Development of a High Performance Lead-Free Wave Solder Alloy

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Abstract

Lead Free Wave soldering has developed with two main alloy systems. The Sn/Ag/Cu range of solders having typically 3 – 4 % Ag content and the Sn/Cu eutectic based systems. Both of these systems have inherent drawbacks when comparing the value equation from a user perspective. The Sn/Ag/Cu range having 3 –4 % Ag offers good reliability and good process yield but with inherent high cost of the raw materials. As an alternative the Sn/Cu Eutectic and the modifications of this base system (Sn/Cu/Ni) has lower material costs but drawbacks in terms of process yield, and joint reliability. A new alloy SACX0307 has been developed that has been designed to mitigate the drawbacks of the currently available systems mentioned above.

This study reviews the testing of four alloy systems SAC305, Sn99.3/Cu0.7, Modified Sn99.3/Cu0.7 (Sn/Cu/Ni) and SACX0307, to evaluate the four key characteristics of Lead-Free soldering Process Yield, Copper leaching rate, dross formation and Thermal/Mechanical reliability. The wave soldering experiment used a test board that had been designed to be difficult, and thus discriminate between the process conditions, three fluxes including water and alcohol based formulation and two board finishes, Copper OSP and Immersion Silver.

The tests indicate that SACX0307 bridge the gap between SAC305 alloy and the Sn/Cu Eutectic based alloy systems. Offering better performance on the 4 key characteristics than the Sn99.3/Cu0.7 and (Sn/Cu/Ni) Sn99.3/Cu0.7but at a lower raw material cost than SAC305.

Introduction

The transition to lead free soldering is rapidly becoming a reality for electronics assemblers in many sectors. Most assemblers find themselves beyond the initial investigation stages of alloy family selection, equipment and design requirements etc, and are now facing the economic reality of this step change on their own businesses. The change in alloy will have economic impact on daily business in terms of material costs and process yield at the same time that competitive pressures have increased markedly, especially in the consumer electronics sector. One of the greatest examples of this is the rapid deflation of high street prices of DVD players, a relatively new technology. Lower cost manufacturing centers and new brands have increased the price pressure on the established brands.

Wave soldering is a very key process to many sectors of the electronics industry, and the switch to lead free production has several cost implications, one of which is the cost and performance of the alloy. The use of a tin-copper system alone will more than double the users alloy cost, and have even greater impact through its poor process performance.

Currently available tin-silver-copper (SAC) range of alloys will take alloy costs to more than 3 times that of tin-lead, but will typically give a much higher process yield than the tin-copper family. For this reason alone many producers have opted for the more expensive alloy as process performance has a very tangible link to business success, and sometimes to viability.

The dilemma posed by this choice has prompted the development of an alloy system that has the ability to achieve high process yields without the restrictive costs of the typical SAC systems.

Selection of Alloys

The Lead-Free wave solder process is in the early stages of development, it is estimated that currently less than 5% of all wave solder baths are using Lead-Free alloys. The initial part of this project was to look and evaluate the current alloys. The evaluation was initially scoped based on the systematic selection of the key performance attributes of a wave solder alloy. The attributes were selected as below:

Table 1 - Performance Attributes of a Wave Solder alloy

Measurable	Customer issues
Yield	Bridges, skips, poor hole fill, fillet lifting, dross.
Machine maintenance	Bath monitoring and adjustment, replacement of damaged parts.
Mechanical reliabililty	In service failures.
Component and board compatibility	Maximum operating temperatures for boards and components.
Unit Cost	Customer spend $$
Total Cost	Unit cost solder, levels of waste, yield.

The focus of the Product Development team was then to look at the variables in the materials that would influence the key performance attributes.

Table 2 - Influential Material Variables

Measurable	Influential materials variables
Yield	Wetting speed, solidification crystal structure, surface tension.
Machine maintenance	Copper Erosion rate, stainless steel erosion rate.Dross rate.
Mechanical reliabililty	Pull tests, shear tests, thermal cycling.
Component and board compatibility	Operating temperatures.
Unit Cost	Raw materials
Total Cost	Raw material selection, dross rates and Yield.

