Accumulated Creep Strain and Energy Density Based Thermal Fatigue Life Prediction Models for SnAgCu Solder Joints

Ahmer Syed
Amkor Technology, Inc.
1900 S. Price Road
Chandler, AZ 85248
asyed@amkor.com

Abstract

Pb free solder is fast becoming a reality in electronic manufacturing due to marketing and legislative pressures. The industry has pretty much concluded that various versions of SnAgCu solder alloy offer the best alternative for eutectic Sn/Pb solder currently in use. With the current trend of cheaper, faster, and better electronic equipment, it has become increasingly important to evaluate the package and system performance very early in the design cycle using simulation tools. This requires life prediction models for new solder alloy systems so that the package-to-board interconnect reliability can be predicted for various environmental and field conditions.

This paper describes in detail the life prediction models for SnAgCu solder joints. The models are based on published constitutive equations for this alloy and thermal cycle fatigue data on actual components. The approach uses advanced finite element modeling and analysis techniques and is based on mechanics of deformation. Both accumulated creep strain and creep strain energy density based models are developed. The model has been correlated with a number of data points and predicts life within 25% in most cases. The framework of modeling and prediction methodology described here is fully compatible with the framework used for SnPb solder previously.

Introduction

The reliability of solder joints is one of the most important factors when selecting a package for a particular application. The CTE and stiffness mismatch between the package and the board results in thermal stresses in solder joints during temperature and power cycling. The damage caused by these stresses accumulates as the electronic assembly is subjected to multiple cycles, ultimately causing failures of solder joints. This is a very well documented failure mode for electronic assemblies and a wealth of data is available in the literature for SnPb solder. Due to this reason, the reliability of Pb free solder joints is an important factor for selecting the proper replacement of SnPb solder. Based on various studies conducted, the industry as a whole has converged towards SnAgCu solder alloy (with different compositions) to replace SnPb solder. Based on various studies conducted, the industry as a whole has converged towards SnAgCu solder alloy (with different compositions) to replace SnPb solder.

The reliability of SnAgCu solder joints has been a subject of major research in electronic industry and a number of researchers have published data [1, 2, 3] showing SnAgCu performs better or worse than SnPb solder, depending on the components tested and test conditions employed. While more test data is being gathered under accelerated test conditions, it is also becoming apparent that this will not be enough due to rapid implementation of this soldering system. Today, electronic industry uses electronic components using lead frame or laminate technology with countless number of packages in various lead counts, lead/pitch sizes. Since every component has a different interconnect reliability behavior, it is unrealistic and cost prohibitive to generate test data for every case. The interconnect reliability also depends on other factors such as the motherboard thickness and actual end use application and data generated on one test condition may not be useful for all. With the current trend of cheaper, faster, and better electronic equipment, it has become increasingly important to evaluate the package and system performance for its intended application very early in the design cycle using simulation tools. The life prediction of solder joints is an important part of this evaluation and models are needed to virtually qualify a package without extensive test data. This requires a life prediction model, which is based on damage mechanisms and can predict life accurately.

Developing a life prediction model for solder joints requires four main ingredients and all of these contribute significantly to the accuracy of life prediction model:
- Constitutive equation and material properties for the applicable range of stress conditions,
- A damage mechanism based methodology based on constitutive behavior of the material,
- Actual test data on real components including failure mechanism, and
- Simulation to calculate the response of solder joint under different stress conditions.

Using the above four ingredients, the author has proposed a life prediction model for SnPb solder joints previously [4, 5]. This model has been validated with more than 75 data points and predicts life within 25% in most cases. This proven approach is used here again to develop the life prediction model for SnAgCu solder joints.

