An Acceleration Model for Lead-Free (SAC) Solder Joint Reliability under Thermal Cycling

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Abstract

The electronics industry has successfully transitioned from Sn/Pb to Pb free (LF) solder for computing and consumer electronics applications. However, there is no industry-wide standardized LF solder joint reliability model (neither empirical nor FEA-based) available for solder fatigue reliability assessment. A LF solder fatigue model has been proposed in this paper based on a 3-parameter modified Coffin-Manson approach. The proposed model showed best fit to the experimental data (17 pairs of temperature cycle test data) from different sources for multiple package types and sizes including various test conditions. The model fit to the experimental data was excellent and the error was less than 6%. This analysis showed that the LF acceleration factor (AF) model is not significantly different from the Sn/Pb model and proposed model provides best fit to experimental results.

1. Introduction

While the electronics industry has successfully completed the transition to Pb-free (LF) technology for computing and consumer electronics applications, there is still no standardized LF solder joint reliability model (neither empirical nor FEA-based) available for solder fatigue. Numerous studies have been published regarding the thermal cycling reliability of SnAgCu solder joints under accelerated test conditions [e.g., 1-5]. The acceleration factor (AF) models for LF are of particular interests to the electronics industry for the simple reason that the solder joint reliability in field power cycling conditions can be predicted in a simple yet accurate manner. Pan et al [6] first attempted to obtain an acceleration factor model using several thermal cycle profiles, in which the temperature range, maximum temperature and the cycle time or frequency were systematically varied. However, it has been shown in several studies [7,8] that this model prediction is not well correlated with experimental results. Studies by Salmela [8], and Zhang and Clech [7] evaluated several different types of AF models. Those AF models also include models based on the compact strain energy analysis and the finite element analysis. It showed that the FEA based models have limited success in predicting the AF factors, especially when test conditions and package types vary dramatically.

In this paper, a LF acceleration factor model is proposed based on the Norris-Landzberg equation. A total of 17 pairs of experimental data suitable for acceleration factor computations, taken from Intel and industry published test data, were used to calibrate and support the model. These data come from various types of packages, such as FCBGA, CBGA, CSP, QFP and die-side capacitor packages. The test data also include extended cycle time effect and maximum temperature as well as the temperature range effect.

2. Review: Lifetime Prediction Models for Solder Joint Fatigue

Solder joint fatigue is considered as low-cycle failure. Therefore almost all lifetime prediction models originate from the Coffin-Manson's equation

$$N(\Delta\varepsilon_p)^n = C \tag{1}$$

where N is the number of cycles to failure, $\Delta\varepsilon_p$ is the plastic strain range per cycle, n is an empirical material constant, and C is a proportionality factor. A fatigue failure always begins at a local discontinuity such as the area of stress concentration near solder/pad interface. Plastic strain accumulates each cycle resulting in failure. The acceleration factor (AF) can be defined based on equation (1) as follows

$$AF = \frac{N_1}{N_2} = \left(\frac{\Delta\varepsilon_p{}^1}{\Delta\varepsilon_p{}^2}\right)^{-n} \tag{2}$$

where N_1 and N_2 are fatigue life under two different cyclic loading conditions, which correspond to the plastic strain range $\Delta\varepsilon_p{}^1$ and $\Delta\varepsilon_p{}^2$ respectively. Equation (2) has been widely used since the field life (e.g. N_1) can be related to a test life (e.g. N_2) with an empirical material constant n if the plastic strain range at each loading condition can be calculated. Norris and Landzberg [9] assumed that the plastic strain range is proportional to the temperature excursion range, and further introduced two more factors to account for the effects of temperature-cycling frequency f and the maximum temperature Tmax of the solder material. By doing this, the AF equation obtains the form:

$$AF = \frac{N_{\text{field}}}{N_{\text{test}}} = \left(\frac{f_{\text{field}}}{f_{\text{test}}}\right)^{-m}\left(\frac{\Delta T_{\text{field}}}{\Delta T_{\text{test}}}\right)^{-n}\left(e^{\frac{E_a}{k}\left(\frac{1}{T_{\max,field}}-\frac{1}{T_{\max,test}}\right)}\right) \tag{3}$$

