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Lead-Free and Mixed Assembly Solder Joint Reliability Trends

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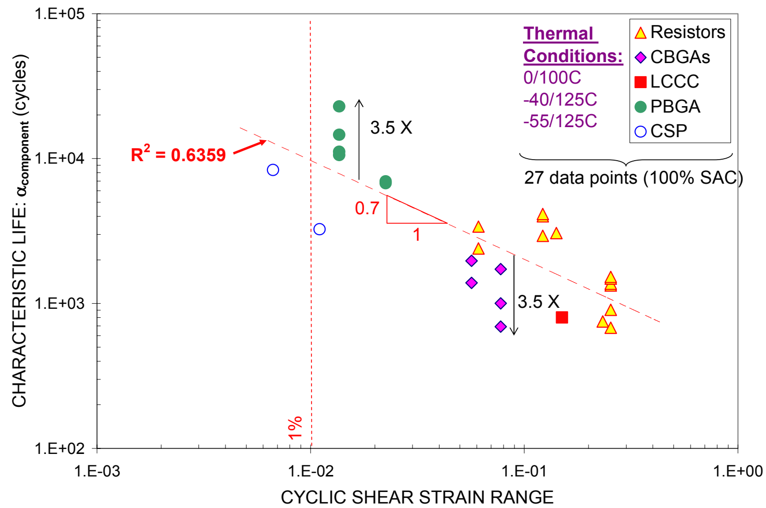
Abstract
This paper presents a quantitative analysis of solder joint reliability data for lead-free Sn-Ag-Cu (SAC) and mixed assembly (SnPb + SAC) circuit boards based on an extensive, but non-exhaustive, collection of thermal cycling test results. The assembled database covers life test results under multiple test conditions and for a variety of components: conventional SMT (LCCCs, resistors), Ball Grid Arrays, Chip Scale Packages (CSPs), wafer-level CSPs, and flip-chip assemblies with and without underfill. First-order life correlations are developed for SAC assemblies under thermal cycling conditions. The results of this analysis are put in perspective with the correlation of life test results for SnPb control assemblies. Fatigue life correlations show different slopes for SAC versus SnPb assemblies, suggesting opposite reliability trends under low or high stress conditions. The paper also presents an analysis of the effect of Pb contamination and board finish on lead-free solder joint reliability. Last, test data are presented to compare the life of mixed solder assemblies to that of standard SnPb assemblies for a wide variety of area-array components. The trend analysis compares the life of area-array assemblies with: 1) SAC balls and SAC or SnPb paste; 2) SnPb balls assembled with SAC or SnPb paste.

Introduction
Attachment reliability being the ability of solder joints to survive the planned design life of a given product, blanket statements as to the reliability, or the lack of it, of lead-free assemblies need be put in context and generalizations should be based on extensive supporting data. Reliability is *application-specific* and can only be established through the careful acquisition of failure distributions under accelerated test conditions, followed by careful extrapolation of test failure times to field service conditions of interest to a particular application. To this author's knowledge, the latter step has not been enabled, as of yet, given the lack of proven lead-free life prediction models or acceleration factors in the public domain. Numerous efforts to that effect are in progress (see references, [1-4] for example). The development of SnPb solder joint reliability models spread over three-decades starting with the landmark paper of Norris and Landzberg[5] in 1969. It would be optimistic to expect robust lead-free reliability models to become available in a semester or two. In the mean time, it is useful to gather reliability test data for comparison purposes. Our experience working with SnPb and lead-free assemblies has been that a wide range of test data need be consolidated to establish firm reliability trends. In this paper, we present the results of a quantitative analysis of SAC and mixed assembly thermal cycling data. The main objective is to put the data in perspective, presenting lead-free versus SnPb test results for a variety of components, board finish and test conditions.

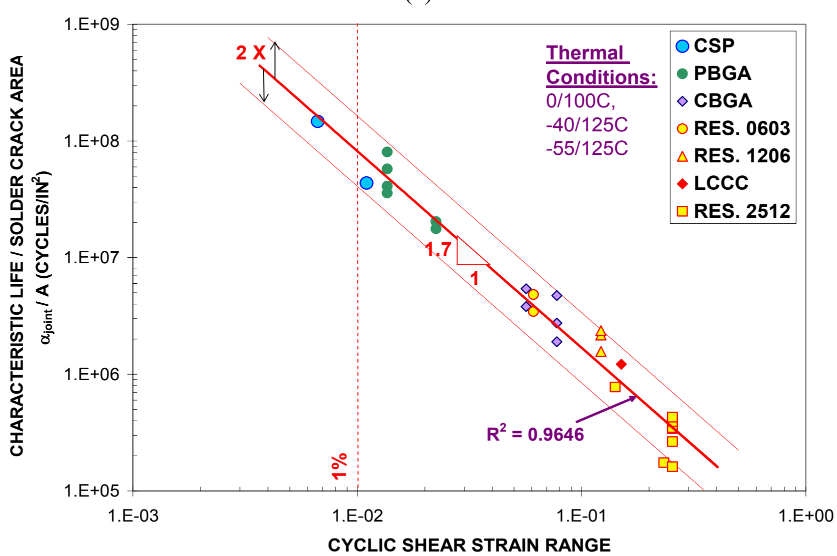
Empirical Correlations of SAC Thermal Cycling Test Data
Figure 1a is an attempt at correlating characteristic lives and cyclic shear strain ranges as per the classical Coffin-Manson[6] approach for fatigue of metals. The characteristic lives (cycles to 63.2% failures) are from failure distributions for 100% lead-free SAC assemblies[7-15] and component populations subject to accelerated thermal cycling under a range of conditions: 0 to 100°C, -40 to 125°C and -55 to 125°C. The cyclic shear strain range is defined as: $\Delta\gamma = \dfrac{L\Delta\alpha\Delta T}{h}$ where L is the maximum Distance to Neutral Point (DNP) for the outermost joints, $\Delta\alpha$ is the board-to-component mismatch in Coefficients of Thermal Expansion (CTE), h is the average component stand-off height or joint thickness, and ΔT is the temperature difference between the hot and cold sides of a given thermal profile. All components were leadless and mounted on FR-4 type boards: resistors (sizes: 0603, 1206 and 2512), 32 x 32 mm and 42 x 42 mm square Ceramic Ball Grid Arrays (CBGAs), 169 I/O Chip Scale Packages (CSP), 20 I/O Leadless Ceramic Chip Carriers (LCCC) and 1.27 mm pitch Plastic Ball Grid Arrays (PBGAs). The reader is referred to the original sources of data[7-15] for more detailed information on components, test vehicle parameters, other conditions and test results. Twenty seven data points are shown in Figures 1a and 1b. Nominal alloy composition varied slightly (Sn3.8Ag0.7Cu or Sn3.9Ag0.6Cu), board finishes were immersion Ag, Organic Solderability Preservative (OSP) or NiAu. The board finish was unspecified for three of the 27 datasets.