Actual test data on various packages is generated and the same package attributes and test conditions are simulated using published constitutive equations for SnAgCu solder. The solder joint response (partitioned creep strain, total creep strain, and creep strain energy density) are then used to determine the parameters of damage mechanism based life prediction models. The life prediction models reported here are only applicable for thermal and power cycle fatigue, where the

A Note to reader: This paper was originally published in ECTC 2004 conference proceedings (pp 737 – 746), however, due to errors in data processing the constants for life prediction models published in the original paper were not accurate. These constants, along with associated figures, have been corrected here.
Constitutive Models for SnAgCu solder

The melting point of SnAgCu (Ag: 3.0 – 4.0%, Cu: 0.5 to 1.0%) is typically observed as 217°C. This means that the homologous temperature (the ratio of operating and melting temperature in absolute scale) is about 0.47 at -40°C. It is well documented that creep plays a very important role in deformation behavior of materials at homologous temperatures close to and above 0.5 if the loading rate is slow enough for creep deformations to occur. Since in actual use conditions, the temperature cycle duration is in the order of minutes to days and the homologous temperature is more than 0.5, solder joints formed by using SnAgCu solder alloy are expected to deform primarily due to creep.

Recently, a number of papers have been published [6, 7, 8, 9] on the constitutive equation for creep deformation for SnAgCu alloy for compositions currently in considerations. Wiese et al [6] studied the creep behavior of bulk, PCB sample, and Flip Chip solder joint samples of Sn4.0Ag0.5Cu solder and identified two mechanisms for steady state creep deformation for the bulk and PCB samples. They attributed these to climb controlled (low stress) and combined glide/climb (high stress) behavior and represented steady state creep behavior using double power law model.

Schubert et al [7] combined data from different sources and from their own testing on different compositions of SnAgCu solder (Sn3.8Ag0.7Cu, Sn3.5Ag0.75Cu, Sn3.5Ag0.5Cu, and Castin™). They also identified two regions for stress-strain rate behavior, but postulated the high stress region as power law break-down region, and chose hyperbolic sine function to represent creep data.

Zhang et al [8] generated their data on single lap shear specimen of Sn3.9Ag0.6Cu solder alloy. The also modeled the steady state creep behavior using hyperbolic sine function postulating power law break-down at high values of stress. Finally, Morris et al [9] used double power law constitutive model to represent creep data on single lap shear specimens of Sn3.0Ag0.5Cu solder joints. The stress exponents of 6.6 and 10.7 were suggested for the low and high stress regions.

The above constitutive equations and their respective parameters, converted to tensile stress-strain rate format, are shown in Table 1. The reported modulus, CTE, and Poisson’s ratio values are also included for the respective model, wherever provided. It should be noted that while steady state creep deformation is usually attributed to distinct regions - and different regions have been suggested for creep deformation of SnAgCu by different researchers - these regions are identified as “Mechanism 1” and “Mechanism 2” in the following to avoid multiple subscripts.

The above constitutive models as well as measured data from [9, 10] are plotted in Figure 1 for three different temperatures and are compared with published constitutive model of SnPb solder [11]. The figure clearly shows that the predicted steady state creep rate for SnAgCu solder is two to four orders of magnitude lower than that for SnPb solder for the same temperature at low stress levels. As the stress increases, all models for SnAgCu show steeper slope of strain rate vs. stress curve compared to SnPb solder with different cross-over points depending on the constitutive model and the temperature. This means that except for very high stress values, SnAgCu is generally more creep resistant than SnPb solder. This partly explains why solder joints made with this particular solder tend to last longer in temperature cycle tests except for the stiffer assemblies which result in higher stresses [1, 2, 3].

Table 1: Constitutive Relations for SnAgCu Solder

<table>
<thead>
<tr>
<th>Reference</th>
<th>Constitutive Model</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wiese et al [6]</td>
<td>( \dot{\varepsilon}_{cr} = A_1 \exp \left( \frac{-H_1}{kT} \right) \left( \frac{\sigma}{\sigma_n} \right)^{n_1} + A_2 \exp \left( \frac{-H_2}{kT} \right) \left( \frac{\sigma}{\sigma_n} \right)^{n_2} )</td>
</tr>
<tr>
<td>Schubert et al [7]</td>
<td>( \dot{\varepsilon}_{cr} = A_1 \left[ \sinh(\alpha \sigma) \right]^n \exp \left( \frac{-H_1}{kT} \right) )</td>
</tr>
<tr>
<td>Zhang et al [8]</td>
<td>( \dot{\varepsilon}_{cr} = A_1 \left[ \sinh(\alpha \sigma) \right]^n \exp \left( \frac{-H_1}{kT} \right) )</td>
</tr>
<tr>
<td>Converted to tensile form</td>
<td>Double power law:</td>
</tr>
<tr>
<td>Morris et al [9]</td>
<td>( H_1/k = 11425, n_1 = 6.6 ), ( H_2/k = 9020, n_2 = 10.7 ), ( G(MPa) = 27360 - 46.667T(°K) )</td>
</tr>
</tbody>
</table>

