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FACTORS IMPACTING THE RELIABILITY OF ULTRALOW SILVER LEAD FREE ALLOYS

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ABSTRACT

Although the price of silver has stabilised, it remains the most expensive element of the lead free Tin silver Copper (SAC) alloys. Lowering the level of silver has a number of effects beyond simply the cost of the alloy. It has been shown that decreasing the silver can improve the drop/mechanical shock resistance, a desirable parameter for many hand held applications, but at the cost of an increase in liquidus and a drop in thermal fatigue resistance. Although this impact has been studied for low silver alloys 1-3% little work has been don on ultralow silver alloys (less than 1%). In this paper the key parameters impacting the thermal fatigue of SAC0307 are studied, as well as the delta of the thermal cycle being important the peak temperature and dwell at each end of the thermal cycle are determined to be significant contributors to the ultimate performance of the solder joint. The contribution was determined to vary with the component tested. Thus care should be taken in extrapolating the thermal cycle data from one test vehicle to an actual circuit assembly.

Key words: Low silver, Reliability

INTRODUCTION

Accelerated life testing has been used widely across the PCB assembly industry to determine the reliability and expected filed life for new designs. The reliability requirements for a circuit assembly are and always will be determined by the application that they will go into. With this in mind it is not surprising at different applications would benefit from using different alloys. High reliability lead free alloys utilising up to six different metals have been developed for applications which require a high level of thermal cycling of the final assembly [1] while alloys base on the popular near eutectic tin silver copper (SAC) formulations with low levels of silver have found favour in applications where mechanical shock is of primary interest.

Reducing the level of silver is in the alloy has generated significant interest with many assembly houses not just because of the improved mechanical shock performance but also form a price perspective as well[2]. The high cost of silver means that it has a disproportionate impact on the price of the alloy, and a small change in the silver level can significantly impact cost. Reducing the level of silver may have advantages in mechanical shock performance there are a number of less desirable changes. There is data that shows that reducing the level of silver compromises the alloys thermal cycle performance [3,4]. Reducing the level of silver will also increases the liquidus to that of the tin copper eutectic227°C, in so doing the use of such alloys is likely to require a higher peak temperatures. As well as increasing the liquidus temperature, the proportion of pure tin phase in the joint also increases, this increase will impact other properties that such as the ultimate tensile strength [5] which typically reduces with increasing tin phase. How each of these changes manifests itself in the reliability of a given joint is what will determine when these alloys can be safely utilised.

However desirable these alloys may be from a cost perspective especially the ultralow silver materials they are still required to meet all the reliability requirements for the proposed application. In this paper the iNEMI test data is reviewed to determine factors impacting the thermal cycle reliability, with the aim of trying to optimise the process by understanding the inter relationship of the key parameters in accelerated life testing, namely, the peak temperature of the thermal cycle, the ΔT of the thermal cycle and the dwell time at either end of the thermal cycle. By better defining the thermal cycle capabilities and the factors that impact them it should be easier for potential users to determine if these low cost alloys have the potential to meet their performance requirements and thus if it is worth the significant investment of performing the necessary approval testing.

EXPERIMENTAL AND METHODOLOGY

The iNEMI testing utilised a simple 4^2 factorial experimental design was used (see table 1) to investigate the effect of component (unfortunately it was not possible to look specifically at the impact of bump size since the larger pitch device was also a different size with a different number of interconnects), thermal cycle ΔT, dwell time at the ends thermal cycle and maximum thermal cycle temperature.

Table 1. Experimental Design

Parameter	Max	Min
ΔT	140ºC	100ºC
Max Temp	125ºC	100ºC
Dwell time	60 min	10 min
Component Pitch*	0.8 mm	0.5 mm

* The 0.8 mm pitch BGA component having 192 460μm SAC 305 bumps, the 0.5 mm pitch BGA component having 84 300μm SAC 305 bumps.

While there is ample anecdotal evidence that the thickness of the PWB can impact thermal cycle performance especially with very thin substrates only one thickness was used. By using a thick PWB (0.092″) the deformation of the substrate due to the components presence can be effectively eliminated, and with components on only a single side, the board was not constrained during the thermal cycling beyond the soldering of the through hold connector used for the monitoring of the connectivity of the components. Each board had 16 components of both sizes present (see Figure 1). One board was used for each of the thermal cycle conditions, yielding sufficient data to run create a reasonable Weibull failure plot and to calculate characteristic life times for each condition.