The correlation coefficient for the power-law trendline going through the data in Figure 1a is $R^2 = 0.64$. Clearly, there is a discrepancy between the data and the basic Coffin-Manson approach. The data is re-plotted in Figure 1b with the following modifications: 1) instead of characteristic lives for a population of components, cyclic lives are given on a per joint basis as was done in the past in the development of SnPb reliability models – this allows to account for the number of most critical joints per component,[16] 2) the joint characteristic life is then scaled for the solder joint crack area, as justified in previous work.[16,17] The scaling of characteristic lives for the solder crack area is intended to account for differences in crack propagation times through joints of varied sizes. The resulting parameter - characteristic life over the solder joint area - is interpreted as the inverse of an areal crack propagation rate and is given in Figure 1b with units of cycles/in^2. The correlation coefficient for the power-law trend line in Figure 1b is R^2 = 0.96. This R^2 value is remarkably high, which suggests a reasonable empirical correlation of the data within the strain range under consideration. What this means is that the data is very consistent across a range of component sizes, joint sizes and thermal cycling conditions. However, the correlation in Figure 1b is purely empirical and should not be used to extrapolate test results to field conditions since important parameters such as dwell times or test frequency are not accounted for. The latter effects may not matter within the context of this exercise since all tests were rather rapid with similarly short dwell times compared to long dwell periods that may be encountered in service. Nevertheless, the correlation in Figure 1b is of use to investigate the effect of other parameters such as board finish or alloy composition effects, as shown in the next section.

Another observation of interest in Figures and 1b is that, out of the 27 data points that were accumulated; only one is below the 1% shear strain range. A 1% strain is considered high, leading to a reduced cyclic life, and would definitely raise a red-flag if this was to occur under service conditions. While our database of SAC test results is far from exhaustive, this suggests a definite lack of test results under mild conditions. It appears that many tests are run under highly accelerated conditions to gather failure data rapidly for comparison purposes. These results in a scarcity of data in low to medium stress conditions, slowing down efforts to validate reliability models in regions closer to the milder conditions encountered in many applications.



(a)



(b)

Figure 1 - Correlations of (a) Component Characteristic Life and (b) Joint Characteristic Life Scaled for Solder Joint Crack Area Versus Average Cyclic Shear Strain Range in Temperature Cycling. Data is for 100% Lead-free SAC Assemblies

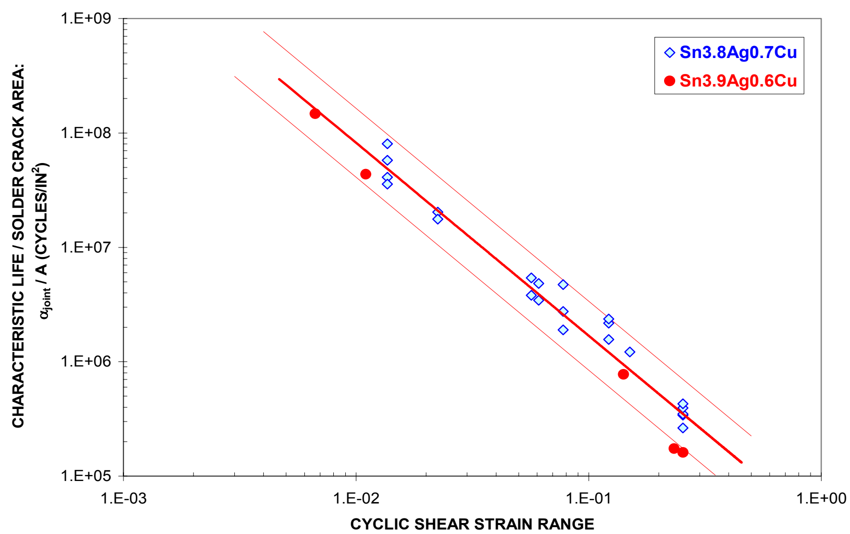
Alloy Composition and Board Finish Effects

The data in Figure 1b is re-plotted in Figures 2a and 2b where, instead of showing component types, results are shown according to alloy composition or board finish. Out of the 27 datasets of interest, five had the nominal solder composition: Sn-3.9Ag-0.6Cu (SAC 3906) while all the others had the nominal composition: Sn-3.8Ag-0.7Cu (SAC 3807). In Figure 2a, the SAC 3906 data points are all below the correlation center line. It might be tempting to conclude that the SAC 3807 alloy leads to a slightly longer life than SAC 3906. However, the SAC 3906 population in the analysis is small (5 data points out of a total of 27) and more data is needed to test the statistical differences between the SAC 3807 and SAC 3906 populations.

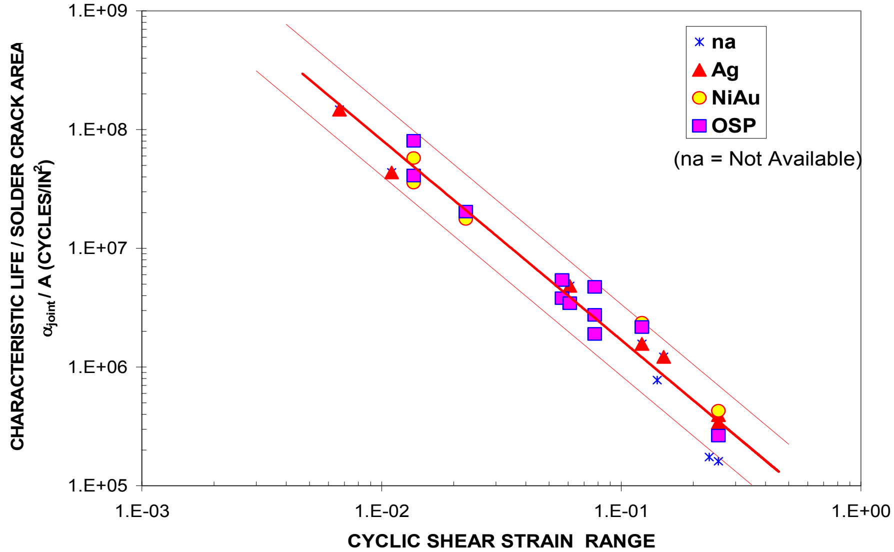
In Figure 2b, the same data points are grouped and labeled by board finish: immersion Ag, OSP, NiAu or not specified. For a given group, the data is above or below the centerline and no definite trend is visible on the basis of board finishes. For example, looking at the four NiAu and OSP data in the upper left of the plot, the OSP points are above the NiAu points. The opposite is observed for the NiAu and OSP data points in the lower right region of Figure 2b. Over a wide range of cyclic shear strains, no board finish appears to provide consistently better results than the others.

Lead-Free to SnPb Comparison: Reflowed SAC and Sn0.7Cu Versus Near-Eutectic SnPb

The 100% lead-free SAC data in Figure 1b are shown in Figure 3 along with thermal cycling results for standard SnPb assemblies from the same experiments.[7-15] Each group shows some scatter as is expected with fatigue data. The power-law trendlines that are fitted through each dataset intersect at a shear strain level of about 6.2%. To the left of the cross-over point, SAC assemblies have longer lives than SnPb assemblies. For most points at cyclic shear strains less than 3%, the SnPb data is clearly below the SAC data. The opposite holds for data points at shear strains above 20%. The empirical correlations in Figure 3 indicate that, under high stress conditions, the life of SAC solder joints is less than that of SnPb. The differences in the slopes of the SAC and SnPb trendlines and the intersect of the two lines, suggest that when SAC assemblies do not perform as well as SnPb assemblies under highly accelerated test conditions, SAC assemblies are likely to be more reliable than SnPb assemblies under milder conditions. This trend reversal further highlights the need to extrapolate test results to field conditions in an accurate manner. Relying on accelerated test results alone may lead to the rejection of some SAC designs and assemblies that would perform as well or better than SnPb assemblies under mild enough conditions. Last, assuming that the trendlines in Figure 3 extrapolate further to the left, if SAC test results are better than for SnPb assemblies, the trend will likely hold under milder service conditions.