A subjective evaluation was undertaken to rank the commonly available Wave Solder alloys.
The analysis conducted highlights the drawbacks of the two existing alloys:

Tin/Silver/Copper (SAC): Has been shown to offer the best yields in the wave solder process and is trusted by many users to provide good reliability. It currently the most popular selection for the wave solder process. This alloy system, due to the formulation containing 3-4% Silver, has a higher unit material cost.

Tin/Copper Eutectic based alloys: While offering a lower raw material cost than SAC alloys, the basic Tin-Copper and modifications of this alloy have been consistently shown to have inferior yield to the SAC alloys.

The formulation strategy followed the design rules of producing an alloy that when compared to the SAC alloys has a lower unit material cost, while delivering equivalent process yield, machine compatibility, component and board compatibility and reliability.

Evaluating a New Alloy

During the evaluation of the potential product formulations it is not possible to test all of the various formulations and even when this is possible only a limited number of test boards can be manufactured. For this reason the evaluation of the alloys is done in three stages, the first evaluation criteria are deemed to Process Performance Indicators. They are not direct measurements of the wave solder process or PCB functionality but measures of the alloys key characteristics that are known to impact these two areas. The second stage is the actual performance of the alloy formulation in a controlled wave solder process and is a measure of Process Yield. The third stage is the testing of the solder alloys for in service reliability using mechanical testing and accelerated aging by thermal cycling.

Process Performance Indicators

1. Solidus/Liquidus temperatures. Laminates and components are constrained by a maximum operating temperature above which they will be damaged; this data indicates the suitability of a particular alloy system within these constraints and also the "operating window".
2. Bulk alloy mechanical properties –
   - Hardness
   - Stress at maximum load
   - Elongation

   These combined will give an indication of the mechanical strength of the solder joint.
3. Wetting Speed – Wetting Balance Tests have been generally used to measure the solderability of components and as an aid to developing and testing fluxes. However if test variables are kept constant then this can be used as a relative measure of the alloy performance. A faster wetting speed will enable reduced solder contact time and hence faster throughput and potentially reduced copper dissolution.

4. Copper Dissolution rate – The rate at which copper is dissolved from the PCB into the wave solder bath is a significant issue for lead-free processes, particularly where CuOSP pad finish is used. Historically in the Sn/Pb process copper was dissolved up to a level of around 0.3 at which the solder bath reached an equilibrium point. For Lead-Free processes, the higher pot temperatures and higher tin contents accelerate copper dissolution. Increasing Copper levels increases the liquidus temperature so that the pot temperature would have to be increased in order to maintain the temperature delta above the liquidus (so as to maintain the process yield). This action would however increase the copper dissolution rates and so the process continues in a downward spiral. Therefore good process control of the Copper levels in the bath are essential in order to maintain yield.

Process Yield

All production professionals know that the cost of materials has little influence in comparison to their effect on process yield. A step change in process yield could have very dire consequences on the profitability of a production line, especially for the contract electronics manufacturer (CEM).

The number of soldering defects created in wave soldering is intrinsically linked to the flux, alloy, alloy purity, PCB/component finish, PCB layout, and atmosphere and process settings. In moving to lead-free wave soldering we are moving towards a reduced process window, and therefore the key task for process engineers is to widen the process window enough to achieve acceptable results (outputs), whilst minimizing the cost impact on the process (inputs).

As already discussed, some key characteristics of an alloy have very significant effects on wave soldering results. Slower wetting and lower fluidity can translate into an increase in unsoldered or partially wetted joints. An unsoldered joint may not be detected at In-Circuit Test (ICT) or at functional verification testing (FVT) as electrical contact between the termination and the PCB pad will be intermittently possible. Solder bridges that cause permanent effects on circuit functionality are easy to detect by manual and automatic inspection methods. Increased bridging has been seen in most lead-free installations and is caused primarily by the alloys higher surface tension and therefore poorer drainage from the solder joint.

The natural process remedy for the two gross failure modes (solder bridging and solder skipping) is to decrease the conveyor speed and increase the pre-heat and pot temperature. Decreasing the conveyor speed does increase the opportunity for the alloy to wet to the desired surfaces, but also slows down production and increases the likelihood of re-flowing top-side components, which can damage solder joints. Increasing solder pot temperatures does increase alloy fluidity, which in turn improves drainage and therefore reduces bridging. The downside to this action is that we increase the chance of laminate and component damage, increase the chance of secondary re-flow, copper dissolution and increase drossing rates.