Comparing the creep curves for SnAgCu from different constitutive models, the steady state creep behavior for this alloy seems to be bounded is a narrow band even though there are differences between samples preparation, test methods, and alloy composition. It should be noted that all plots in Figure 1, except for data from [10], are based on constitutive models, which are themselves fitted from actual data. The plots show that constitutive model proposed by Schubert et al [7] and Zhang et al [8] predict very similar behavior at low stresses but start diverging at higher stresses (around 30 MPa). On the other hand, the model proposed by Wiese et al [6], predicts lower creep rate at low stresses (below 30 MPa) but higher rate than Schubert’s model at high stresses.

A Note to reader: This paper was originally published in ECTC 2004 conference proceedings (pp 737 – 746), however, due to errors in data processing the constants for life prediction models published in the original paper were not accurate. These constants, along with associated figures, have been corrected here.
The actual data from [10], however, shows different behavior depending on the temperature. It correlates better with Wiese’s model at lower temperatures but falls close to Schubert’s and Zhang’s model at high temperatures. This difference can be attributed to significantly different alloy composition for this data (Sn3.0Ag0.5Cu) compared to the other data generated on higher Ag percentage.

Because of narrow band in data scatter, any of these constitutive models can be employed to simulate the deformation behavior of SnAgCu solder joints. However, the models given by Equation 1 and 2 in Table 1 are selected here as the solder composition is closer to one used to generate the test data and because of similar modulus values reported.

**Figure 1: Comparison of Creep Models for SnAgCu.**
where \( \varepsilon_{cri} \) is the steady state creep rate for stress level \( \sigma \).

Realizing that the numerator term within the summation sign is the creep strain accumulated during time \( \Delta t \), the summation for all steps \( n \) within a cycle gives the Accumulated Creep Strain, \( \varepsilon_{acc} \), for the whole cycle. Thus, the above Equation 4 can be simplified as

\[
N_f = \left( \frac{1}{C'} \right)^{1} \left( \varepsilon_{acc} \right)^{-1}
\]

(5)

The above models were originally developed with a limited set of data points [14] but have since been validated with more than 75 data points.

A similar approach is attempted here for SnAgCu solder using the constitutive equations given by Equations 1 and 2. The constitutive model from Equation 1 is a double power law model and creep strain and energy density can be partitioned into their respective mechanisms. On the other hand, the constitutive model in Equation 2 does not separate the two damage mechanisms and partitioning of creep strain or energy density is not attempted.

The determination of life prediction model parameters requires actual test data measuring the cycles to failure during temperature cycle tests (\( N_f \)), and some way of quantifying the strain or strain energy density during the temperature cycle. In the following sections the test data is first described followed by simulation methodology to calculate solder joint response.

**Solder Joint Reliability Test Data**

In order to evaluate the reliability of solder joints, accelerated temperature cycle tests were conducted on various packages comparing the reliability of SnAgCu solder with that of SnPb eutectic solder. Table 2a lists the test data points used here for life prediction model development. The data was generated on packages of sizes varying from 8x8 mm to 27 x 27mm and various die sizes. The packages were constructed of three substrate materials, four ball pitches, and four ball sizes to cover the range of BGAs and CSPs.

The daisy chained packages were assembled using either SnAgCu (4.0Ag0.5Cu or 3.9Ag0.5Cu) or SnPb balls and were mounted on test boards using SnAgCu or SnPb paste, respectively. The test boards of various thickness’ had alternate daisy chains so one or more nets were formed after package assembly on board. All packages used in this comparison used electrolytic NiAu plating on the ball lands and the test boards had OSP surface finish.