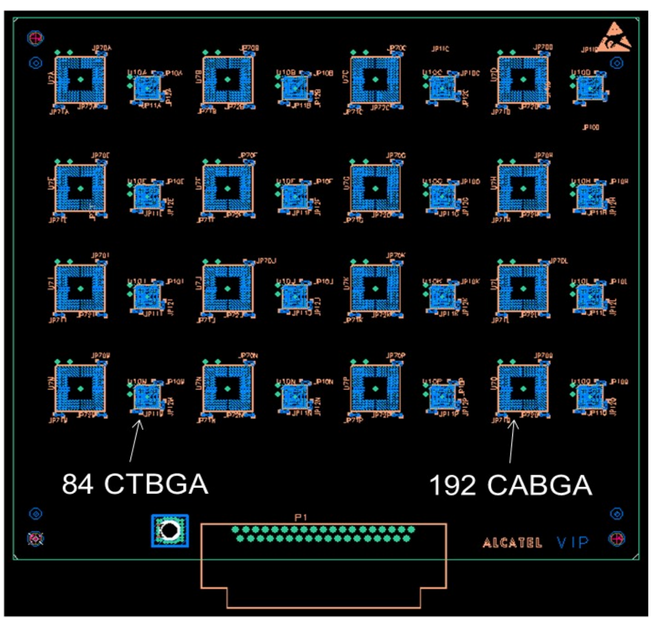

Figure 1. Test Board Layout

Thermal cycling was air to air thermal shock, and although the ramp rate was not controlled between the two set points, the dwell time was. The dwell time was not considered to have started until the board temperature had reached the zone set point and was not considered to have finished until the temperature of the assembly dropped below the zone set point (see Figure 2). In keeping with the IPC-9701 the max temperature has to be no less than the zone temperature and no more than 5ºC above the zone temperature. This approach does not eliminates the impact of changes in the ramp time due to changes in the ΔT of the thermal cycle being used. It is reasonable to assume that increasing ΔT and the will tend to increase the ramp rate, and that this in turn will impact strain rate.

A failure was determined to have occurred when the resistance of the part increases to at least 1000Ω during a single cycle, and the phenomenon was repeated at least nine more times in the next 10% cycles as per IPC-9701. Once this criteria was met the failure was defined as the cycle when the first event occurred.

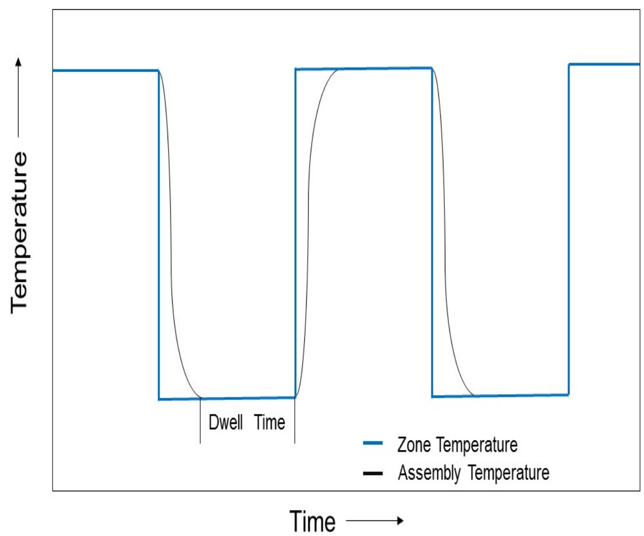

Figure 2. Schematic of Thermal Cycle

RESULTS AND DISCUSSION

The complete raw data is presented in tables 2 and 3 below. In cases where there is no data this is because either the part was defective prior to testing or the testing was stopped prior to failure.

The raw data was, initially evaluated for each component separately and, used to construct Weibull failure plots (see figures below) and from this the characteristic life (the number cycles required to achieve 62.3% failure). By consolidating the data the impact of each control parameter was evaluated, by comparison of Weibull plots and by the impact on the characteristic life. The calculated characteristic life times of each condition were then used to create a simple linear model for each component.

Table 2. Thermal Cycles to Failure for 0.8 mm BGA

ΔT (°C)	100	100	100	100	140	140	140	140
Max Temperature (°C)	100	100	125	125	100	100	125	125
Dwell Time (min)	10	60	10	60	10	60	10	60
	2984	1379	1687	1338	1710	1822	1559	884
	3199	1649	2037	1510	1711	1824	1646	962
	3262	1970	2089	1636	1921	1863	1722	977
	3454	2101	2224	1682	1960	1864	1844	1072
	3602	2138	2245	1759	2060	1941	1851	1090
	3730	2199	2286	1761	2266	1943	1899	1114
	3860	2279	2325	1822	2386	1993	1912	1216
Cycles to Failure	3886	2280	2403	1868	2387	1996	1955	1232
	3927	2319	2424	1881	2418	2056	1971	1294
	3933	2389	2436	1966	2498	2094	1990	1326
	3948	2408	2451	2109	2506	2122	2000	1360
	4208	2443	2547	2064	2611	2177	2037	1366
	4238	2634	2551	2087	2627	2212	2066	1396
	4449	2683	3006	2513	2643	2232	2097	1458
	4559	2691	3195	2268	2788	2302	2110	1514
	4622	2705	3332	2298	3046	2431	2212	1611