Drossing of alloys has significant impact on the wave soldering process economics. Although this is less important than process yield, the increase in alloy cost makes drossing more important than ever before, and ways of minimizing dross formation is at the forefront of every Engineer's mind. Alloy formulation will affect the inherent drossing rate of the metal. There are six variables that affect this, they are temperature, agitation, ambient atmosphere, alloy purity, alloy conditioning and dross reducing agents. For alloy purity it has been shown that levels of Aluminum, Zinc and Cadmium as low as 50ppm can cause excessive drossing. Most virgin pure raw materials contain levels of suspended oxides that are higher than acceptable. Alloy conditioning using multistage chemical treatments can remove these suspended oxides during the alloying process. The type of dross that is produced is also important, many alloys produce a dross that is a heavily saturated with metal, this is undesirable as it results in good metal being removed from the bath during the dross removal process. There are various dross reducing agents that can be added to wave solder alloys in amounts of around 50 – 100ppm that dramatically change the type of dross into a dry powder and so help to reduce drag out of good solder alloy during the dross removal process. Many studies have shown that wetting speed, a key factor in wave soldering, is vastly increased by inerting the local atmosphere an alternative to increases in pot temperature, whilst minimizing drossing by the expulsion of oxygen.

In Service Reliability

The move to Lead-Free PCB assemblies has raised the question of the in service reliability of Lead-Free alloy solder joints. This is a legitimate concern for OEM's anxious to retain good reputations for quality and reliability. The testing in this program was in two stages, first being an assessment of the strength of the solder joints. This involves the physical removal of components from a board and measurement of the force required. The second was accelerated life testing using thermal cycling. There are different profiles that are used for thermal cycling depending on the end use of the PCB. They range from 0 to 80°C, which is acceptable for some consumer electronics to -40 to 165°C that may be an aspiration for electronics in a harsh environment such as under bonnet (hood) applications. The profile selected for the testing of the new alloy was between the conditions indicated above –40 to 125°C with a ramp rate of less than 20°C per minute and a 10 minute soak at the upper and lower limits. The test boards were selected from the process yield experiments and consisted of FR4 boards with a CuOSP solder pad finish. The components monitored were all surface mount chip resistors, these were selected in preference to the SOIC components as it was assumed that the stresses in the joints of the chip resistors would be greater than that of the gull wing leads on the SOIC. The number of components on each board was 1200 arranged in a daisy chain consisting of 50 per chain, resulting in 24 circuits per board.

Experimental Design and Results

Evaluation of the new Wave Solder alloy has included the following testing regime:

Process Performance indicators:

1. Wetting Performance of alloys.
2. Copper dissolution rates.

Process Yield measures:

3. Process Yield
4. Drossing rates

Reliability Measures

5. Mechanical testing.
6. Accelerated Life Tests.

The formulation candidates were evaluated against all of the tests indicated and also benchmarked against the following alloys, Sn96.5/Ag3.0/Cu0.5 (SAC305), Sn99.3/Cu0.7, Modified Sn99.3/Cu0.7 (Sn/Cu/Ni).

1. Wetting Performance of alloys

The wetting balance test (sometimes referred to as meniscograph) was used to determine the wetting performance of the alloys. This test is a well-established and accepted method for solder wetting comparisons. Three Lead-Free alloys were compared in their wetting behavior: SAC305, Modified Sn99.3/Cu0.7 (Sn/Cu/Ni) and the leading candidate formulation of SACX0307. Five test fluxes were used for the test to check the performance over a range of different flux technologies. The testing was conducted on a **Minisco ST50** solderability tester. Copper test coupons that were 25.5mm x 12.78mm x 0.28mm were cleaned in isopropyl alcohol and then dipped in 10% fluoroboric acid solution, rinsed with tap water, flushed with DI water and dried.
The alloy was prepared in the holding pot and held at 260 Celsius, the copper coupons were dipped in the flux to a depth of 10mm for 5 seconds, excess flux was removed by touching the coupon on clean filter paper. The coupon was then positioned in the machine and tested. The wetting time is defined as the time for the measured wetting force to return to zero. A lower Fmax number indicates and poorer wetting angle.
The results are shown in the table 3.