The assembled boards were placed inside thermal cycle chambers and cycled according to prescribed condition. Three test conditions were used to generate this data:

- TC1: -40 to 125°C temp cycle, 15 minutes ramps and dwells, 1 cycle per hour,
- TC2: -55 to 125°C, 12 minutes ramps and 3 minutes dwells, 2 cycles/hour, and
- TC3: 0 to 100°C, 10 minutes ramps and 5 minutes dwells, 2 cycles/hour.

These temperature cycle conditions cover the range of accelerated conditions typically used by the industry to evaluate solder joint reliability for various applications. The temperature profiles mentioned above were measured at the test boards during the cycling and are not the chamber profiles. The testing also employed in-situ resistance measurement to detect failures. The resistance of each electrical net was measured every two minutes and was compared with the threshold resistance of 300 ohms. A net is considered as failed at the first instance when its resistance exceeded the threshold value followed by ten additional such instances within 10% of the time of first failure. The failures
were also confirmed manually within a week of first occurrence. The failure data was further analyzed by Weibull analysis software to determine Weibull parameters (slope $\beta$ and characteristic life $\varepsilon$) and the mean life. Note that the mean life is not the characteristic life and is calculated from $\beta$ and $\varepsilon$ parameter using Gamma function.

Table 2a: Package and test condition for board level reliability tests

<table>
<thead>
<tr>
<th>Data Point</th>
<th>Package Type</th>
<th>Substrate Type</th>
<th>Body Size</th>
<th>I/O</th>
<th>Pitch</th>
<th>Die Size</th>
<th>Pad Type</th>
<th>Pad Size</th>
<th>Ball Dia</th>
<th>Test Type</th>
<th>Board Thickness</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>CABGA</td>
<td>Laminate</td>
<td>15 x 15</td>
<td>208</td>
<td>0.8</td>
<td>8.5 x 8.5 x 0.265</td>
<td>SMD</td>
<td>0.4</td>
<td>0.46</td>
<td>TC1</td>
<td>1.0</td>
</tr>
<tr>
<td>2</td>
<td>CABGA</td>
<td>Laminate</td>
<td>15 x 15</td>
<td>256</td>
<td>0.65</td>
<td>10 x 10 x 0.265</td>
<td>SMD</td>
<td>0.32</td>
<td>0.4</td>
<td>TC2</td>
<td>0.8</td>
</tr>
<tr>
<td>3</td>
<td>CABGA</td>
<td>Laminate</td>
<td>8 x 8</td>
<td>64</td>
<td>0.8</td>
<td>4.8 x 4.8 x 0.29</td>
<td>SMD</td>
<td>0.4</td>
<td>0.46</td>
<td>TC1</td>
<td>1.6</td>
</tr>
<tr>
<td>4</td>
<td>CABGA</td>
<td>Laminate</td>
<td>8 x 8</td>
<td>64</td>
<td>0.8</td>
<td>4.8 x 4.8 x 0.29</td>
<td>SMD</td>
<td>0.4</td>
<td>0.46</td>
<td>TC2</td>
<td>1.6</td>
</tr>
<tr>
<td>5</td>
<td>Ceramic BGA</td>
<td>Ceramic</td>
<td>8 x 8</td>
<td>64</td>
<td>0.8</td>
<td>None</td>
<td>SMD</td>
<td>0.4</td>
<td>0.46</td>
<td>TC1</td>
<td>1.6</td>
</tr>
<tr>
<td>6</td>
<td>Ceramic BGA</td>
<td>Ceramic</td>
<td>8 x 8</td>
<td>64</td>
<td>0.8</td>
<td>None</td>
<td>SMD</td>
<td>0.4</td>
<td>0.46</td>
<td>TC3</td>
<td>1.6</td>
</tr>
<tr>
<td>7</td>
<td>CBVGA</td>
<td>Laminate</td>
<td>12 x 12</td>
<td>288</td>
<td>0.5</td>
<td>7.1 x 7.1 x 0.175</td>
<td>SMD</td>
<td>0.25</td>
<td>0.3</td>
<td>TC1</td>
<td>0.8</td>
</tr>
<tr>
<td>8</td>
<td>fleXBGA</td>
<td>Tape</td>
<td>12 x 12</td>
<td>144</td>
<td>0.8</td>
<td>6.4 x 6.4 x 0.3</td>
<td>SMD</td>
<td>0.3</td>
<td>0.46</td>
<td>TC1</td>
<td>1.6</td>
</tr>
<tr>
<td>9</td>
<td>fleXBGA</td>
<td>Tape</td>
<td>12 x 12</td>
<td>144</td>
<td>0.8</td>
<td>6.4 x 6.4 x 0.3</td>
<td>SMD</td>
<td>0.3</td>
<td>0.46</td>
<td>TC2</td>
<td>1.6</td>
</tr>
<tr>
<td>10</td>
<td>fleXBGA</td>
<td>Tape</td>
<td>12 x 12</td>
<td>144</td>
<td>0.8</td>
<td>6.4 x 6.4 x 0.3</td>
<td>SMD</td>
<td>0.3</td>
<td>0.46</td>
<td>TC3</td>
<td>1.6</td>
</tr>
<tr>
<td>11</td>
<td>PBGA</td>
<td>Laminate</td>
<td>27 x 27</td>
<td>256</td>
<td>1.27</td>
<td>10 x 10 x 0.30</td>
<td>SMD</td>
<td>0.65</td>
<td>0.75</td>
<td>TC2</td>
<td>1.6</td>
</tr>
<tr>
<td>12</td>
<td>TSCSP</td>
<td>Tape</td>
<td>12 x 12</td>
<td>288</td>
<td>0.5</td>
<td>7.1 x 7.1 x 0.175</td>
<td>SMD</td>
<td>0.24</td>
<td>0.3</td>
<td>TC2</td>
<td>0.8</td>
</tr>
</tbody>
</table>