Table 3. Thermal Cycles to Failure for 0.5 mm BGA

ΔT (°C)	100	100	100	100	140	140	140	140
Max Temperature (°C)	100	100	125	125	100	100	125	125
Dwell Time (min)	10	60	10	60	10	60	10	60
	4490	2329	3367	2796	1009	2251	1995	1906
	4732	2707	3525	3033	1039	2647	2121	1983
	4742	2817	3997	3132	1087	2744	2218	2009
	4792	2986	4102	3141	1335	2795	2478	2042
	5091	2987	4435	3155	2464	2920	2486	2060
	5110	3197	4501	3278	3365	2946	2700	2073
	5114	3302	4514	3436	3431	3005	2712	2111
Cycles to Failure	5139	3673	4650	3502	3580	3075	2788	2204
	5510	3862	4677	3502	3582	3076	2875	2231
	5522	3970	4763	3513	3583	3082	2890	2258
	5552	4119	4922	3514	3632	3116	3061	2338
	5680	4180	4996	3606	3710	3228	3210	2340
	5850	4208	5132	3639	3859	3245	3270	2360
	5881	4589	5481	3734	3899	3342		2408
	6049	4609	5588	3913	4389	3419		2049
	6418		5646	4060	4538	4092		2586

Comparison of the Weibull plots for the 0.8 and 0.5 mm components across all the different test conditions shows the larger pitch component is actually less reliable than the finer pitch device with the overall characteristic life dropping from 3922 for the 0.5 mm component down to 2522 for the 0.8 mm component. The expected increase in reliability from the larger interconnects of the0.8 mm pitch component is most likely outweighed by the increase in stress arising from the component being approximately four times the area which results in an almost 300% increase in the length of the diagonal, generating substantially more stress on the corner interconnects. The two components have very similar slops suggesting similar fatigue mechanisms may be present in both components.

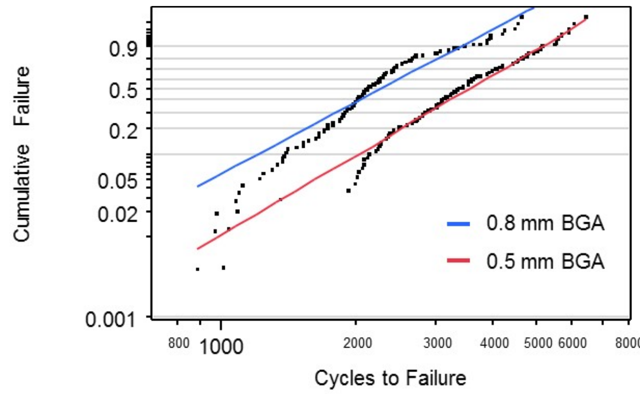

Figure 3. Weibull Plot for Different pitch BGA Components

By comparing all the data for a single peek temperature (irrespective of the ΔT or dwell time), it is possible to compare the performance of the two components with respect to that specific condition. The same can be done for the variables. The same can be done for the individual components so that the impact of changing the parameter on the performance of the different components can be determined.

One way of comparing performance is by the so called "Characteristic Life" which is the number of cycles required to get 63% of the parts to fail. This is often preferred to the time to first failure, which although important for many applications, can lead to erroneous conclusions if early failures due to defective parts. The characteristic life utilizes all the data rather than a single point, making it less sensitive to false early failure.

The overall reduction in characteristic life going from the large 0.8 mm component to the small 0.5 mm part 37% (3922 down to 2522) 4179 2930.

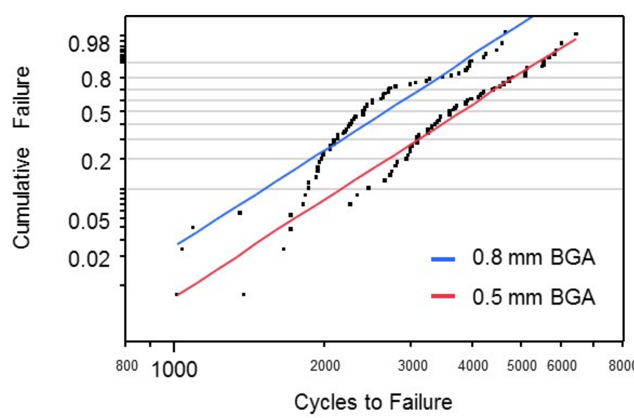

Figure 4. Effect of Component on reliability for thermal cycles that peak at 100°C.