(a) Alloy Composition Effect



(b) Board Finish Effect

Figure 2 - Figure 1a Correlation and Data Shown by (a) SAC Alloy Composition; and (b) Board Finish

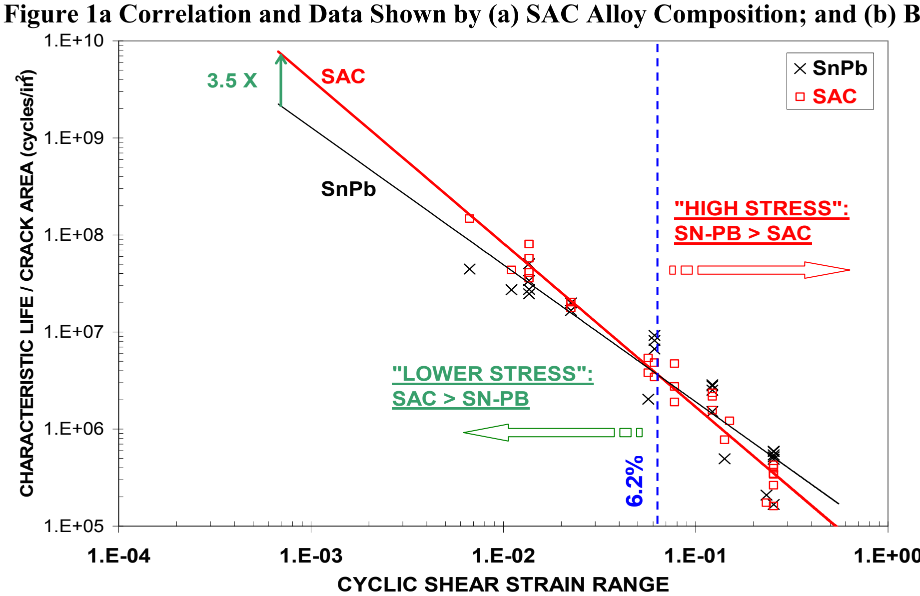


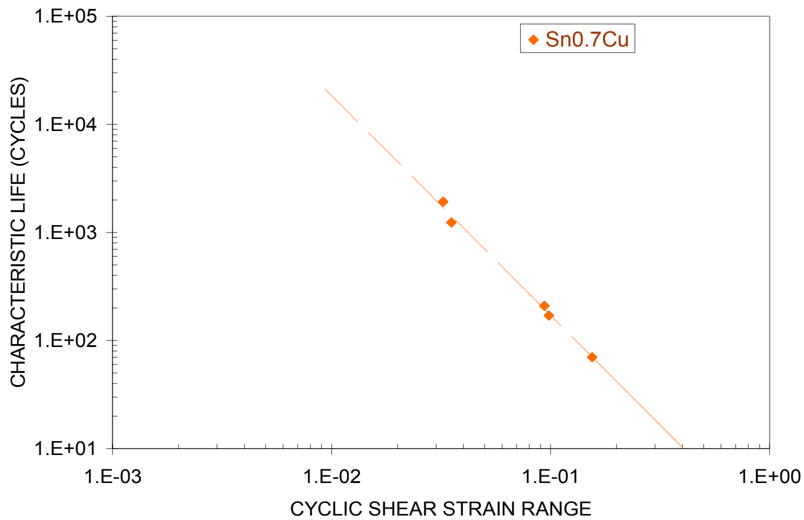
Figure 3 - Correlations of Joint Characteristic Life Scaled for Solder Joint Crack Area versus Average Cyclic Shear Strain Range in Temperature Cycling for Standard SnPb and for 100% Lead-Free SAC Assemblies

Figure 4 shows simple correlations of characteristic lives to cyclic shear strains for bare chip assemblies using Sn0.7Cu (5 data points in Figure 4a), Sn37Pb or Sn36Pb2Ag (9 data points in Figure 4b) and SAC solders (8 data points in Figure 4c) of nominal composition close to that of Sn3.8Ag0.7Cu. Here, we did not attempt to scale the characteristic life for the solder joint crack area since all assemblies had similar pad sizes, at least to a first order. For each alloy type, the test data was from multiple independent sources.[2, 18-20] Components were either of the flip-chip type or wafer-level CSPs (all without underfill) with a variety of metallizations or under bump metallurgies. Thermal cycling conditions covered the following temperature extremes: -50/20°C, 0/70°C, 50/120°C, 0/100°C, -40/125°C and -55/125°C. Shear strain ranges are all above 1% because of the large CTE mismatch between silicon chips and organic substrates.

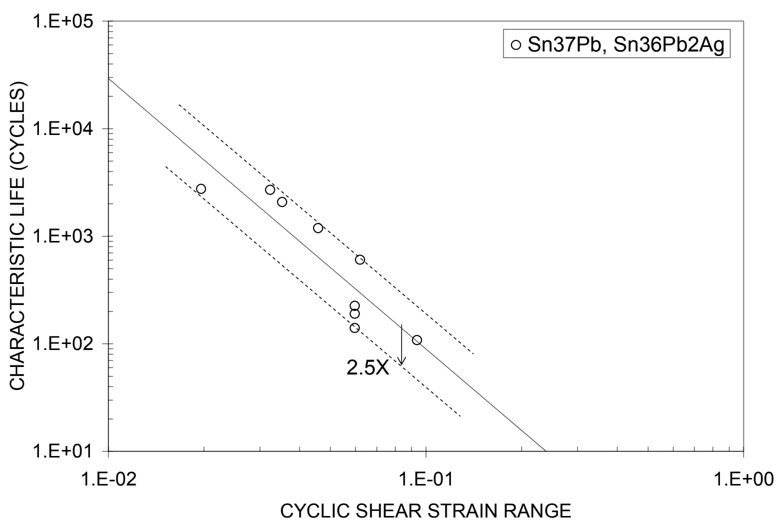
The correlations for each alloy group show scatter that is typical of fatigue data (as much as 2.5-3X above or below the trendlines). However, the Sn0.7Cu correlation is remarkably tight. The power-law trendlines for the three groups are shown on the same graph in Figure 4d. The SAC and SnPb trendlines intersect and have similar relative positions as in Figure 3, thus confirming, as discussed earlier, the reversal of reliability trends under low or high stress conditions. The two lines, which are for bare chip data alone, intersect at a shear strain level of about 6.2%. Interestingly, this is the exact same shear strain as for the intersect of the SAC and SnPb trendlines for un-related data in Figure 3. The SnCu and SnPb trendlines in Figure 4d intersect as well. However, their relative positions follow an opposite trend of the relative positions of the SAC and

SnPb trendlines. More data is needed to test the validity of this SnCu trendline. If it holds, more caution will be needed when interpreting SnCu test results. To the right of the intersect of the SnCu and SnPb lines, the trend is that SnCu assemblies have longer solder joint lives than SnPb assemblies. To the left of that same cross-over point, SnCu assemblies would have shorter lives than SnPb assemblies. This lower stress region is representative of many use conditions and accurate acceleration factors are needed to assess whether Sn0.7Cu still meets product-specific field reliability requirements.