Table 2b: Board level reliability test results for SnAgCu and SnPb solder joints

<table>
<thead>
<tr>
<th>Data Point</th>
<th>Package Type</th>
<th>Body Size</th>
<th>I/O</th>
<th>1st</th>
<th>Failure</th>
<th>SnAgCu Solder</th>
<th>SnPb Eutectic Solder</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>1st</td>
<td>Failure</td>
<td>Weibull Slope</td>
<td>Weibull Char. Life (Cycles)</td>
</tr>
<tr>
<td>1</td>
<td>CABGA</td>
<td>15 x 15</td>
<td>208</td>
<td>8.92</td>
<td>3717</td>
<td>3520</td>
<td>2539</td>
</tr>
<tr>
<td>2</td>
<td>CABGA</td>
<td>15 x 15</td>
<td>256</td>
<td>15.4</td>
<td>4096</td>
<td>3960</td>
<td>1856</td>
</tr>
<tr>
<td>3</td>
<td>CABGA</td>
<td>8 x 8</td>
<td>64</td>
<td>8.36</td>
<td>4843</td>
<td>4570</td>
<td>2445</td>
</tr>
<tr>
<td>4</td>
<td>CABGA</td>
<td>8 x 8</td>
<td>64</td>
<td>9.81</td>
<td>3263</td>
<td>3103</td>
<td>2205</td>
</tr>
<tr>
<td>5</td>
<td>Ceramic BGA</td>
<td>8 x 8</td>
<td>64</td>
<td>7.08</td>
<td>445</td>
<td>417</td>
<td>340</td>
</tr>
<tr>
<td>6</td>
<td>Ceramic BGA</td>
<td>8 x 8</td>
<td>64</td>
<td>9.55</td>
<td>1103</td>
<td>1047</td>
<td>982</td>
</tr>
<tr>
<td>7</td>
<td>CBVGA</td>
<td>12 x 12</td>
<td>288</td>
<td>5.81</td>
<td>2005</td>
<td>1890</td>
<td>1700</td>
</tr>
<tr>
<td>8</td>
<td>fleXBGA</td>
<td>12 x 12</td>
<td>144</td>
<td>19.06</td>
<td>2948</td>
<td>2868</td>
<td>2369</td>
</tr>
<tr>
<td>9</td>
<td>fleXBGA</td>
<td>12 x 12</td>
<td>144</td>
<td>20.4</td>
<td>2792</td>
<td>2720</td>
<td>1902</td>
</tr>
<tr>
<td>10</td>
<td>fleXBGA</td>
<td>12 x 12</td>
<td>144</td>
<td>15.7</td>
<td>10370</td>
<td>10027</td>
<td>5042</td>
</tr>
<tr>
<td>11</td>
<td>PBGA</td>
<td>27 x 27</td>
<td>256</td>
<td>7.2</td>
<td>6812</td>
<td>6381</td>
<td>3656</td>
</tr>
<tr>
<td>12</td>
<td>TSCSP</td>
<td>12 x 12</td>
<td>288</td>
<td>175</td>
<td>296</td>
<td>275</td>
<td>NA</td>
</tr>
</tbody>
</table>