Table 3 - Wetting Balance test results

Flux Type		SAC305		SACX0307		Modified Sn/Cu (Sn/Cu/Ni)	
Flux Base	Solids Content	To Seconds	Fmax mN	To Seconds	Fmax mN	To Seconds	Fmax mN
Water A	3.50%	0.60	6.50	0.90	5.55	1.25	5.06
Water B	3.50%	0.60	6.92	0.75	5.34	1.00	2.63
Water	6.20%	0.50	7.57	0.75	7.15	1.00	6.06
Alcohol	2.50%	0.50	7.40	0.75	6.95	0.90	6.51
Water	10%	0.50	7.34	0.60	7.21	0.75	6.65

Two conclusions can be drawn from the data; the first is that the new formulation offers a faster wetting speed than the modified Tin Copper (Sn/Cu/Ni) but not as good as SAC305. Secondly the variation of the results across the different flux technologies is less for SACX0307 compared to Tin Copper, and that this variation is at a minimum for SAC305.
Generally speaking a wetting time of less than 1 second is desirable for the wave solder process.

2. Copper Dissolution Rates

The test for Copper dissolution was conducted by dipping a pre-fluxed copper wire specimen into the test alloys for a specified time period. The change in diameter of the copper wire is measured and a rate of erosion is determined by the formula:

$$\text{Erosion Rate} = \frac{do - df}{\text{Time}}$$

Where do = Original Diameter, df = Final Diameter.

For the tests the dipping times selected were 3 seconds to represent a typical contact time in a wave solder process and 30 seconds. The alloy temperature was set at 260°C.
The results of the tests are shown in table 4:

Table 4 – Copper Dissolution rates

Alloy Composition	Time	do	df	Rate
	Sec	Microns	Microns	Microns/s
Vaculoy SACX0307	3	1879.6	1847.6	10.7
SAC305	3	1879.6	1846.6	11.0
Modified Sn99.3/Cu0.7	3	1879.6	1844.6	11.7
Vaculoy SACX0307	30	1879.6	1818.2	2.0
SAC305	30	1879.6	1818.8	2.0
Modified Sn99.3/Cu0.7	30	1879.6	1817.2	2.1

The results of the three-second test show much higher rates of erosion than the thirty-second test. This is attributed to the boundary effect of a highly saturated Cu rich phase that acts to reduce the erosion rate.
Overall the rate of erosion shows very little difference and in practice the difference between the three alloys will be negligible, however the new alloy formulation showed the lowest rate of Copper erosion of the three tested.

3. Dross testing

The testing of alloys was conducted on two alloy systems, the development alloy SACX0307 that was Vaculoy treated and modified Sn99.3/Cu0.7 (Sn/Cu/Ni). The testing was done on a bench top mini-wave machine with a bath capacity of 14kg; the temperature was set at 260°C and the pump speed kept constant. The tests were conducted in air and oxide (dross) removed on each hour of fourteen-hour test. The dross removed from the pot includes some metal drag out, for the analysis this material was then separated into a metal portion and a fines (oxide) portion.

The results of the testing are shown in table 5.

Table 5 – Dross test results.

Hours	Modified Sn99.3/Cu0.7			SACX0307		
	Metal	Fines	Total	Metal	Fines	Total
1	9.64	6.56	16.20	12.37	1.93	14.30
2	18.57	13.73	32.30	25.96	4.94	30.90
3	27.99	21.21	49.20	38.08	7.72	45.80
4	39.32	27.78	67.10	48.20	11.00	59.20
5	46.16	34.24	80.40	59.59	14.11	73.70
6	53.84	40.96	94.80	71.62	16.88	88.50
7	61.51	47.09	108.60	81.17	19.83	101.00
8	67.22	52.88	120.10	91.26	23.84	115.10
9	77.49	58.51	136.00	100.30	28.50	128.80
10	86.23	64.67	150.90	108.94	32.76	141.70
11	95.46	73.84	169.30	117.34	36.96	154.30
12	103.85	79.45	183.30	126.61	41.69	168.30
13	113.09	84.01	197.10	135.28	45.82	181.10
14	120.97	90.93	211.90	142.58	51.22	193.80