where " *field* " and " *test* " denote the field and the test condition, respectively. The Norris-Landzberg model can also be used to compare two different field or test conditions. E_a is the activation energy, and k is Boltzmann's constant. For SnPb eutectic solder,

$$m=1/3,\ n=1.9,\ \text{and}\ E_a/k = 1414 \tag{4}$$

Pan et al [6] obtained a new set of parameters based on their experiments for SnAgCu soldered components, including ceramic Ball Grid Array (CBGA) components, Chip Scale Packages (CSP), and Thin Small-Outline Packages (TSOP). The new set of coefficients are

m=0.136, n=2.65, and $E_a/k = 2185$ (5)

Engelmaier [10] proposed an analytical form of the Coffin-Manson's equation to obtain the plastic strain range analytically. The original form of Engelmaier's model consists of two parts: the physical part and the statistical part by a 2-parameter Weibull distribution. The combination of these two parts can be presented as a number of cycles N (x%) until x% of the population have failed as

$$N(x\%) = \frac{1}{2}\left(\frac{2\varepsilon_c}{\varepsilon_p}\right)^{-\frac{1}{c}}\left(\frac{\ln(1-0.01x)}{\ln 0.5}\right)^{\frac{1}{\beta}} \quad (6)$$

where ε_p is the potential cyclic fatigue damage at complete stress relaxation, and ε_c is the fatigue ductility coefficient, c is the fatigue ductility exponent, and β is the shape parameter of the Weibull distribution. ε_p for leadless packages can be presented as

$$\varepsilon_p = \frac{FL\Delta\alpha\Delta T_e}{h} \quad (7)$$

where F is empirical non-ideality factor, L is half of the maximum distance between component solder joints (Distance form Nnutral point), $\Delta\alpha$ is the absolute difference in coefficients of thermal expansion of the component and the substrate, ΔT_e is equivalent cycling temperature range and h is solder joint height. ΔT_e can be presented as

$$\Delta T_e = \left|\frac{\alpha_s\Delta T_s - \alpha_c\Delta T_c}{\Delta\alpha}\right| \quad (8)$$

where s denotes substrate and c denotes component. For leaded packages, the strain range is approximated as

$$\varepsilon_p = \frac{FK_d(L\Delta\alpha\Delta T_e)^2}{Ah} \quad (9)$$

where K_d is the diagonal flexural lead stiffness and A is the effective solder bond area. Salmela [12] recalibrated the Engelmaier model by replacing the fatigue ductility coefficient by temperature-dependent and solder material specific correction term. Osterman [11] presented a new set of constants based on the Engelmaier model for SnAgCu solder.

An extension to the original Coffin-Manson equation is to use the plastic strain energy density instead of the plastic strain range to represent the cumulative damage on solder joint. Equation (1) and (2) based on the plastic strain energy density range can be re-written as

$$N(\Delta W_p)^m = C' \quad (10)$$

$$AF = \frac{N_1}{N_2} = \left(\frac{\Delta W_p{}^1}{\Delta W_p{}^2}\right)^m \quad (11)$$

It is noted that the empirical material constant (exponent m) will be different from that when the plastic strain range is used.

Clech [13] developed an analytical model to compute the plastic strain energy range. The stabilized hysteresis loops are computed for shear deformations driven by the global CTE mismatch between board and component, and for normal stresses and strains driven by local CTE mismatches between solder and the interconnected parts. The methodology was first developed by Hall [14, 15] in the simulation of measured hysteresis loops for SnPb assemblies. The method applies to any shape of a periodic temperature profile, including trapezoidal, saw-tooth and sine profiles.

Finite Element Analysis (FEA) has been utilized extensively to calculate the plastic strain range or plastic strain density range [1-5, 16-19]. Finite element models can take into consideration the interaction among components in an assembly with little or no geometric simplification. It also offers the advantage of being able to solve the full field equations and provide stress/strain information on all solder joints. However, this does not necessarily translate the FEA approach into one with superior accuracy in predicting the fatigue life over other simplified empirical models. There are several FEA based SnAgCu fatigue life models such as [17], [18], and [19]. However, many of them showed limited success.