The relative positions of the fatigue trendlines in Figure 4d are supported by similar trends observed in mechanical shear fatigue tests at 20°C, as shown in Figure 5. The collected data is from fatigue strength tables[21] for stress-controlled fatigue experiments on copper ring and plug joint specimens soldered with alloys of slightly different compositions (Sn1.0Cu instead of Sn0.7Cu, and Sn3.5Ag instead of SAC). Figure 5 shows that Sn1Cu solder has a shorter life than that of 60Sn40Pb solder in the lower stress area of the plot, similar to what was observed for Sn0.7Cu in Figure 4d.



(a)



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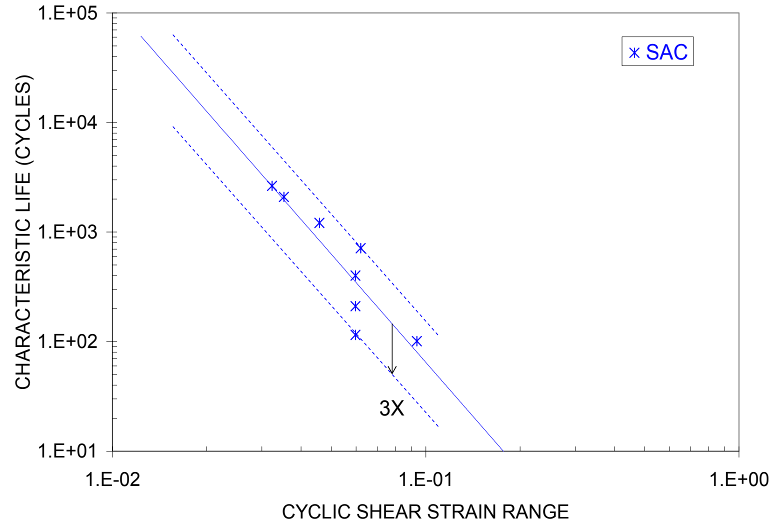

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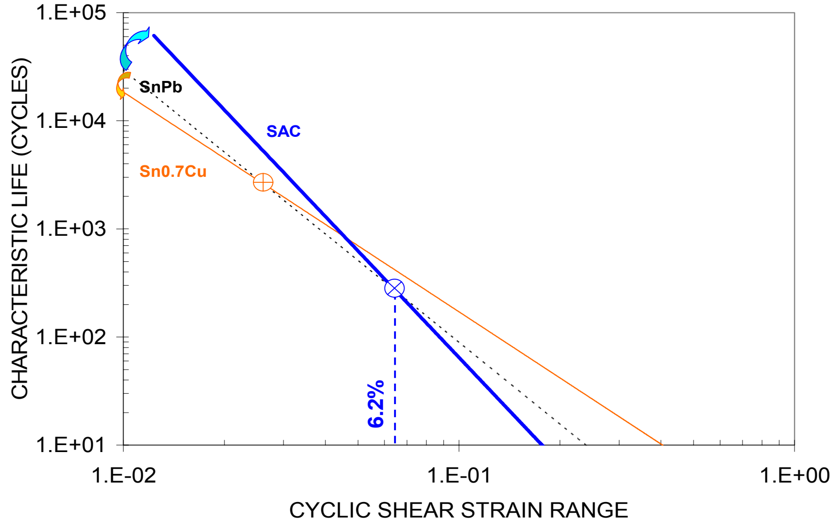


(d)

Figure 4 - Correlations of Characteristic Life to Cyclic Shear Strain Range for Bare Chip Assemblies: (a) Sn0.7Cu Data; (b) SnPb Data; (c) SAC Data; and (d) Power-Law Trendlines for SnCu, SnPb and SAC Assemblies

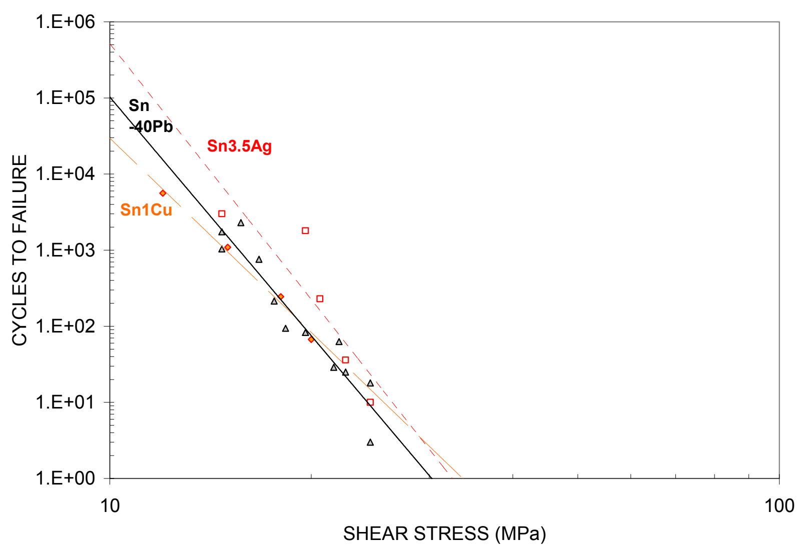


Figure 5 - Plot of Mechanical Fatigue Strength Data[21] at 20°C and Cross-head Speed of 0.2 mm/Minute for Copper Ring and Plug Joints Soldered with Sn1.0Cu, Sn40Pb or Sn3.5Ag Solder

Life Test Data for SAC and SnPb TSOP Assemblies

Figure 6 shows correlations of Alloy42 TSOP characteristic lives versus temperature swings, ΔT, in accelerated thermal cycling. The characteristic lives were read off failure distributions in two independent studies.[22, 23] The paste composition (Sn3.9Ag0.6Cu or Sn3.0Ag0.7Cu) and lead finish (SnPb for all except for one Sn2Bi data point) are as shown in the legend of Figure 6. Temperature cycling conditions were: -55/125°C, -40/125°C, 0/100°C (ref. 22) and -25/125°C (ref. 23). For components with SnPb finish and for a given paste type (SnPb or lead-free SAC), the data from the two sources appear to fit together, at least to a first order. No significant departure is visible for the TSOPs assembled with one type of SAC paste or the other. The data, although limited, does not show a marked effect of SAC alloy composition on life. The all-SnPb data from the two studies fit together in a similar manner. Power law trendlines are shown by paste type for the merged datasets, SAC or SnPb. The trendlines have similar slopes and the "SAC paste / SnPb finish" solder joint lives are less than for the all-SnPb assemblies under the stated test conditions. For example, looking at the data in the lower right region of Figure 6, the characteristic life of the lead-free TSOP assemblies is 1.63 times lower than that of the conventional SnPb TSOP assemblies. For the Sn3.0Ag0.7Cu paste assemblies, TSOPs with Sn2Bi finish have a solder joint life 31% longer than in the case of TSOPs with Sn10Pb finish.

The relative position of the two trendlines in Figure 6 is similar to that of SAC and SnPb lines in Figures 3 and 4d although the slopes of the two lines are much closer. The intersect - not shown - corresponds to a cross-over point at a ΔT of about 9°C. Assuming that the SAC and SnPb lines in Figure 6 can be extrapolated to smaller ΔT's, the life of "SAC paste / SnPb finish" Alloy42 TSOP joints would be shorter than that of conventional SnPb TSOP assemblies, even for temperature swings as low as 9°C. Given the small size of the TSOP datasets in the above analysis, more data is needed to validate the observed trends. However, given that Alloy42 TSOPs assembled with SnPb on FR-4 boards have application-limited reliability (e.g., their use is not recommended[24] in telecommunication products with a five year or longer life span), their implementation in lead-free products will require detailed board-level reliability evaluations.