The results show that the total mass removed for both alloys was similar but that the level of fines (oxide) was much less for the development alloy. This suggested that with better care in removing dross in the SACX0307 system would give a better yield.
In subsequent full-scale production trials in the field it was noted that the dross produced was mainly a finely divided powdery oxide with very little entrained metal.
Another comment made on several occasions by those testing the alloy was that the wave surface was exceptionally clean and bright with no visible dross “streaking” on the surface.

4. Soldering Process Yield

The process yield of the candidate alloy versus the other alloys was tested using a DOE; the factors are shown in table 6.

Table 6 – Process Yield DOE Factors

Run	Alloy	Flux	Board Finish
Run 1	Sn99.3/Cu0.7	ALPHA EF-4102	Cu OSP
Run 2	Sn99.3/Cu0.7	ALPHA EF-4102	Im Ag
Run 3	Sn99.3/Cu0.7	ALPHA NR-330	Cu OSP
Run 4	Sn99.3/Cu0.7	ALPHA NR-330	Im Ag
Run 5	Sn99.3/Cu0.7	ALPHA SMX018	Cu OSP
Run 6	Sn99.3/Cu0.7	ALPHA SMX018	Im Ag
Run 7	Modified Sn99.3/Cu0.7	ALPHA SMX018	Cu OSP
Run 8	Modified Sn99.3/Cu0.7	ALPHA SMX018	Im Ag
Run 9	Modified Sn99.3/Cu0.7	ALPHA EF-4102	Cu OSP
Run 10	Modified Sn99.3/Cu0.7	ALPHA EF-4102	Im Ag
Run 11	Modified Sn99.3/Cu0.7	ALPHA NR-330	Cu OSP
Run 12	Modified Sn99.3/Cu0.7	ALPHA NR-330	Im Ag
Run 13	ALPHA Vaculoy SACX0307	ALPHA NR-330	Cu OSP
Run 14	ALPHA Vaculoy SACX0307	ALPHA NR-330	Im Ag
Run 15	ALPHA Vaculoy SACX0307	ALPHA EF-4102	Cu OSP
Run 16	ALPHA Vaculoy SACX0307	ALPHA EF-4102	Im Ag
Run 17	ALPHA Vaculoy SACX0307	ALPHA SMX018	Cu OSP
Run 18	ALPHA Vaculoy SACX0307	ALPHA SMX018	Im Ag
Run 19	SAC305	ALPHA EF-4102	Cu OSP
Run 20	SAC305	ALPHA EF-4102	Im Ag

- **Board Design**: Cookson Performance Solutions test board, designed to produce failures and hence give discriminating results. Surface mount and though hole components in mixed orientations. Double sided plated through hole 1.6mm thick, topside partially populated, one prior heat cycle (150°C for 5 minutes). Component count:
    - **35 SOW16**
    - **36 SO16**
    - **600 R1206 Chip resistors (0 Ohm)**
    - **600 R0805 Chip resistors (0 Ohm)**
    - **1 x PGA 100 pin array.**
    - **1 x 96 Pin Connector**
    - **2 x DIP 16 Connector**
    - **1 x 50 Pin Connector**

- **Board Finish : CuOSP and Immersion Ag**
- **Fluxes: EF4102** – water based 10% solids content, **SMX018** – Alcohol based 7.5% solids content, **NR330** – water based 4% solids content.
- **Machine settings:** were kept constant for the experiment and were as indicated in table 7.

Table 7 – Wave solder machine settings

Wave Solder Machine Settings	
Conveyor Speed	1.1m/mim
Solder Pot temperature	260 Celsius
Top side board temp	110 Celsuis water, 95 alcohol
Contact time	3.5 Secs
Atmosphere	Air
Wave configuration	Lambda and Chip
Flux Quantity	According to advised cover for each flux type

- **Experiment run design:** The experiment was a run of 20 with 5 boards being produced for each run.