Table 2b lists the Weibull parameters and the mean life for both SnPb and SnAgCu solder joints for each data point. The data shows that while SnAgCu solder joints had a higher reliability for most cases SnPb solder joints lasted longer in some cases. The measured mean life covers a range of data from 275 cycles to 10027 cycles for SnAgCu and 416 to 5953 cycles for SnPb solder joints, respectively.

In all cases reported here, the solder joints failed at package interface. Figure 2 shows a typical cross-section of failed joint showing crack very close to intermetallic on package side.

![Figure 2: Typical failed SnAgCu solder joint cross-section.](image)

Finite Element Simulations

The above test data points were simulated in finite element analysis using ANSYS™ to calculate the accumulated creep strain or energy density during each temperature cycle. The details of the simulation approach have been described elsewhere [5] and are not repeated here. Briefly, the modeling approach involves a global-local method where a 3-D global model (1/4th or 1/8th symmetric) model is generated in the first step using SOLID185 elements in ANSYS, encompassing all geometric details of the package-board assembly and linear material properties. The model is analyzed for a unit temperature drop using sub-structuring analysis methods. The super-element so generated is then used in a detailed model of the critical solder joint using SOLID185 elements. This detailed solder joint model includes the geometric shape of the joint as well as intermetallics and interfacing package and board pads. The super-element is also added to this model to get the effect of package stiffness. The solder material is modeled using creep and temperature dependent properties. The model is then analyzed for one or two complete temperature cycles, simulating the actual profile as much as possible. The output from this simulation includes the accumulated creep strain or energy density (ANSYS Output parameters: NL, CREQ and SEND, CREEP). A volume averaging technique is then employed to calculate the accumulated creep strain or energy density for 25 micron thick

A Note to reader: This paper was originally published in ECTC 2004 conference proceedings (pp 737 – 746), however, due to errors in data processing the constants for life prediction models published in the original paper were not accurate. These constants, along with associated figures, have been corrected here.
layers of solder at package and board interface, respectively. These layers contain two elements across the thickness to mitigate any stress singularity issues [14]. Figure 3 shows a sample finite element model for package and solder joint.

This modeling approach has been successfully used for SnPb solder and is applied for SnAgCu solder joints as well. It should be noted here that although advanced finite element analysis techniques are used here, they are primarily to enhance the efficiency of analysis. It is not required that the simulation approach be implemented as is to use the life prediction model. The only requirements are: 3-D modeling (1/4th or 1/8th symmetric), and volume averaging on a 25 micron thick layer of solder at interfaces, each with at least two elements across the thickness.

Figure 3: Global finite element model and detailed solder joint model. Blue and red elements in solder joint model indicate 25 micron thick solder layers at package and board interface, respectively.

Life Prediction for SnPb Solder Joints

The test data described above contains measured mean life for both SnPb and SnAgCu solder joints. In order to revalidate the earlier published model for SnPb solder, the 11 data points for SnPb solder were simulated first in finite element using above methodology to predict the life.

For SnPb solder, the following constitutive equation [11] is used to simulate the creep behavior

\[
\dot{\varepsilon}_{cr} = B_1 \exp\left(\frac{-H}{kT}\right)\left(\frac{\sigma}{E(T)}\right)^n + B_2 \exp\left(\frac{-H}{kT}\right)\left(\frac{\sigma}{E(T)}\right)^{n_2}
\] (12)

<table>
<thead>
<tr>
<th>Steady State Creep Model Parameters (SnPb)</th>
</tr>
</thead>
<tbody>
<tr>
<td>(B_1)</td>
</tr>
<tr>
<td>1.7e12 1/sec</td>
</tr>
</tbody>
</table>

With \(E(T) = -0.0888T(\degree C) + 32\) GPa.