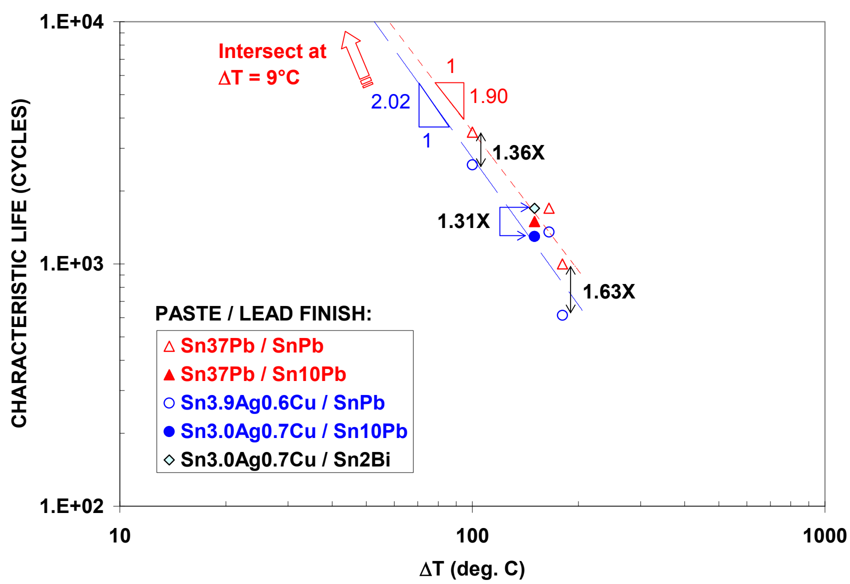


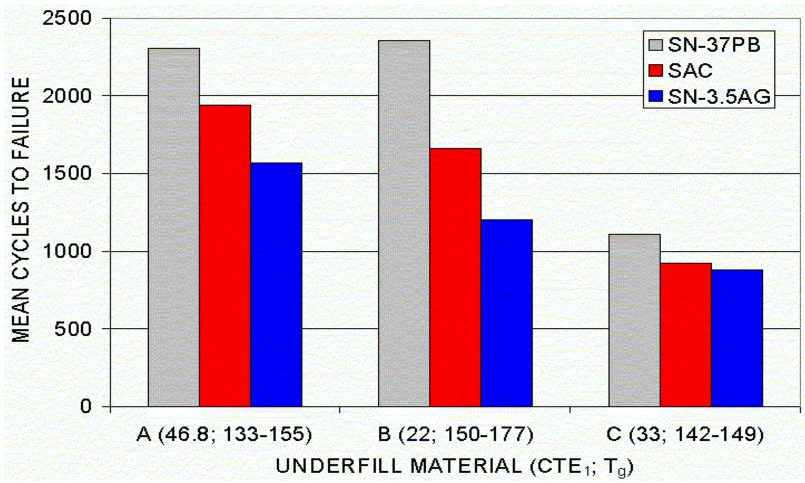
Figure 6 - Correlations of Characteristic Lives to Temperature Swings ΔT for 48 I/O Alloy42 TSOPs

Flip-Chip with Underfill Data

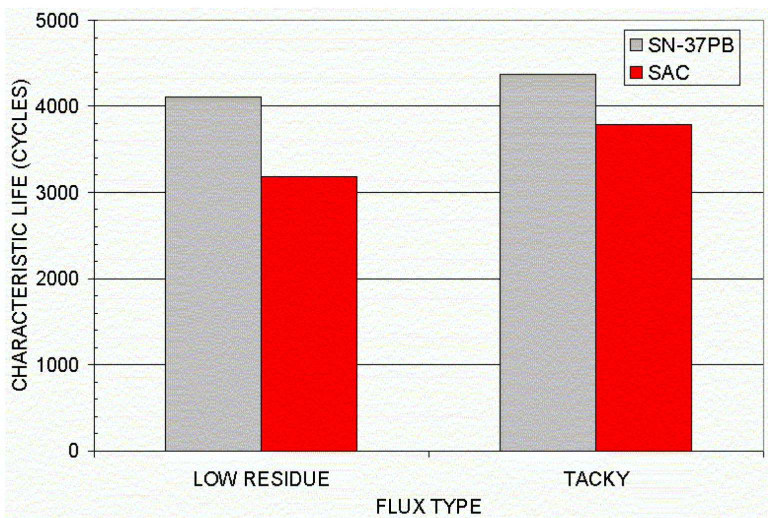
Flip-chip with underfill thermal cycling results from two sets of experiments[25-27] are plotted in Figure 7 with the failure times given as mean cycles to failure for SnPb and lead-free assemblies.

- In the first experiment,[25] failure times are for assemblies using different underfill materials with CTEs and glass transition temperatures (T_g) as shown in Figure 7a. Thermal cycling was between -55°C and 125°C with dwell times of 10 minutes at the temperature extremes and a 30 minute cycle duration. Solder fatigue was the primary failure mode.
- In the second experiment,[26-27] SnPb and SAC results are for assemblies that used low residue or tacky flux. Thermal cycling was between -40°C and 125°C with dwell times of 5 minutes at the temperature extremes and a 12 minute cycle duration. The underfill material was as a standard material with a CTE of 35 ppm/°C and a T_g of 130°C. Failure modes were mixed, including solder fatigue and underfill delamination, with more of the latter in the SAC case than in the SnPb case.

Regardless of the test variable – underfill material or flux type – the SAC failure times are consistently less than failure cycles for SnPb flip-chip assemblies, 20 to 30% less in Figure 7a and 14 to 23% less in Figure 7b. Results for Sn3.5Ag underfilled assemblies in Figure 7a are also worse than for SAC assemblies and 20 to 50% less than for SnPb assemblies. While this is a cause for possible concern, the reliability of the SAC assemblies under service conditions may still be acceptable or even exceed that of SnPb underfilled assemblies if the stress-dependent life-trend reversal that was observed earlier holds for underfilled assemblies. Again, this illustrates the heightened importance of having reliable life prediction tools to extrapolate accelerated test results to field conditions.



(a)



(b)

Figure 7 - SnPb vs. SAC Underfilled Flip-Chip Thermal Cycling Results. Parameters: (a) Underfill[25] (b) Flux Type[26,27]

Reflowed Conventional Leadless SMT Assemblies with Pb Contaminant

In Figure 8, we have plotted cycles-to-1% failures for SAC paste assemblies with some Pb contaminant versus cycles-to-1% failures for 100% lead-free SAC assemblies under thermal cycling conditions: -40°C to 125°C or -55°C to 125°C. When data points fall above the main diagonal, life for assemblies with Pb contamination is longer than that of 100% lead-free assemblies. The data[7, 8, 13] is for conventional leadless SMT components: 20 I/O LCCCs and resistors ("R") of sizes 0603, 1206 and 2512. The source of Pb contamination is the SnPb HASL board finish or the SnPb component termination in the case of 1206 resistors. In the case of 20 I/O LCCC SAC boards with SnPb HASL finish, Woodrow[13] measured a 0.5% Pb contamination level. The cycles to 1% failure were calculated from Weibull parameters - characteristic life and slope of failure distributions – provided in the original studies.[7, 8, 13] Similar trends as shown for cycles-to-1% failure would hold for characteristic lives. We chose to plot cycles to 1% failure since the early part of failure distributions is more relevant to product reliability, especially in the case of boards where a possible "defect" such as Pb contamination may reduce early life product reliability.

