration** /24/

Based on the electrical, mechanical and microsectional tests for all the components and TCT conditions, evaluations were initiated to rank the different solder alloys based on the damage quantity (Figure 11 and 12 for comparison only). Interconnect related ranking results are listed in Figure 9, only focused on the shear data, but here for two different finishes on the PCB side. Lowering the Ag content supports the fatigue resistance. The SAC405 has the advantage that a eutectic alloy offers, in particular a lower incidence of shrinkage cavities.

Whether the "impurities" from the pad finish, as dissolved elements, influences the fatigue mode must be analyzed. The dependencies of the board level reliability data were also observed in /21, 22/. SnAgCu solder alloys undergo significant aging (microstructure evolution) which manifests itself as a change in material behavior /Figure 11, 12/. This issue is very relevant to the problem of life prediction of a solder joint subjected to thermo-mechanical fatigue.

Microstructure evolution depends on the composition, microalloying elements and the strain/stress conditions applied. In relation to the test conditions (ΔT), the evolution of the microstructure must be compared for different strain levels (re-crystallization).

Fine intermetallic compounds particles can also significantly reduce sliding of the grain boundaries. Such additions, such as Ni, have been shown to improve the high strain-rate performance of SAC alloys.

| Shear Force Degradation after TCT TS-40/+125 (30'/10"/30'), N1000 PCB-Finish imm. Sn Ratio FN / F0 | Shear Force Degradation after TCT TS-40/+125 (30'/10"/30'), N1000 PCB-Finish Ni-Au Ratio FN / F0 |
|---|---|
| InnoLot<br>SnPb<br>SnCuNi<br>SAC305<br>SAC309<br>SAC405<br>SAC409 | InnoLot<br>SAC305<br>SAC309<br>SAC405<br>SAC409<br>SnCuNi<br>SnPb |

**Figure 9: Shear force degradation / Ranking of different solder compositions** /24/

Not only the TCT behavior was tested, but also the creep properties for bulk materials as well as for the solder materials after reflow processes, the performance in the drop test and the behavior after combined tests.

Because TCT evaluations are driven by high reliability requirements in the field, testing has focused on the high Ag content alloys, such as SAC405(9), SAC305(9), SnAgCuBiSbNi (InnoLot), middle Ag content SAC2704 and low Ag content SAC105Ni, SAC1302Ni0.05, SAC1305Ni0.05x,

Only a few thermal fatigue data exist for lower Ag alloys, such as SAC105, what makes it complicated to compare. This poses a potential problem because the lower Ag alloys are being implemented in long life, high reliability requirements.

Due to resource limitations, the costs, and time required, only a few thermal fatigue studies have been performed on low Ag alloys.

Further, there is no consensus on selection of test parameters, including dwell and ramp times, temperature extremes, and test duration. These factors hinder relevant comparisons, and as a result published data contains contradictions and are not always complete.

| **Strength**<br>**Strain**<br>**Ø Rm , ε** | **Creep Resistance**<br>**T ≤ 150°C**<br>**KW / Creeprate** | **Creep Resistance**<br>**KW / Creeprate** |
|---|---|---|
| **InnoLot**<br>**SnAg2.7Cu0.4Ni0.05**<br>SnAg2.7Cu0.4Ni0.05P0.001<br>SnAg1.3Cu0.5Ni0.05P0.004 | **InnoLot**<br>SAC305<br>SAC2704 | FHA<br>**SnAg2,7Cu0,4Ni0,05**<br>SnAg2,7Cu0,4Ni0,05P0,001<br>SnAg2,7Cu0,4Ni0,05P0,004<br>IZM<br>SnAg1,3Cu0,5Ni0,05P0,001<br>SnAg1,3Cu0,2Ni0,05<br>SnAg1,3Cu0,5Ni0,05P0,004<br>SnAg2,7Cu0,4Ni0,05P0,001 |
| **Nanohardness GF**<br>**NH**<br>**Initial TCT-40/+125**<br>**NH / Gpa** | **Drop**<br>**N without IF-Defect** | **Creep Strain MLV**<br>TUD<br>**1 / sec** |
| InnoLot SAC305<br>SAC405 SAC405<br>SAC309 SAC309<br>SAC305 InnoLot | **SnAg2,7Cu0,4Ni0,05P0,001**<br>SnAg1,3Cu0,2P0,001<br>SnAg1,3Cu0,5Ni0,05P0,001 | **InnoLot**<br>SAC3575<br>SAC407<br>SAC2705<br>SAC1305 |