3. Experimental Data Collection

In the following, the experimental data from various sources will be listed, and used to recalibrate the Norris Landzberg model. In order to achieve this, the test data must the following criteria:

1. The experimental data must be available to calculate the life with 50% failure rate and the requirement on the statistical pattern is met;
2. The test data must include two temperature cycling conditions, with all specific cyclic loading details included to obtain the temperature range, maximum temperature and the cyclic frequency.

Table 1 shows those test data taken from published papers by Intel on FCBGA, socket, and die side capacitor (DSC) packages. Both SAC105 and SAC405 data are shown in Table 1 and the temp behavior is similar for both alloys. The experimental test procedures were provided in our previous paper [1]. An Air to air temperature cycle test was used. The in-situ monitoring on the resistance change were correlated to solder joint cracks using dye and pull test and cross-section analysis. In order to investigate the SnAgCu fatigue performance under the extended cycle time, several special temperature cycle profiles have been defined. For socket, the total cycle time is 480 minutes per cycle to investigate the SnAgCu performance in power cycling conditions.

Table 1: SAC thermal cycling data collection from Intel (refs.1, 3)

Solder Alloy	Package	TC Conditions 1 & 2	AF test
SAC405	FCBGA	-40°C to 85°C, cycle time 46min	1.2
		-40°C to 85°C, cycle time 76min	
SAC105	CSP-BGA	-40°C to 125°C, cycle time 30min	2.5
		-25°C to 100°C, cycle time 30min	
SAC405	Socket	-25°C to 100°C, cycle time 60min	2.1
		-25°C to 100°C, cycle time 480min	
SAC405	CSP	-40°C to 85°C, cycle time 46min	1.4
		0°C to 125°C, cycle time 120min	
SAC405	FCBGA	-40°C to 85°C, cycle time 46min	3.2
		0°C to 125°C, cycle time 120min	
SAC405	FCBGA	-40°C to 85°C, cycle time 46min	2.5
		0°C to 125C, cycle time 120min	
SAC405	Die-side capacitor package	-25°C to 100°C, cycle time 30min	1.5
		-25°C to 125°C, cycle time 30min	
SAC405	Die-side capacitor package	-25°C to 125°C, cycle time 30min	1.9
		-55°C to 125°C, cycle time 30min	

Table 2 gives the test data used by Zhang and Clech [7]. For PBGA assembly, the accelerated thermal cycling conditions were thermal cycling between 0°C and 100°C with 10 minutes ramps (up and down), 10 minutes dwells at 0°C, and 10 minutes or 60 minutes at 100°C, respectively. For CBGA, three temperature cyclic profiles were used, but with the fixed total cycle time as 80 minutes. Total cycle time was used for acceleration factor calculation.

Table 2: Test conditions and acceleration factors from test (ref. 7)

Solder Alloy	Package	TC Conditions 1 & 2	AF test
SAC305	PBGA	0°C to 100°C, cycle time 90min	1.2
		0°C to 100°C, cycle time 48min	
SAC305	CBGA	0°C to 100°C, cycle time 80min	2.5
		30°C to 80°C, cycle time 80min	
SAC305	CBGA	-40°C to 125°C, cycle time 80min	2.1
		30°C to 80°C, cycle time 80min	

Table 3 lists the package information and test data from ref. [18] for SAC305/405. In order to evaluate the reliability of solder joints, accelerated temperature cycle tests were conducted on various packages. The data were generated on packages of sizes varying from 8x8mm to 27mmx27mm and various die sizes. All packages used in this study used electrolytic NiAu plating on the ball lands and the test boards had OSP surface finish. Three test conditions were used to generate the test data as shown in Table 3. These temperature cycle conditions cover the range of accelerated conditions typically used by the industry to evaluate solder joint reliability for various applications.