Since the data in Figure 8 falls either above or below the main diagonal, the record is mixed with positive or negative effect of Pb contamination on assembly reliability under accelerated thermal cycling conditions. Of the two data points below the main diagonal, the 0603 resistor data[7] may have large confidence bands since the Weibull parameters were obtained from a population with a low failure count. The 1206 / NiAu data point[8] did not present any such anomaly. Since the 1206 / immersion Ag data point from the same study[8] is well above the main diagonal, the problem of Pb contamination is possibly confounded with board finish effects. More data will be added to Figure 8, when available, to further investigate the sensitivity of Pb contamination effects to board metallization. Thus far, the available data (as shown in Figure 8) suggests that Pb contamination at the 0.5% level raises a potential reliability concern for organic boards with NiAu finish on copper pads.

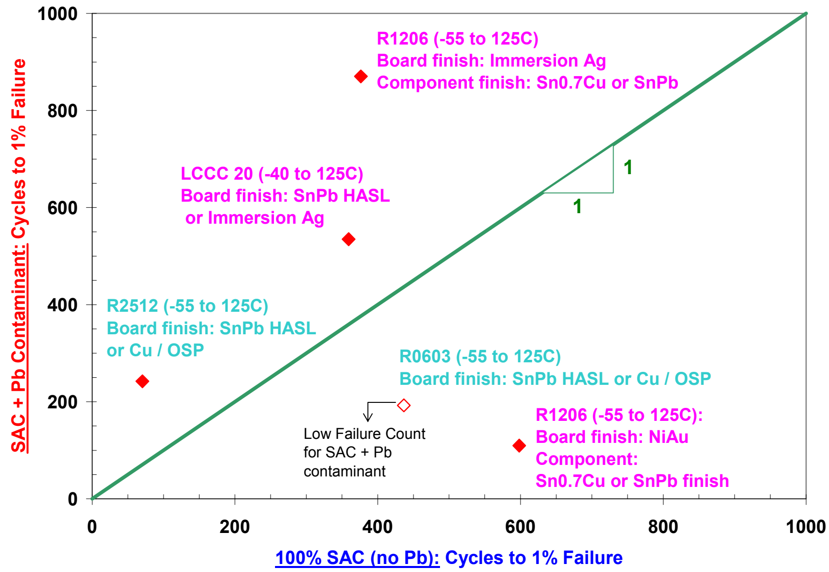


Figure 8 - Cycles to 1% Failure for SAC Assemblies[7, 8, 13] with or without Pb Contaminant. Pb is from SnPb HASL Boards or SnPb Component Finish. Labels Indicate: Component Type, Temperature Extremes, Board and/or Component Finishes

Area Array Assemblies with SAC Balls and SAC or SnPb Paste: Backward Compatibility

During the transition phase to 100% lead-free technology, lead-free components may be assembled with conventional, eutectic or near-eutectic SnPb paste. This scenario, described as "Backward Compatibility", raises the issue of how the board-level reliability of lead-free components assembled with SnPb paste compares to that of conventional 100% Pb assemblies.

Figure 9 shows cycles-to-failure for lead-free area array components ("SAC Balls") assembled with SnPb paste versus cycles-to-failure for SnPb area array components ("SnPb Balls") that were also assembled with SnPb paste. Board finish labels are given along with component names. The data was gathered from several studies[9, 28-31] where test vehicles were assembled using standard SnPb or SAC reflow profiles. In the case of "SAC ball" assemblies, the peak reflow temperature was above the melting point for typical SAC alloys (217°C). For example, for the data point[30] labeled "wbPBGA, OSP" in Figure 9, the peak reflow temperature was 222°C (soak profile) with a Time Above Liquidus (TAL) quoted in the range 60-90 seconds. The reader is referred to the original studies[9, 28-31] for more detailed information on the test vehicles, including component information for the various BGAs or CSPs labeled in Figure 9. Cycles-to-failure are given as cycles to a low percentage of failures that were either read-off failure distributions at the 0.1% failures[28] level, cycles to first failure[29] (at a cumulative failure level between 1% and 5%) or calculated at the 1% failure level when Weibull distribution parameters were available. The data points in Figure 9 are above or below the main diagonal, that is, thermal cycling test lives for SAC assemblies with SnPb paste are either better or worse than for conventional SnPb assemblies. For the four data points below the main diagonal, the life of SAC ball / SnPb paste assemblies is less than that of SnPb assemblies by 10 to 32%. Looking at data point labels in Figure 9, no definite board finish effect is apparent. Similarly, Figure 9 does not show any definite temperature profile effect. The one data point for thermal cycling between 0°C and 100°C is above the main diagonal but more data under similar conditions would have to be added in before any conclusion can be drawn with regard to the possible effect of thermal cycling profiles. In conclusion, the record for SAC balls/SnPb paste assemblies under accelerated thermal cycling conditions is mixed. To our knowledge, no life prediction model or acceleration factors are available for such mixed assemblies. Thus, we are unable to extrapolate SAC balls / SnPb paste assemblies test results to field conditions and no firm conclusion can be drawn as to the field reliability of these assemblies compared to conventional SnPb assemblies. Nevertheless, since the record under test conditions is mixed, close attention needs to be paid to the reliability of SAC balls / SnPb paste assemblies.

In the next phase of the transition to lead-free technology, lead-free components assembled with SnPb paste will eventually be assembled with SAC paste. Relevant test data[9, 28, 29, 31] for area array components with SAC balls is shown in Figure 10 where cycles-to-failure for SAC paste assemblies is plotted versus cycles-to-failure for SnPb paste assemblies. The presentation of the data is similar to that of Figure 9 with symbols and labels identifying temperature profiles, components and board finishes. All seven data points in Figure 10 are close to or above the main diagonal, suggesting that, during the transition from mixed assemblies (SAC balls / SnPb paste) to 100% lead-free boards (SAC balls / SAC paste), reliability concerns are likely minimized. More relevant data will be added to Figure 10 in the future to double-check that the spotted trend remains valid for other components and test conditions.

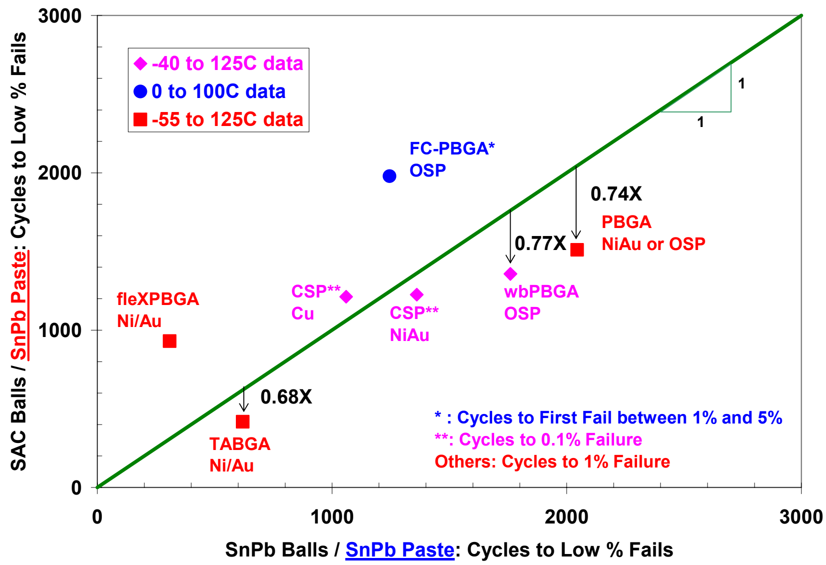


Figure 9 - Thermal Cycling Data for SAC or SnPb Ball Area Array Components Assembled with SnPb Paste. For SAC ball Assemblies, Peak Reflow Temperature is Above 217°C. Labels are for Component Names and Board Finishes