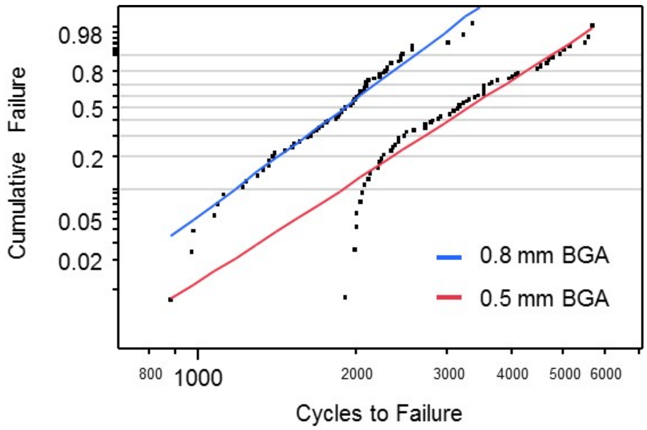

Figure 5. Effect of Component on reliability for thermal cycles that peak at 125°C.

When considering just the impact of the maximum thermal cycle temperature on the two components the calculated characteristic life drops by only 30% at 100°C (4179 down to 2930) when going from the 0.5 mm component to the o.8 mm part. This increases to 43% (3641 to 2069) when the maximum temperature is increased to 125°C.

By plotting the data for each component at the different temperatures it can be seen that increasing the maximum thermal cycle temperature has a relatively small impact on the 0.5 mm component with the characteristic life decreasing by only 13% (4179 to 3641) while the 0.8 mm component falls by more than double 29% (from 2930 to 2069), suggesting that that the solder joint is in the 0.8 mm BGA is fatiguing more quickly at elevated temperatures than the smaller 0.5mm BGA.

The Coffin-Manson [(6)] equation (equation 1) relates the level of fatigue in a single thermal cycle to the proportion of plastic deformation that the material is subjected to in each cycle. Plastic deformation being an irreversible process, unlike elastic deformation. During plastic deformation there is movement of the atoms and defects within the in the metal matrix. This can result in grain growth and ultimately slippage at grain boundaries.

Equation 1

$$Nf = \theta(\Delta\gamma)^{-\Phi}$$

Nf is the number of Cycles to failure
Δγ is the plastic strain range
Θ & Φ are constants

The level of plastic deformation is a result of a combination of the amount of strain the joint is exposed to and the creep resistance of the metal. Since both components have the same alloy the creep resistance will be constant for the two components however the creep resistance will drop with increased temperature. The difference in performance can only reasonably be assigned to an increase in strain resulting from the different geometries of the two components.

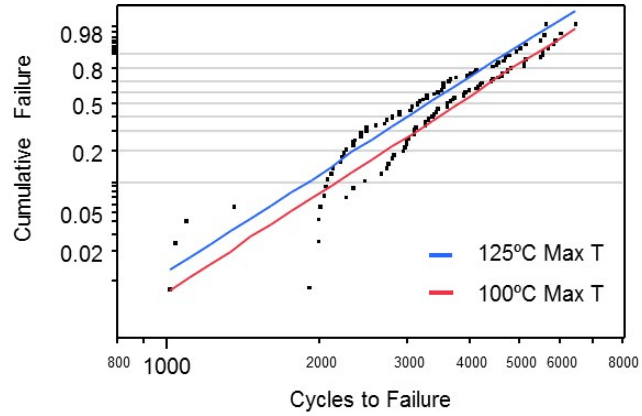

Figure 6. Weibull Plot for 0.5mm Pitch BGA Thermally Cycled to Different Maximum Temperatures.