Table 3, Test conditions and acceleration factors from test (ref. 18)

Alloy	Package	Test conditions TC1 & TC2	AF Test
SAC	flexBGA	0°C to 100°C, cycle time 30min	3.5
		-55°C to 125°C, cycle time 30min	
SAC	flexBGA	0°C to 100°C, cycle time 30min	3.7
		-40°C to 125°C, cycle time 60min	
SAC	Plastic CSP	-40°C to 125°C, cycle time 60min	1.5
		-55°C to 125°C, cycle time 30min	
SAC	CBGA	0°C to 100°C, cycle time 30min	2.5
		-40°C to 125°C, cycle time 60min	

CALCE [11] investigated the SnAgCu performance for CLCC, TQFP and TSOP packages under thermal cycling, as shown in Table 4. In that study, two temperature-cycling conditions were applied to independent groups of test assemblies. The first test subjected a set of test assemblies to a temperature cycle of -55 to 125°C. The second test subjected another set of test specimens to a smaller temperature cycle of -20 to 80°C. For both tests, the dwell time at the maximum temperature was 30 minutes and dwell time at the minimum temperature was 10 minutes.

Table 4 Test conditions and acceleration factors from test (ref. 11)

Solder Alloy	Package	TC Conditions 1 & 2	AF Test
SAC Sn3.9 Ag 0.7 Cu	CLCC20	-20°C to 80°C, cycle time 76min	1.2
		-55°C to 125°C, cycle time 60min	
SAC Sn3.9 Ag 0.7 Cu	TQFP 144	-20°C to 80°C, cycle time 70min	2.5
		-55°C to 125°C, cycle time 60min	
SAC Sn3.9 Ag 0.7 Cu	TSOP50	-20°C to 80°C, cycle time 76min	2.1
		-55°C to 125°C, cycle time 60min	

4. Acceleration Model

SAC solder is more creep resistant than Sn/Pb solder under most conditions. However, temperature, and cycle time still have significant impact on the thermal fatigue life of SAC solder joints, as shown from the test data above. The impact of the extended cycle time on solder joint reliability for both Sn/Pb and SAC 405 has been characterized by Vasudevan et al [1] and showed no cross-over for both Sn/Pb and LF even after 8 hrs cycle time. Both Sn/Pb and LF solder showed decrease in fatigue performance with the increase in dwell time. Solder joint fatigue life scales inversely with cyclic shear strain range ($\Delta\Gamma$) for both Sn/Pb and LF. High strain components ($\Delta\Gamma = \{L.\ \Delta\alpha.\ \Delta T/h$) such as large ceramic BGA and CLCC showed a temperature-dependent behavior [20] for solder fatigue performance. Osterman [20] showed that there is a cross-over in temperature cycle performance for SAC solder compared to Sn/Pb for high strain packages such as CLCC. Their study showed that for the same temperature range, if the Tmax is 100°C or lower, LF performed better than Sn/Pb. However, when Tmax was 125°C, LF showed poor performance compared to Sn/Pb. This behavior was hypothesized as a potential shift in solder fatigue damage mechanism. Based on Intel test data, when Tmax was below 100°C and the ramp rate was below 15°C/min, the LF temperature cycle results showed improved solder fatigue performance compared to Sn/Pb [1]. Typically when cyclic shear strain is lower than ~6%, the SAC alloy showed better fatigue performance. As a general design practice for reliability, the recommended strain ranges are lower than 6% (1-2% range typical). The failure mode, failure signature, the location, and the interface separation for LF solder are similar to Sn/Pb solder in temperature cycle test, even in extended cycle time testing [1]. Therefore, the modified Coffin-Manson equation proposed by Norris and Landzberg should still be a viable empirical acceleration model for SAC alloys. For this reason, we used the same form as in equation (3) for our SAC solder acceleration model. The coefficient in the temperature range, frequency, and T_{max} terms were fit from the experimental results for SAC solder joints at various thermal cycle conditions. Different from Pan et al's extension, the cyclic frequency is sill used other than dwell time. A nonlinear curve fit was performed to simultaneously fit the three coefficients with the thermal cycling test results given in Tables 1-4. In order to have a consistency with the original Norris-Landzberg model, some adjustment has been made. The resulting acceleration model is given as follows