IF-Interface

**Figure 10: SAC alloy ranking after additional tests** /24/

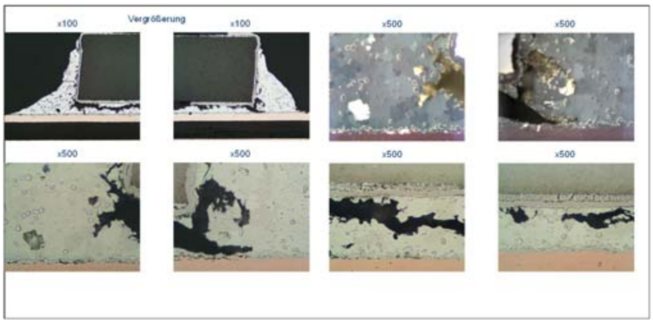


**Figure 11: SnAg3,8Cu0,7, CR 1206, Finish NiSn, N = 2000 cycles TCT –40°C/+125°C (30'/10''/30'), PCB HTG, imm. Sn; microsection and polarized illumination**

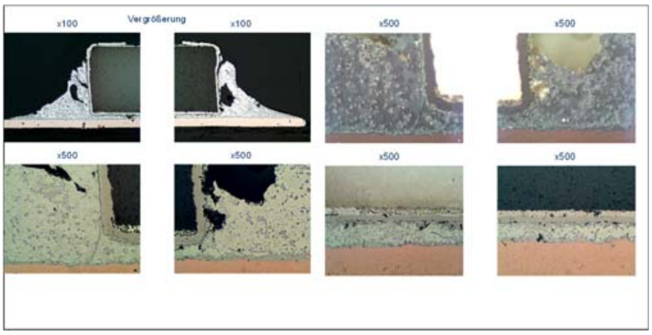


**Figure 12: SnAg3,3Cu0,3Bi2Sb1Ni0,2, CR 1206, Finish NiSn, N = 2000 cycles TCT –40°C/+125° (30'/10''/30'), PCB HTG, imm. Sn, microsection and polarized illumination**

Temperature cycling test conditions should be consistent with the IPC 9701 specification. The different test parameters (Figre 6-8) were taken into account to study the performance of lead-free interconnects. Mostly the TCT conditions were linked to compare results with SnPb based experiences and to guarantee the equivalence by choosing lead free solders.

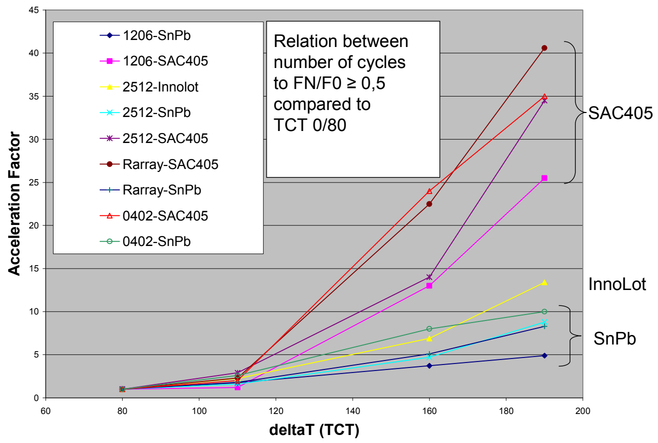


**Figure 13: Experimental based AF values (relation between number of cycles FN/F0 ≥ 0,5 compared to TCT 0/80) between different solders** /24/

Results in Figure 13 show the influence of expected different damage mechanisms between SnPb and SAC. About the microstructure change in SAC solders was reported in /24/, we found that the creep strain and the creep strain energy density can be accepted as an indicator for failure free cycles or solder crack initiation /24/ (Figure 15). Therefore three different methods were applied to evaluate the experimental data in relation the expected field behavior.