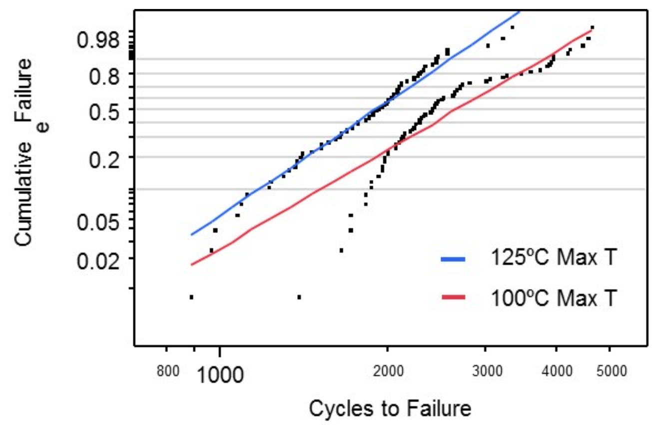

Figure 7. Weibull Plot for 0.8mm Pitch BGA Thermally Cycled to Different Maximum Temperatures.

A similar relative response is observed between the two component types when comparing the impact of increasing the range of the thermal cycle (ΔT) (see figures 8 and 9), with the large pitch component exhibiting decreased reliability. The impact of even a modest 100°C ΔT is significant with the characteristic life dropping by 37% from 4650 to 2920, interestingly there is less of a change in the relative performance when the ΔT is increased to 140 °C which exhibits a 32% change (3028 cycles down to 2074).

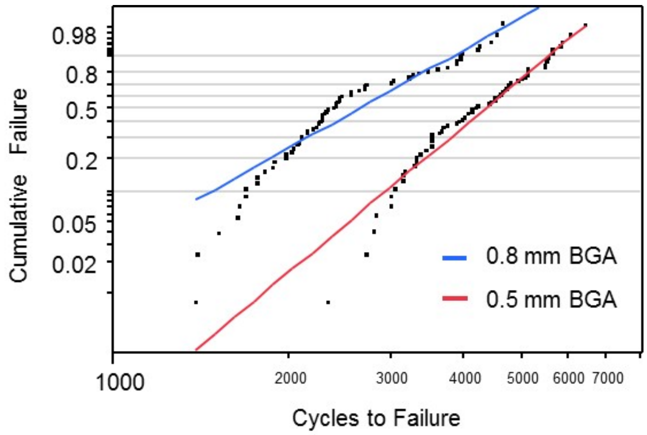

Figure 8. Effect of Component on reliability for parts Cycled through ΔT of 100°C

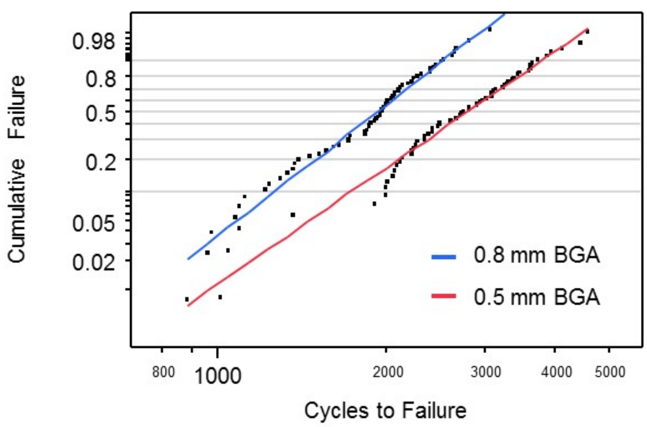

Figure 9. Effect of Component on reliability for parts Cycled through ΔT of 140°C

Again by comparing the performance of the individual components at the two different conditions additional insight can be gained. The 0.5 mm component shows a consistent performance under the two conditions with the failure curves being close to parallel. The 0.8 mm component on the other hand exhibits a convergence of the two Weibull curves, for early failures, inspection of the data revealed no unusual early failures and that the shape of the curve is due to a tail in late failures for the 100°C ΔT. The reason for this is not immediately apparent but may due to interactions between the different mechanisms operation during the different thermal cycles, e.g. strain rate and yield point.

Assuming the same principal as above that the change in reliability is a result of the increase in plastic deformation through each cycle, then this time the driver is likely to be the increased stress in the joints from the increase strain resulting from the larger thermal cycle, the other thing to consider is the ramp rat as strain rate can impact both UTS and yield points increasing the ΔT can also impact the ramp rate, the larger 0.8 mm components bay be partially buffered to this hence the different performance at high ΔT.