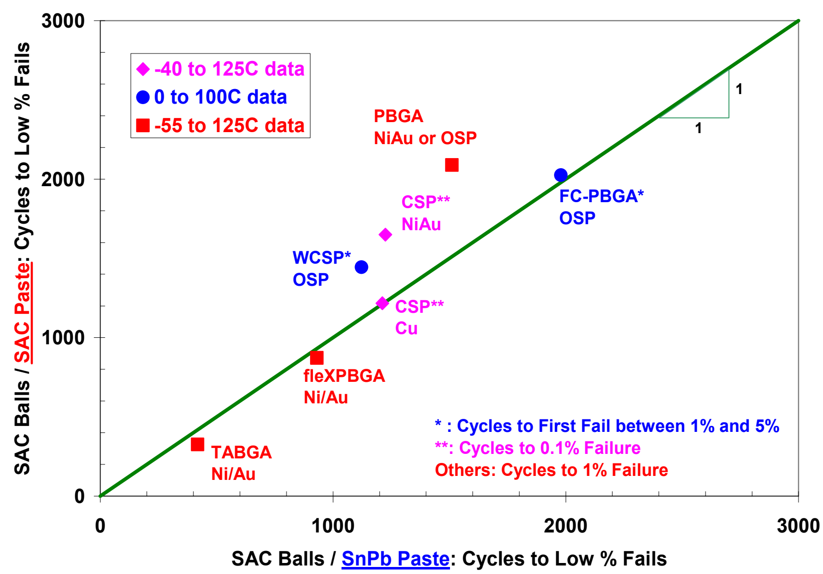
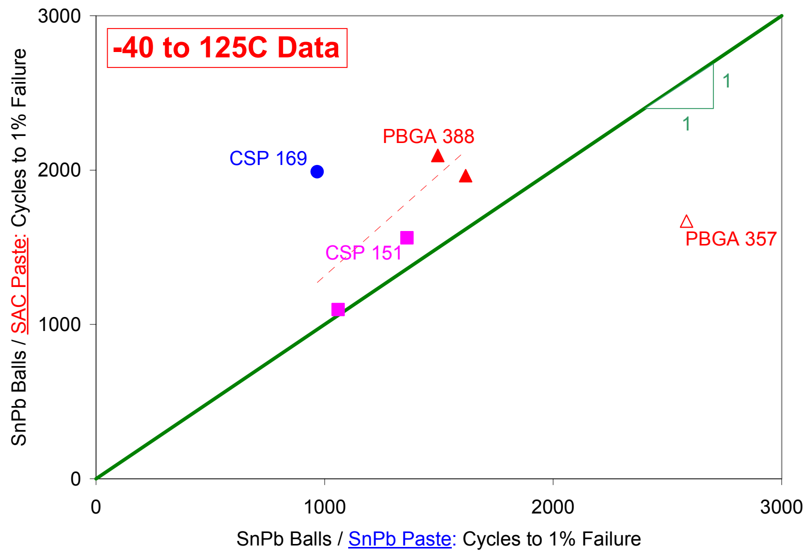


Figure 10 - Thermal Cycling Data for SAC Ball Area Array Components Assembled with SAC or SnPb Paste. For SAC Ball Assemblies, Peak Reflow Temperature is Above 217°C. Labels Give Component Names and Board Finishes

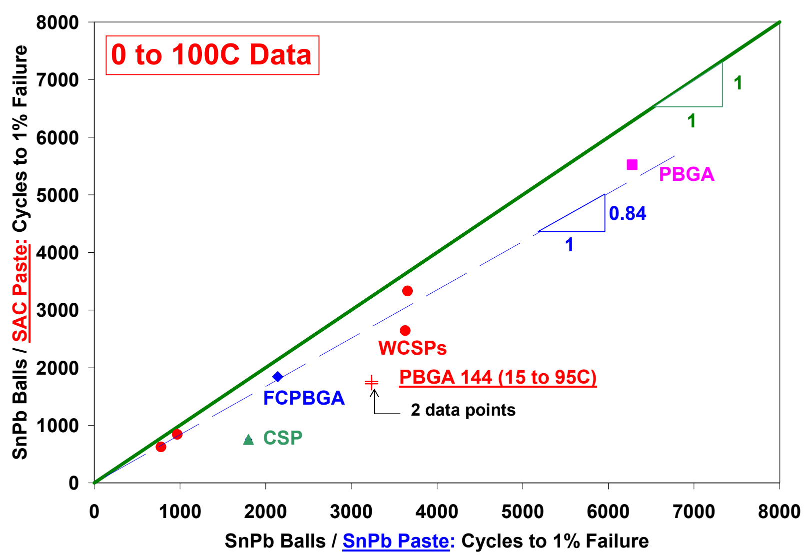
Area Array Assemblies with SnPb Balls and SAC or SnPb Paste: Forward Compatibility

Another scenario of interest during the transition to lead-free technology is that of conventional area-array components using SnPb balls and assembled with SAC paste. This scenario is often described as a "forward compatibility" situation. In Figure 11, we show cycles-to-1% failure for SnPb ball area array components assembled with SAC paste versus cycles-to-1% failure for similar components assembled with SnPb paste. The data was gathered from relevant test cells in several independent studies.[3, 11, 12, 22, 29, 32, 33] Figure 11a shows the data for assemblies that were cycled between -40°C and 125°C (6 data points). Figure 11b shows similar test data for thermal cycling under milder conditions: 0°C to 100°C (7 data points) and 15°C to 95°C (2 data points[3] for 144 I/O PBGAs assemblies with NiAu or SnCu HASL board finish).

Figures 11a and 11b suggest a strong dependence of relative trends on thermal cycling conditions. Under harsher conditions (-40/125°C data in Figure 11a), the data for the SnPb ball components using SAC paste - except for one data point labeled "PBGA 357" - falls above the main diagonal. Under milder conditions (0/100°C and 15/95°C data in Figure 11b), all data points are below the main diagonal. A trendline drawn through the 0/100°C data points in Figure 11b has a slope of 0.84, which gives an average 16% life reduction under 0/100°C thermal cycling conditions. The 15/95°C data points are below the 0/100°C trendline, suggesting further relative reliability losses under milder conditions. This raises potential reliability concerns for conventional Sn-Pb ball area-array components assembled with SAC paste.