Systematically influences from different peak temperatures in the reflow process were not observed, only low level of differences after electrical measurements and shearforce testing (Figure 14).

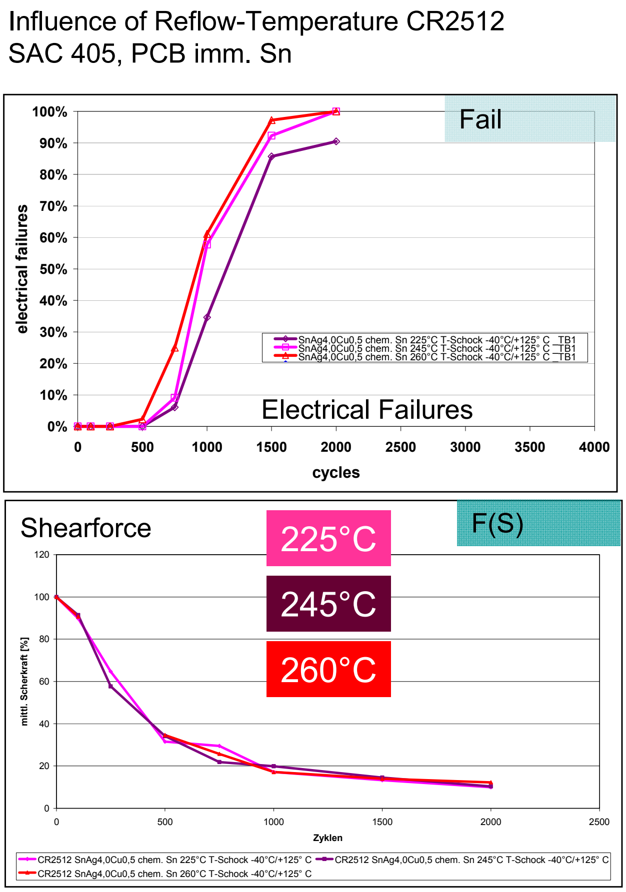


**Figure 14: Comparison of different peak temperatures, CR2512 / PCB imm. Sn in terms of electrical and mechanical degradation** /24/

Whether the cooling rate influences reliability data, as observed in /23/, was not analyzed but expected. The microstructure of a SAC solder varies with the cooling rate because of the relationship between degree of undercooling and the distributions of $Ag_3Sn$ and $Cu_6Sn_5$ intermetallics on the dendritic boundaries /25/. Furthermore the initial solder microstructure and the coarsening of precipitates during ACT depend strongly on the solder joint size (e.g. CR0201 up to CR2512, Figure 13, 16) /25/, complicating comparisons of different experiments.

ACT based on TCT 0°C/+80°C (30'/10"/30') and a field simulation 0°C/+80°C (0'/60'/0'/360‘) were performed to study the influence of hold and ramp times. Up to 2000 cycles no differences were detected.

The need for predicting fatigue life in solder joints is well appreciated at the present time. Currently, however, there are very few experimentally validated material parameters for SnAgCu alloys. Figure 15 and 16 include data from extended reliability investigation for passive devices first.