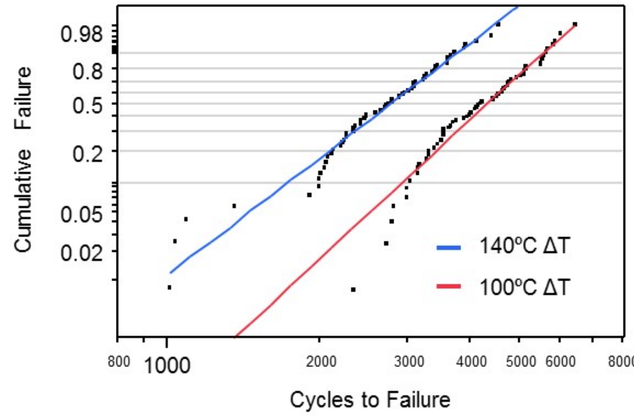

Figure 10. Weibull Plot for 0.5mm Pitch BGA Thermally Cycled through Different ΔT

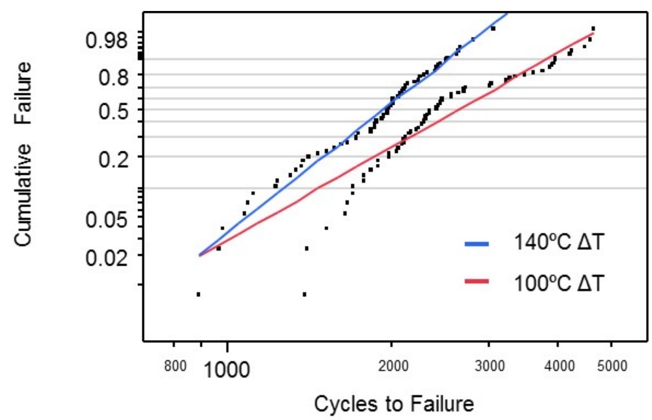

Figure 11. Weibull Plot for 0.8mm Pitch BGA Thermally Cycled through Different ΔT

Finally the impact of dwell time must be considered. It has often been the case that the dwell time is reduced to a minimum to increase the number of cycles that can be completed in a given amount of time, (as boards get bigger and more densely populated and the ΔT and peak temperatures increase it becomes increasingly likely that for some assemblies, or parts of assemblies, only a cursory amount of time is spent at the two extremes). The assumption being that dwell time has minimal or no impact on the reliability. The use of liquid to liquid helps to insure that the assemblies achieve the necessary temperatures with short dwell times. If indeed dwell time was of no significance in determining reliability then there should be no difference in performance between the two components. Analysis of the data clearly shows this not to be the case (see figures 12 and 13). The characteristic life of the large 0.8 mm component is 33% lower only 2945 compared with 4439 for the 0.5 mm pitch component. Increasing the dwell time not only reduces the reliability but also increases the differential with the 0.8 mm component now having a 39% shorter characteristic life only 2039 compared to 3337. The fact that there is a difference between the two components may suggest that the parts are not reaching equilibrium during the dwell and that this is causing the differential performance. If this is in fact the case then components with a large ΔT and a low peak temperatures may be expected to exhibit the least difference.

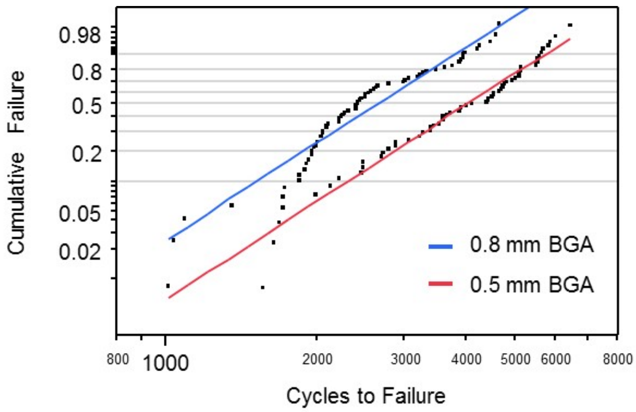

Figure 12. Effect of Component on Reliability for Parts with a Dwell time of 10 minutes

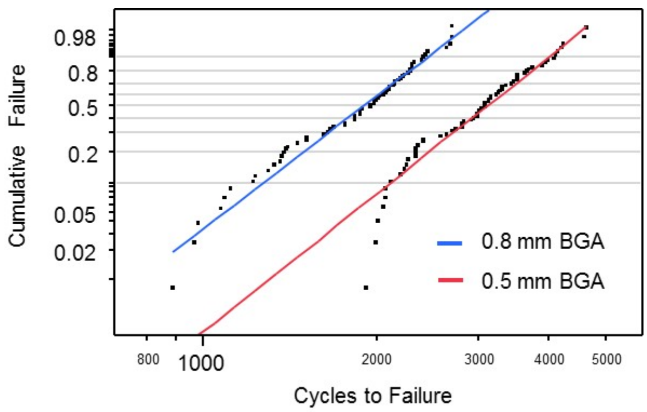

Figure 13. Effect of Component on Reliability for Parts with a Dwell time of 60 minutes

If the above supposition is correct the impact of dwell time should be dependent on both the ΔT and the peak temperatures then this should be manifest by significantly different slopes in the Weibull curves for the two dwell times.