For the experiment the boards were produced using the same machine set up and flux volume (by Flux) for all of the test runs. The boards were inspected and defects counted by hand.

- **Experimental Results**

The experimental results shown in table 8 are ranked in order of lowest to highest incidence of defects. The defect count is the total defects for all 5 boards and the relative percentage column indicates the relative percentage worse than the best performing combination. The test board was designed to discriminate between different set ups and worked well in this respect. From the data the following statements can be made:

Table 8 – Process Yield – Experimental test results

Run	Alloy	Flux	Board Finish	Total Defects (5 boards)	Relative % v's best
Run 20	SAC305	ALPHA EF-4102	Im Ag	207	0
Run 16	ALPHA Vaculoy SACX0307	ALPHA EF-4102	Im Ag	221	7%
Run 19	SAC305	ALPHA EF-4102	Cu OSP	235	14%
Run 15	ALPHA Vaculoy SACX0307	ALPHA EF-4102	Cu OSP	272	31%
Run 10	Modified Sn99.3/Cu0.7	ALPHA EF-4102	Im Ag	334	61%
Run 18	ALPHA Vaculoy SACX0307	ALPHA SMX018	Im Ag	436	111%
Run 9	Modified Sn99.3/Cu0.7	ALPHA EF-4102	Cu OSP	456	120%
Run 12	Modified Sn99.3/Cu0.7	ALPHA NR-330	Im Ag	478	131%
Run 17	ALPHA Vaculoy SACX0307	ALPHA SMX018	Cu OSP	486	135%
Run 8	Modified Sn99.3/Cu0.7	ALPHA SMX018	Im Ag	489	136%
Run 14	ALPHA Vaculoy SACX0307	ALPHA NR-330	Im Ag	496	140%
Run 2	Sn99.3/Cu0.7	ALPHA EF-4102	Im Ag	509	146%
Run 13	ALPHA Vaculoy SACX0307	ALPHA NR-330	Cu OSP	541	161%
Run 7	Modified Sn99.3/Cu0.7	ALPHA SMX018	Cu OSP	558	170%
Run 4	Sn99.3/Cu0.7	ALPHA NR-330	Im Ag	565	173%
Run 1	Sn99.3/Cu0.7	ALPHA EF-4102	Cu OSP	590	185%
Run 11	Modified Sn99.3/Cu0.7	ALPHA NR-330	Cu OSP	617	198%
Run 3	Sn99.3/Cu0.7	ALPHA NR-330	Cu OSP	634	206%
Run 6	Sn99.3/Cu0.7	ALPHA SMX018	Im Ag	888	329%
Run 5	Sn99.3/Cu0.7	ALPHA SMX018	Cu OSP	1195	477%

1. The development alloy ALPHA Vaculoy SACX0307 performed better than the modified Sn99.3/Cu0.7 (Sn/Cu/Ni) alloy and the standard Sn99.3/Cu0.7 alloy.
2. The combination of ALPHA SACX0307, EF4102 flux on a ImAg board finish came second in the ranking producing only 7% more defects than the top ranking combination of SAC305, EF4102 Flux and ImAg board finish. The best performing Sn/Cu alloy was the modified Sn99.3/Cu0.7 (Sn/Cu/Ni), EF4102 flux, ImAg board finish that delivered 61% more defect than the top ranking combination.
3. The modified Sn99.3/Cu0.7 (Sn/Cu/Ni) performed better than the standard Sn99.3/Cu0.7.

In summary the development alloy ALPHA Vaculoy SACX0307 gave almost equivalent performance to the top-performing alloy SAC305.

5. Mechanical Testing

The mechanical testing was conducted on two different board types. The first was done on a single sided FR2 type board that was produced by a TV manufacturer, in order to measure the strength of joints on through hole components. Three test boards were manufactured; the alloys were SAC305, SACX0307 and Sn63/Pb37.
The testing was conducted on three different component types, a large resistor, an aluminium heat sink and a CRT connector socket.
The joints and components were cut from the board using a diamond saw and mounted in an Ingstrom tensile testing machine. There were a total of seven pull tests done on each component, the results are shown in table 9.