$$AF = \frac{N_1}{N2} = \left(\frac{f_1}{f_2}\right)^{-m} \left(\frac{\Delta T_1}{\Delta T_2}\right)^{-n} \left(e^{\frac{E_a}{k}\left(\frac{1}{T_{\max,1}} - \frac{1}{T_{\max,2}}\right)}\right) \tag{12}$$

with

m=0.33, n= 1.9, and E_a/k = 1414

Surprisingly, the coefficients are very similar to the original values of the Norris-Landzberg model for Sn/Pb assembly when all the data were used. Although it has been generally accepted that SnAgCu performs better than Sn/Pb, the acceleration factor, in particular, in terms of the extended cycle time and maximum temperature range effect, is similar to Sn/Pb. The individual data fit for a particular set with respect to the cycle time or maximum temperature may not be ideal using the above coeffients, but the overall fit is very good. The acceleration model in equation (12) was used to compare the predicted and observed acceleration factor (AF), as shown in Figure 1. Figure 1 shows that the acceleration model gives satisfactory results when compared with the data generated from various sources. The error in mean based on the 17 data sets for the new model is 5.8%. It can be seen that the test conditions and data collected above have a wide spread, with different temperature range, different maximum temperature and, in particular, the cycle time ranging from 45 minutes to 480 minutes. The newly proposed model fit all 17 pairs of test data with an average deviation less than 6% and data used were from LF SAC alloy system (3 to 4.0% Ag and 0.5 to 0.7 % Cu range). One can perform similar analysis for low cyclic strain components and expected n values will be at the higher end of Sn/Pb C-M coefficients (2.1 to 2.2 range). It is surprising to see a general fit to the original Norris and Landzberg model and hence for LF solder, the original Sn/Pb solder fatigue model can be used. Depending on the package type and material choices, the fatigue model coefficients can vary slightly.

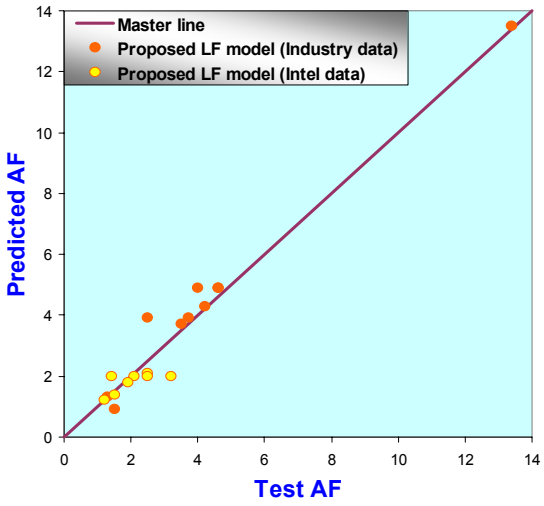

Figure 1 Acceleration factor (AF) predicted with equation (12) vs. observed AF from test data in various sources

5. Extended Cycle Time Effect and Failure Analysis

One of the key concerns for the LF acceleration factor estimation is the incorporation of the effect of LF creep. The effect of extended cycle time on temperature cycle performance of LF solder was compared with Sn/Pb in Fig. 2. The improved fatigue performance in 8 hrs cycle time test for LF was observed. Solder joint analysis was performed for both passing and failing samples to understand the failure mechanism, mode, location etc. Both X-section and dye and peel tests were used to understand the solder crack signature, size, frequency and location. The failure signature, failure

mode, location and mechanism were the same for both LF and Sn/Pb samples. Fig. 3 shows the X-section images for Sn/Pb and LF samples post 1400 cycles of 8 hrs test with bigger size solder crack for Sn/Pb compared to LF. There is no change in failure location, mode, or the type of interface separation (board side cracks) between 60 and 480 minutes cycle time. Fig. 3 showed for the same temperature cycle readout LF had a lower crack size compared to Sn/Pb even at 480 min cycle time. This suggests the frequency term for LF is similar to Sn/Pb for the extended cycle time (use condition).