Inspection of figures 14 and 15 below show such an effect with both components showing significantly different slopes for the two dwell times. In such circumstances comparing characteristic life times can be of limited value, because of the impact of cross terms, and is better discussed when considering data modelling. However for completeness the effect of dwell time on characteristic for the consolidated data has been performed. For the large 0.8 mm BGA the characteristic life is 31% lower with the extended dwell (2039 compared to 2949) and only 25% (4439 dropping to 3337) for the 0.5 mm BGA. The reason for the differential performance with respect to the dwell time is due to the fact that the degree plastic deformation experience by the joints is not simply a matter of the dwell time itself but of factors driving it namely, the strain (related to ΔT) and the creep resistance (related to the peak temperature). More strain and higher peak temperature will result in more plastic deformation.

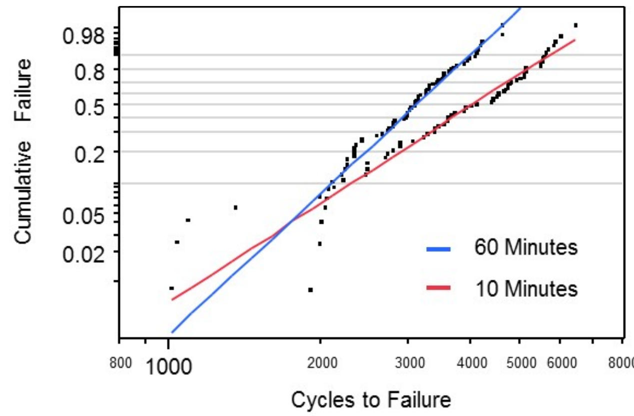

Figure 14. Weibull Plot for 0.5mm Pitch BGA Thermally Cycled with Different Dwell Times

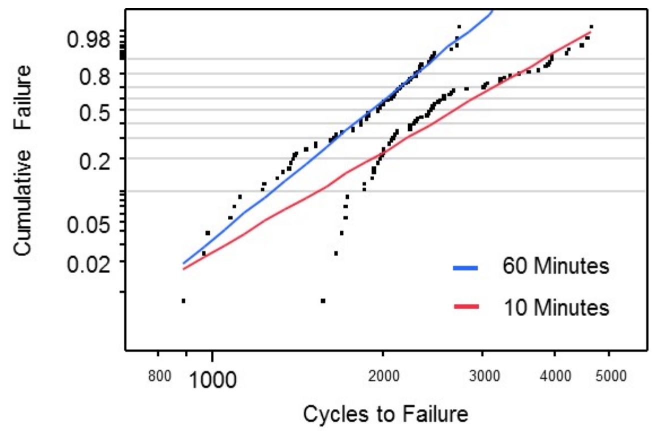

Figure 15. Weibull Plot for 0.8mm Pitch BGA Thermally Cycled with Different Dwell Times

The characteristic life was calculated for each tests condition and is presented in table 4 below. By performing a simple least squares fit on this data and including only the three control parameters and no cross terms a crude predictive formula can be determined for each component (see equation 2 and 3 and figures 16 and 17 below). The fit for this simple model for 0.5mm 0.8 mm pitch components yields a P value of 0.026 and 0.018 respectively confirming the quality of fit. The 95% confidence intervals on the graphs show clearly the pit falls if extrapolating data rather than interpolating, and hence the need to choose the carefully the conditions of any DOE.

Table 4. Characteristic Lives for Different Test Conditions

ΔT (°C)	Max Temperature (°C)	Dwell Time (min)	Component Pitch (mm)	Characteristic Life
100	100	10	0.5	5594
100	100	60	0.5	3856
100	125	10	0.5	4921
100	125	60	0.5	3581
140	100	10	0.5	3402
140	100	60	0.5	3235
140	125	10	0.5	2843
140	125	60	0.5	2293
100	100	10	0.8	4074
100	100	60	0.8	2410
100	125	10	0.8	2630
100	125	60	0.8	1995
140	100	10	0.8	2503
140	100	60	0.8	2138
140	125	10	0.8	2003
140	125	60	0.8	1329

Equation 2 Multiple Regression model for 0.5 mm pitch component

$$CL_{.5} = 11769 - 38.6\Delta T - 25.5P_t - 19.0\,D_t$$

$CL_{.5}$ is the characteristic life of the 0.5 mm pitch component.
ΔT is the range on the thermal cycle (°C)
P_t is peak temperature of the thermal cycle (ºC)
D_t is the well time (min)