(a)



(b)

Figure 11 - Thermal Cycling Data for SnPb Ball Area Array Components Assembled with SAC or SnPb Paste. (a) -40/125°C Data; (b) 0/100°C Data (Except for Two 15/95°C PBGA144 Data Points)

Conclusions

This paper pulled together independent test results in an attempt to put large amounts of apparently unrelated data in perspective, and to spot lead-free reliability trends and possible areas of concern for lead-free or mixed-assembly circuit boards:

- First-order test life correlations (cycles to failure vs. applied shear strains) were developed for lead-free and SnPb assemblies. The empirical correlations show different slopes for SAC, Sn0.7Cu and standard SnPb assemblies. The cross-over points of the various trendlines suggest that the rank-ordering of solder joint lives for the different alloys changes with the applied stress or strain level. The above correlations are purely empirical and should not be used to calculate acceleration factors or for life prediction purposes.
- The life test correlations show a scarcity of data for cyclic shear strains below 1%. For the most part, accelerated testing has been conducted under high stress conditions with the goal of obtaining rapid results for alloy comparison purposes.
  - When SAC test results are inferior to SnPb test results, the higher slope of SAC fatigue life correlations suggests that SAC assemblies may still outperform SnPb assemblies under mild enough thermal cycling conditions.
  - There is a definite lack of reliability test data under mild conditions, which may slow down the development and/or validation of robust life prediction tools or acceleration factors.
- The life data correlations and the analysis of mixed assembly test results did not show any clear or definite effect of common board finishes (immersion Ag, NiAu or OSP) on solder joint reliability.
- “Backward-compatibility” test results over a wide range of test cycles are mixed. Area-array assemblies using SAC balls and SnPb paste require a careful reliability assessment.
- “Forward-compatibility” test results are also mixed with a strong effect of thermal cycling conditions on cyclic life trends. Under conditions 0°C to 100°C, or even milder, area-assemblies using SnPb balls and SAC paste appear less reliable than conventional SnPb area-array assemblies.

While we tried to analyze test failure cycles that cover a wide range of conditions, components and board finishes, the analysis herein is far from exhaustive. In future work, we intend to add new data in to further exploit the correlations presented in this paper and possibly identify new parametric trends. Using two simple metrics to assess progress in SAC or lead-free reliability studies, our estimate is that the industry know-how on SAC assembly reliability is at 10 to 24% up the learning curve compared to the SnPb reliability knowledge base. This rough estimate is based on soft data given in Table 1: 1) number of publications in this author’s reliability reference lists for standard SnPb and lead-free or SAC assemblies; 2) approximate number of years of industry experience: about 50 years for SnPb assembly versus about 12 years for lead-free or SAC, using a starting date of 1992 for the first lead-free consortium project in North America under the auspices of the National Center for Manufacturing Sciences[34] (NCMS). Obviously, many lead-free reliability issues were not addressed in this paper and much work remains to be done for the industry know-how on SAC reliability to come up to par with the established SnPb reliability knowledge base.

Table 1 - Metrics of Solder Reliability Studies

Metric	**SnPb Reliability**	**SAC Reliability**	**Ratio (“SAC” column / “SnPb” Column)**
1. Author’s reference list	~ 2500 publications	~ 250 publications	10%
2. Years of Industry Experience	~ 50 years	~ 12 years	24%

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LEAD-FREE AND MIXED ASSEMBLY SOLDER JOINT RELIABILITY TRENDS

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Introduction

- **Objective: Compare lead-free vs. SnPb solder joint reliability over a wide range of circumstances**
  - Preliminary study limited to thermal cycling data

- **Where are we on the learning curve?**

METRIC	SNPB RELIABILITY	SAC RELIABILITY	RATIO (“SAC” COLUMN / “SNPB” COLUMN)
1. AUTHOR’S REFERENCE LIST	~ 2500 PUBLICATIONS	~ 250 PUBLICATIONS	10%
2. YEARS OF INDUSTRY EXPERIENCE	~ 50 YEARS	~ 12 YEARS	24%

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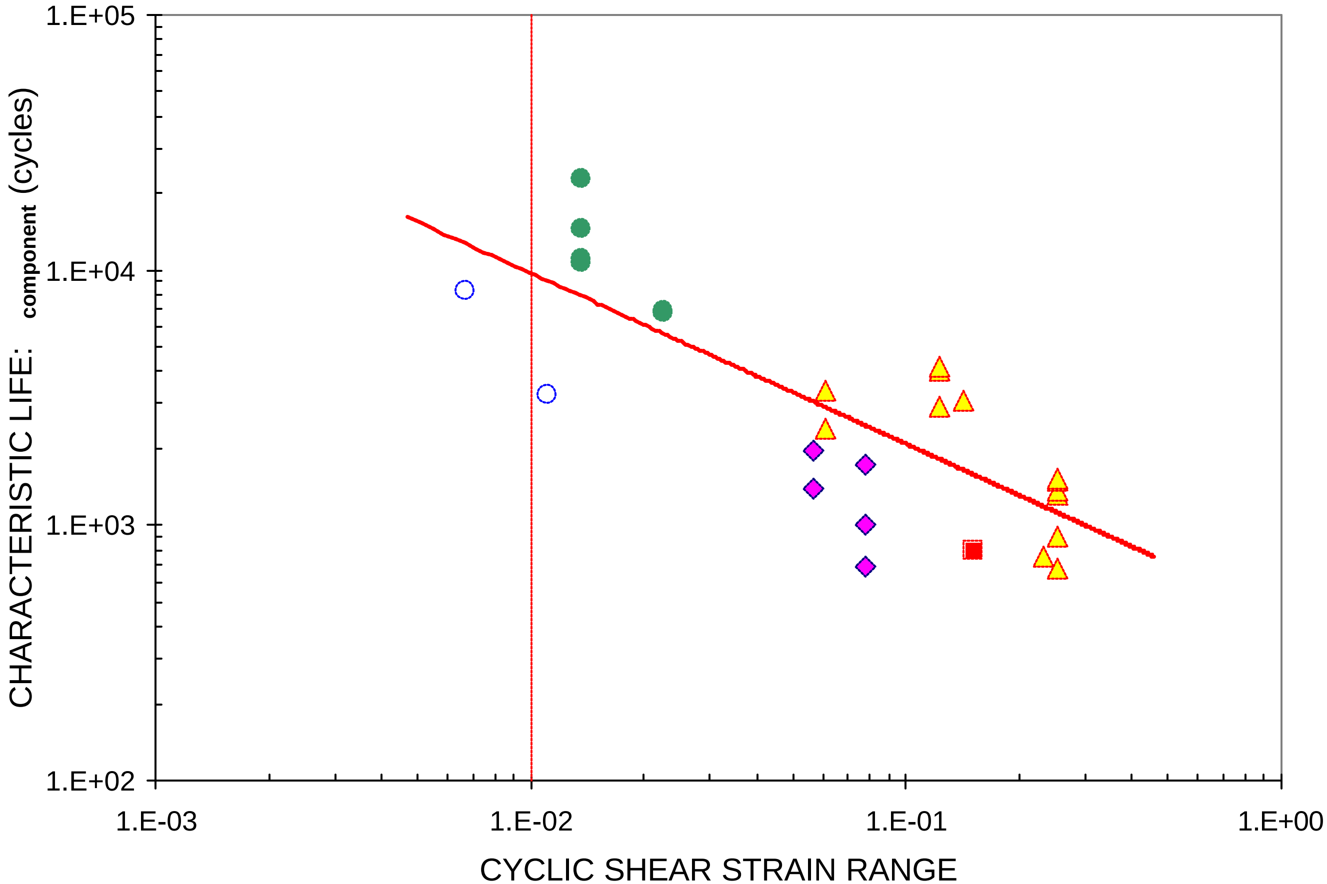
SAC Test Data



- **Coffin-Manson approach:**
  - Correlation coefficient: $R^2 \sim 0.6$