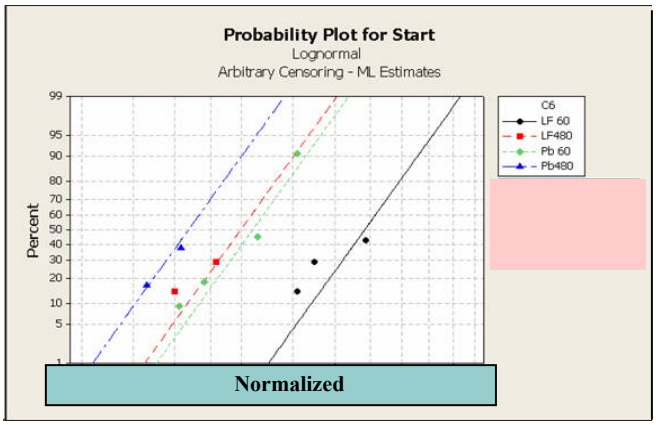

Fig.2 LF (SAC 405) solder showed improved fatigue performance in temp cycle test compared to Sn/Pb in the extended cycle time test (60 min vs. 480 min cycle time and temperature range is from -25 to + 100°C.). The component tested is BGA socket with enabling load.

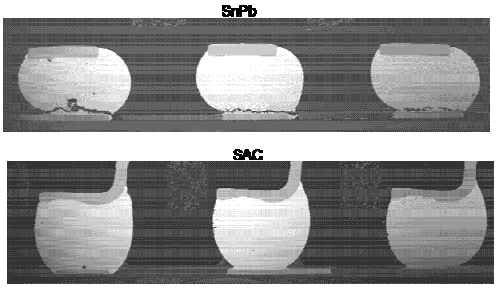

Figure 3 X-section images of post 1400 cycles samples showed the full solder crack for Sn/Pb (top image) compared LF (SAC 405) solder which showed only minor crack (10%, bottom image)) at board side. The temp cycle test parameters: cycle time is 480 min and temperature range is from -25 to + 100 °C). The component tested is BGA socket with enabling load**.**

6. Discussion

As we have discussed earlier, Pan et al [17] proposed an acceleration model based on the Norris-Landzberg model. Fig. 4 plotted the comparison between these two models for the available test data. It is observed that the Pan et al's model presented a reasonable fit when the acceleration factor is less than 3.5. Beyond this range, the model showed large discrepancies with the experimental results. Although Pan's own data fit very well with the predicted values, Syed's data, CALCE's data do not fit the line very well [12]. The error in mean based on all 17 data set was plotted in Fig. 4 for the model proposed here against Pan et al's model.