The result shows that the all the three alloys tested produced very similar results for the mechanical strength of the solder joins on the through hole components. The CRT connector joint did not fail on any of the tests the tensile force caused the component pin to fail before the solder joint.

Table 9 – Through Hole joint Strength.

Component		Alloy		
		Baseline SAC305	**SACX0307**	**63/37**
		Force (Newtons)		
Large Resistors	Mean	**66**	**72**	**79**
	Std Dev	**11**	**11**	**14**
Heat Sink Pins	Mean	**219**	**202**	**192**
	Std Dev	**22**	**19**	**23**
CRT Connector	Mean	**Pin broken not joint**		
	Std Dev	**Pin broken not joint**		

The second phase of the mechanical testing was conducted on surface mount components using the test boards that were produced for the yield testing DOE. The mechanical testing was conducted on the 1206 Chip resistors and the SOW16 gull wing leads. The number of tests was 30 for each alloy for the 1206 component and 20 for the SOW16 leads. The testing was conducted using a Dage Bondtester, the results are shown in tables 10 and 11.

Table 10– Surface mount chip shear test results
Table 11– SOW16 Gull wing lead pull strength

Component		**Chip Shear**		
		SAC305	**SACX0307**	**Modified Sn99.3/Cu0.7**
		Force (Newtons)		
1206 Chip resistor	Mean	**135**	**140**	**115**
	Std Dev	**25**	**12**	**20**

Component		**Tweezer Pull SOW16 Gull wing lead**		
		SAC305	**SACX0307**	**Modified Sn99.3/Cu0.7**
		Force (Newtons)		
SOW16 Gull Wing Lead	Mean	**17.2**	**21.4**	**19.1**
	Std Dev	**5.9**	**5.3**	**6.1**

The test results for the chip shear show that the development alloy SACX0307 produced the best results in the chip shear test having the highest mean force and the smallest standard deviation. It should be noted that the formation of the joint in terms of the geometry and wetting angles will have a significant effect on the results therefore the performance of any alloy is a combination of the mechanical strength of the alloy system and the geometry of the joint formed.
During the tweezer pull test there were a number of tests that resulted in the tweezers slipping from the lead, the force at the point of slip was recorded, therefore the results in the table include joint failure and tweezer slip results. The results show that the development alloy SACX0307 produced the best results, the highest force and the smallest standard deviation.

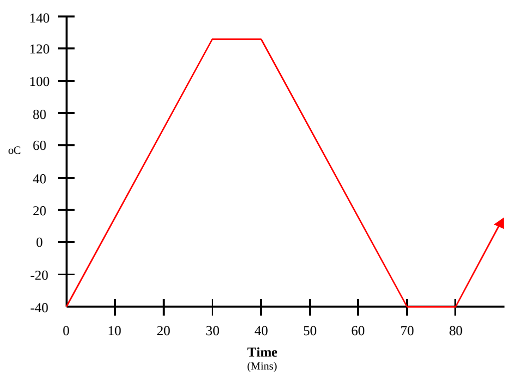
6.Accelerated Life Tests

The test boards used in the yield experiment were tested in a Thermal Cycling chamber. The performance of a solder joint subject to thermal stress is dependent on the physical properties of the solder alloy and the joint formation. Therefore a poorly formed joint will deteriorate to failure more quickly than a well formed joint. The stresses induced during thermal cycling can be large enough to produce micro-structural changes in the solder joint, including the nucleation of fatigue cracks and joint failure. This is a progressive mechanism, once a crack has nucleated it may proceed to grow. It is well known that alloys of different constituents, composition and microstructure have different abilities to withstand fatigue crack nucleation, crack propagation and other associated effects. The fatigue crack mechanism is as follows:

- Stress creates delineation of individual grains and porosity.
- Delineation is caused by a breakdown of inter-granular cohesion, grain deformation effects or micro-structural coarsening effects or a combination of these factors.
- A fatigue crack is caused by the coalescence of voids or during grain boundary separation of highly stressed regions.