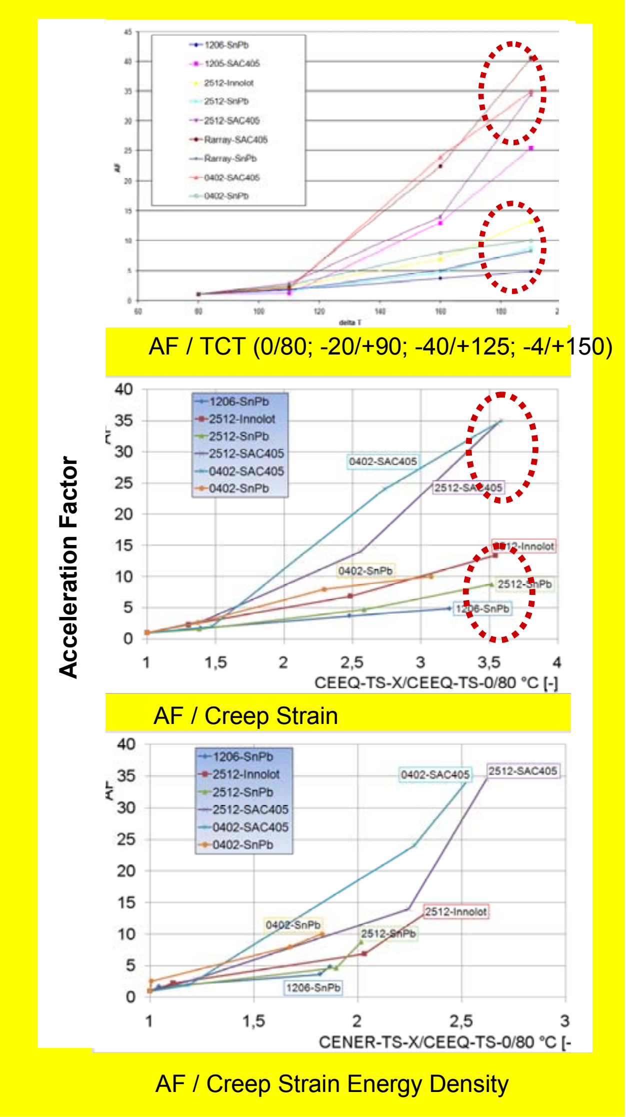


**Figure 15: Comparison between experimental and calculation based acceleration factors** /24/

In addition to the evaluation in Figure 15 the shear force data were be used to compare influences related to the solder composition and the ΔT-driven damage data (degradation of shear force, crack growth) with the goal to identify any dependencies from the solder materials applied in the reliability trials (Figure 16). In general, most of published temperature cycling results showed that SAC solder is better in fatigue resistance than SnPb. Here we detected a clear relation to the size of the components, mainly passive components with resulting differences in the DNP, responsible for the strain level. Note as well the influence of finishes on the PCB side (Figure 9). The goal of such experiments is to gage the field life and identify failure mechanisms of solder joints by subjecting it to temperature cycling conditions that are harsher (larger temperatures and/or more rapid transitions) than expected in the real application. The knowledge about the influences is not complete, therefore tests have to be continued to collect the physics of failure.

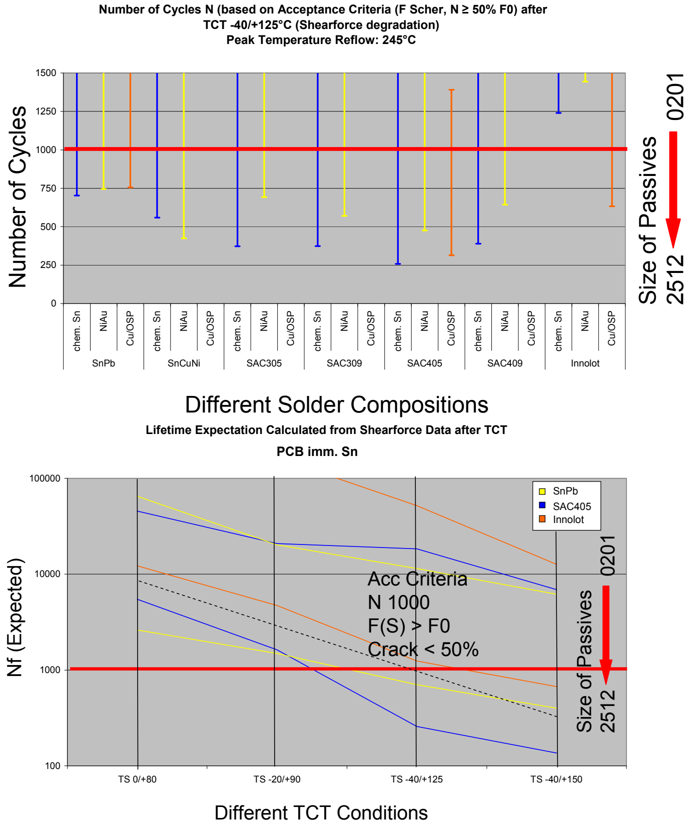


**Figure 16: Number of cycles without results outside the acceptance criteria (above) and expected lifetime of SAC solder joints compared to SP**

Some other experimental results showed the fatigue life of SAC is lower that SnPb solder. Long dwell time impact of SAC alloy has been raised as a concern and appropriate dwell time for SAC temperature cycling testing is a major controversy for product qualification (e.g. TCT 0 / 80). Needed is a industry-accepted SAC solder fatigue model, typical of field conditions.