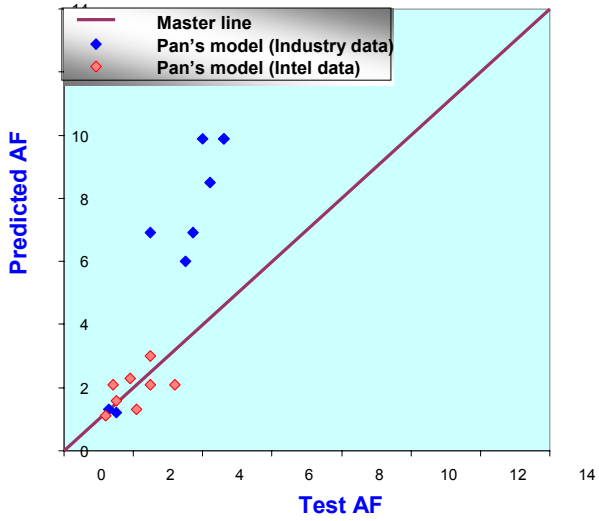

Fig.4. Pan et al' model fit

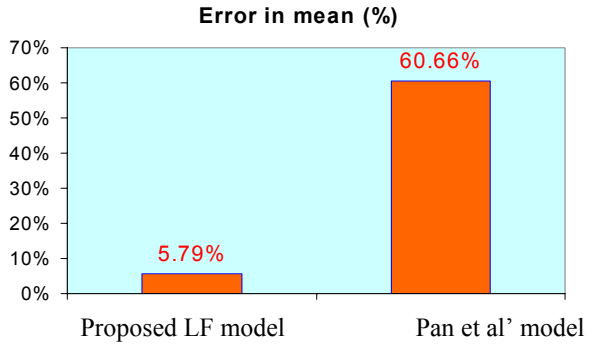

Fig. 5 the comparison of the proposed model with Pan et al's model

There are a number of thermal fatigue life prediction models based on the FEA analysis or analytical solutions using strain energy density range or plastic strain range (or nonlinear strain range). It is clear that when running FEA simulations, it is easier to take into account structural details than the relatively simple analytical models. However, the accuracy of the FEA-based models is not always satisfactory. Fig. 6 summarized some FEA results predictions. It should be noted that the FEA results or analytical results plotted in Fig. 6 are from different FEA based life prediction models but are consistent with each of their predictions.

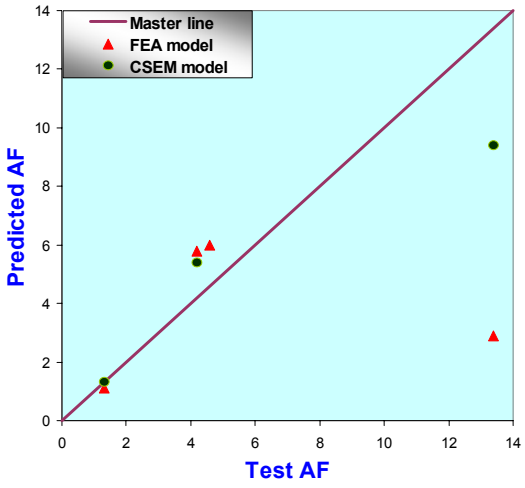

Fig. 6 the comparison of the FEA model prediction with experimental results

The popularity of Norris-Landeberg model is the ease of use and the terms used are only related to the profile of the temperature cycling test. This makes the use of the equation appealing as no information on the test vehicles; -neither the geometry nor the material properties is required. This may sound a bit odd, as it is well known that these factors have significant effect on the reliability performance of the solder joints. However, in terms of the acceleration factor (AF), which is the ratio of the lifetime in field and test, those effects are cancelled out.

The FEA based AF results often predict that the geometry or material properties effects are not cancelled out. It has been noted that the current FEA does not take considerations of the solder softening or aging effect into simulation. This might be one of reasons that the discrepancy using FEA comes from.

It has been debated whether or not a saturation effect needs to be considered for the frequency term since solder joint damage in a certain thermal cycle 'saturates' when the joint reaches a point where the majority of the relaxation has occurred. In our test, we have designed a couple of tests with extended cycle time to make sure that the proposed model is calibrated to include the long cycle time effect. It has shown that, similar to the SnPb assembly, the SAC will eventually reach to a point where the stress is completely relaxed.

The paper also examined the AF predictions based on finite element analysis. Although various existing finite element models were supposed to give a good prediction for certain types of packages and certain test conditions, the FEA results showed poor prediction to other data when package format and accelerated conditions change. One of the reasons that FEA models did not predict well is that the material aging effect is not taken into consideration in current lead-free models in FEA implementation. However, FEA analysis is efficient in predicting the worst-case and qualitative trend for a given family of packages under same test conditions. Future effort will be focused on combining the FEA model approach with the empirical model approach to assess LF reliability

7. Conclusion

In this paper a new set of AF model constants based on the Norris-Landzberg equation has been proposed. The proposed model has been validated using thermal cycle tests. The thermal cycling experimental data from various sources with various types of packages, such as FCBGA, CBGA, CSP, QFP, socket, and die-side capacitor packages have been used for determining the model fit. The temp cycle test conditions have a wide spread, with different temperature range, different maximum temperature and different cycle time, in particular, the cycle time ranging from 15 minutes to 480 minutes. The model fit to experimental data was excellent and the error was less than 6%. This analysis showed that the LF acceleration factor (AF) model is not significantly different from the Sn/Pb model and proposed model provides the best fit to the experimental results.

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