Thermal fatigue mechanisms also produce changes in the surface of the solder joints.
Ripples, distortion and deformation may develop, during cycling these can develop into cracks.
One board of each alloy type was wire up to the monitoring equipment.
The components on the boards were dummy resistors rated at zero ohms. The test chamber was capable of –87 to +190°C, the testing was conducted using the profile of –40 to 125°C with a ramp rate of less than 20°C per minute and a 10 minute soak at the upper and lower limits (Figure 1).
The testing was originally designed to run for 1000 cycles, this number of cycles was reached and only one electrical failure was recorded on any of the test boards – this occurred on the Sn/Cu sample.

Figure 1 – Thermal Cycle



Micro sections of joints were taken on all of the boards for all four alloys to examine the thermal fatigue mechanisms.
All of the alloys show some signs of thermal fatigue damage:

- The SACX0307 and SAC305 alloys show some signs of grain delineation and porosity however the fatigue crack growth is limited. Figure B6
- The Sn99.3/Cu0.7/Ni and Sn99.3/Cu0.7 alloys have more extensive fatigue cracking and presumably at a later stage of development. Figure C10.
- No identifiable fatigue induced surface fissures were found for SACX0307 or SAC305.
- Fatigue induced surface fissures were found in the Sn99.3/Cu0.7/Ni and Sn99.3/Cu0.7 alloys.

The superior thermal fatigue resistance of the SACX0307 and SAC305 could be attributed to the presence of the inter-metallic compound Ag_3Sn.

Figure B2 – SACX0307 – no fatigue cracks

Figure B2. No fatigue cracks can be seen in the heel fillet of the joint at higher magnifications

Figure B6 – SACX0307 Grain delineation

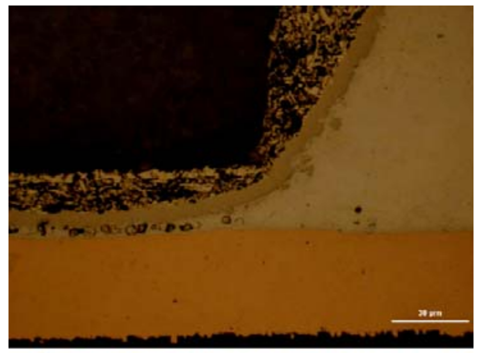


Figure B6. Higher magnification micrograph of a fuller SAC-X 0307 solder joint 0805 chip resistor showing increased grain definition and de-lineation

Figure C10 – Sn99.3/Cu0.7/Ni – fatigue crack

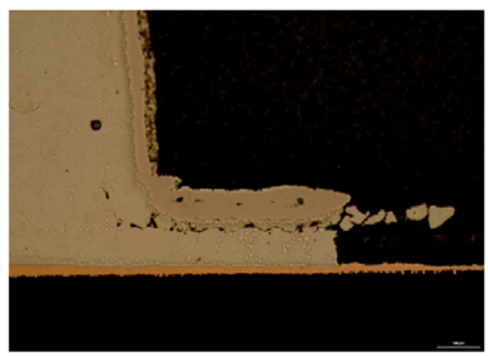


Figure C10. A higher magnification image of the thermal fatigue cracks

Figure C10 – Sn99.3/Cu0.7/Ni – fatigue crack from surface fissure

Figure C5. The fatigue crack emerging at the outer edge of the soldered joint

Conclusions

The SACX0307 wave solder alloy that gives a performance similar to that of SAC305 and far superior to any of the Sn99.3/Cu0.7 based systems and delivers this with a lower raw material cost than the SAC305.
The key measures are:

1. Wetting speed faster than all Sn99.3/Cu0.7 based alloys. This has resulted in excellent soldering results in these tests and the subsequent field testing that has taken place.
2. Copper dissolution rates that are lower than Sn99.3/Cu0.7 based alloys and SAC305.
3. A process yield that is comparable to SAC305 and superior to the Sn99.3/Cu0.7 based alloys.
4. Drossing rates equivalent to other Lead-Free alloys.
5. Mechanical joint strength better than Sn99.3/Cu0.7 based alloys and SAC305.
6. Reliability better than Sn99.3/Cu0.7 based alloys and equivalent to SAC305.

Results show that the SACX0307 Lead-Free alloy will deliver a low total cost of ownership and hence meet the market needs for Lead-Free wave solder processes.