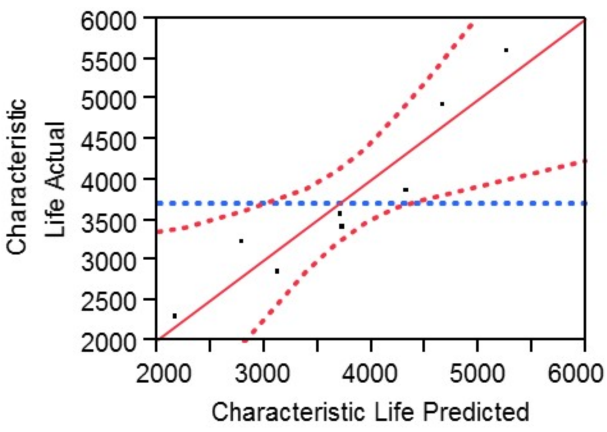

Figure 16. Actual against Predicted Plot of Characteristic Life with 95% confidence interval for 0.5 mm pitch Component

Equation 3

$$CL_{.8} = 8885 - 19.6\Delta T - 31.7P_t - 16.7\,D_t$$

$CL_{.8}$ is the characteristic life of the 0.8 mm pitch component.
ΔT is the range on the thermal cycle (°C)
P_t is peak temperature of the thermal cycle (ºC)
D_t is the well time (min)

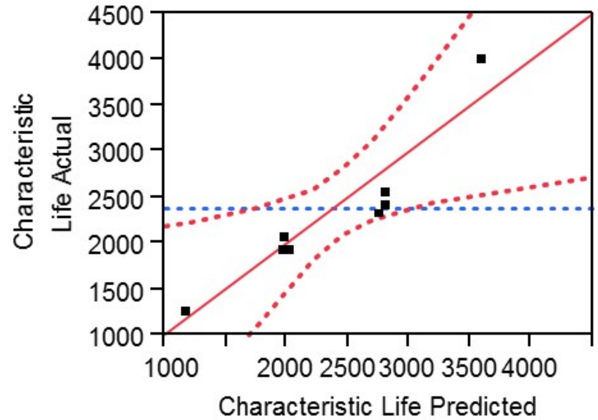

Figure 16. Actual against Predicted Plot of Characteristic Life with 95% confidence interval for 0.8 mm pitch Component

However the dwell time data suggest that cross terms could be important, and although the residuals decreased the so did the quality of fit. In order to determine the role of any cross terms additional data will be required.

CONCLUSIONS

All of the changes in reliability observed above can be explained by changes in the level of plastic deformation generated in each thermal cycle as per the Coffin-Manson equation. These changes in plastic deformation are most likely due a combination of changes in the creep resistance at different temperature, variable levels of induced strain in the joint and the rate of strain relief.

The data yielded viable linear models for both components, suggesting that it may be possible to generate simple models, for components, to predict the characteristic life, under given conditions. It would be desirable to extend the work to include the impact of component size and to have additional data to better understand the impact of cross terms.

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REFERENCES

1) Hector Steen, Ph.D. and Brian Toleno, Ph.D. Development of a Lead-Free Alloy for High-Reliability, High-Temperature Applications. APEX 2009
2) Brook Sandy. Ronald C. Lasky, PhD. Choosing a Low-Cost Alternative to SAC Alloys for PCB Assembly. SMTA International 2011
3) Vikram Srinivas, Nicholas Williard, Preeti Chauhan and Michael Osterman. Board Level

Reliability Evaluation of Low Silver (Ag) Content Lead-Free Solder Joints At Low Strain Rates. International Conference on Soldering and Reliability Proceedings
4) Gregory Henshall, Ph.D. Robert Healey, Ranjit S. Pandher, Ph.D. Keith Sweatman, Keith Howell, Richard Coyle, Ph.D. Thilo Sack, Polina Snugovsky, Ph.D. Stephen Tisdale and Fay Hua, Ph.D. iNEMI Pb-Free Alloy Alternatives Project Report: State of the Industry.
5) Fangjie Cheng, Feng Gao, Jianyou Zhang, Wenshan Jin[1] and Xin Xiao. Tensile properties and wettability of SAC0307 and SAC105 low Ag lead-free solder alloys. Journal of Materials Science 10.1007/s10853-010-5231-8
6) R W.W. Leea, L.T. Nguyena,, G.S. Selvaduray Solder joint fatigue models: review and applicability to chip scale packages. Microelectronics Reliability 40 (2000) 231±244