## DISCUSSION OF THE RESULTS

A series of TCT studies have been conducted to investigate the effect of SAC composition on the formation of lead free interconnects and the board level reliability by modifying the deltaT and the hold and ramp times in TCT.

The following conclusions are drawn from this work:.

- Different TCT parameters were applied to study the influence of the max/min temperatures and hold / ramp times.
- The effects of dwell time must be included in the development of SAC solder fatigue models to enable accurate determination of test acceleration factors and field predictions.
- This time limit is determined by the strain level imposed on the critical solder joint.
- Ranking of solder materials is done based on the complexity of destructive and non-destructive evaluations.
- The chosen selection of SAC alloys has allowed us to identify the effects of Ag content on fatigue behavior (SAC with 1; 1,2; 1,3; 2,7; 3; 3,3 and 4 wt.-% Ag;

- The test results demonstrate that Ag content has a influence on thermal fatigue life. The best fatigue performance is recorded with higher Ag content SAC405 and SAC305 alloys. But the most performing alloy is InnoLot, followed by SAC405 and 305 without relevant differences.
- In terms of the alloy modification the following summaries were collected:
  - High Ag-content increases the creep strength
  - High Ag-content increases the sensitivity of SAC for increased ambient conditions
  - High Ag-content increases the sensitivity of SAC against thermo-cyclic stresses
  - Cu-content between 0.5 and 1,2 wt.-% without any significant influences related to the creep behavior
  - Ni-additions are strongly influencing the microstructure and the formation of intermetallics
  - Ni as micro alloying element does not influence the creep performance significantly
  - Thermal-cyclic loading is resulting in high stress energy and resulting dynamic re-crystallization with grain coarsening, during isothermal loadings the IMC growth is dominant
- In drop testing, SAC405 showed a greater susceptibility to brittle fracture than SACN(P) solder alloy, coincident with the results of the high-speed solder ball shear and pull tests.
- SAC105 has slower IMC growth compared with SAC405 and SAC305.
- Both IMC thickness and morphology will affect the interface strength. The thicker the IMC layer is, the higher the risk for brittle fracture.
- Different reflow peak temperatures does not affect the fatigue behavior significantly
- The size effect followed by the solder joint microstructure varies dramatically with joint size, because of both IMC formation at pad sides and the volume dependent degree of undercooling. The IMC thickness, adhesion and cohesion properties, morphology and composition may affect the thermo-mechanical and mechanical reliability.
- Fast ramping in TCT generates more defects than slow ramping. That was observed for all SMD components. To be closer to the ambient/operating condition in the field requires more studies based on the mission profile.
- For the board level reliability the ranking of solder materials is SnAgCuSbBiNi > SACNiGe > SAC305 > SAC405 > SnCuNi. The result is also dependent on finishes on component and laminate side.
- The original solder composition is modified after x-times of reflow, with the consequence that the process window of acceptable “impurities” must be analyzed.

## CONCLUSIONS

The goal of this study was to determine the influence of different TCT conditions (ΔT and ramp / hold times) related to the board level reliability of SAC solder with different constitutions in terms of Ag content and micro alloying elements, compared to SnPb solder. Thermal fatigue reliability appears to be dependent on processing, microstructure, and microalloy content, and those dependencies have yet to be characterized completely and understood.

Modifying the ramp and hold times during TCT offers non-uniform damage results. Fast ramping generates more defects in solder joints. The acceptability of different alloys can be taken from the degradation of electrical, mechanical and interface data (all in strict relation to the microstructure) like shear and pull forces as well as crack lengths based on commonly applied acceptance criteria as listed above.

The selection of the reliable lead-free solder will be influenced by the finishes on component and laminate side. Formed intermetallics are more-element IMC with different mechanical properties. Studies are required to generate more data for the complete evaluation of solder joint reliability results.

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