The life prediction models are given by Equation 10 & 11.

Figure 4 shows the comparison of measured and predicted mean life. The predicted life for these new data points is again within 25% of measured life and provides further validation of the life prediction model. The good correlation between predicted and measured fatigue life for SnPb solder also indicates that the material properties used for other materials (mold compound, die attach, substrate, test board, etc) are accurate. The property values used here for mold compound and die attach materials are based on DMA and TMA data generated at Amkor’s lab and not from supplier’s provided data sheets.

Figure 4: Comparison of predicted and measured mean life for eutectic SnPb solder joints.

Life Prediction for SnAgCu solder Joints for Double Power Law Creep Model

Having established the confidence in material and geometric parameters of the finite element models for packages with SnPb solder joints, the same models were analyzed again but with SnAgCu constitutive model and material properties. Thus any differences between solder joint response (strain and energy density) for the two solder alloys (SnPb and SnAgCu) were only due to the difference in constitutive models and material properties of solder alloy itself. The constitutive model and elastic modulus given by Equation 1 & 2 in Table 1 are used here to simulate solder joint behavior during temperature cycling. The CTE and Poisson’s ratio for SnAgCu solder were assumed as 20 ppm/oC and 0.36, respectively as per [7]. The simulated results for each data point were post-processed to calculate the volume averaged accumulated creep strain and creep strain energy density per cycle. In addition, since Equation 1 is of double power law form, accumulated creep strain was also partitioned into its respective mechanism to determine if a life prediction model based on partitioned creep strain, similar to the one used for SnPb solder, can be established. This resulted in three life prediction models, one each for partitioned accumulated creep strain, total accumulated creep strain, and creep strain energy density. The following sections discuss each of these life prediction models. In all cases reported here, the failure was observed and predicted at the package interface.

Partitioned Accumulated Creep Strain

The constitutive model for SnAgCu solder given by Equation 1 describes two mechanisms of creep deformation. It can be argued that each of these mechanisms will cause its own damage and the fatigue life of solder joint should be a function of damage from each mechanism, as given by equations 8 and 9 above.

The creep strain partitioning approach requires the separation of total accumulated creep strain into its respective

A Note to reader: This paper was originally published in ECTC 2004 conference proceedings (pp 737 – 746), however, due to errors in data processing the constants for life prediction models published in the original paper were not accurate. These constants, along with associated figures, have been corrected here.
components. Since ANSYS does not provide separate values for each component, post-processing routine was used to separate the total creep strain into its components. The creep equation was implemented using ANSYS standard implicit creep model (TBOPT = 11). Notice that User Subroutine is no longer required for ANSYS 7.0 to partition the creep strain and higher as was done for SnPb solder in the approach described in [5].

In order to determine the constants of life prediction model, Equation 7, linear multiple regression analysis was performed on two extremes and a few intermediate data points (measured mean life) along with the corresponding partitioned accumulated creep strains. The constants were determined to be 0.106 and 0.045, respectively with a co-efficient of determination of 0.997. Notice that these constants can be taken as the inverse of creep ductility for each mechanism. With these, the life prediction model for SnAgCu is given as:

\[ N_f = \left( 0.106 e^{I_{acc}} + 0.045 e^{II_{acc}} \right)^{-1} \] (13)

The above model suggests that SnAgCu is about 2.3X more ductile at higher stress (mechanism II). However, the curve fitting indicated standard error for constants as 0.08 and 0.002, respectively, thus less confidence in the predicted value of 0.106 for \( C_I \). The higher value for standard error for constant \( C_I \) indicates significantly higher scatter in the data, as shown in Figure 5.

Figure 6 compares the relative contribution of accumulated creep strain from low stress mechanism for the two alloys for the 11 cases. It is interesting to note that while strain contributions from low stress mechanism are higher for SnPb solder, they are less than 5% on the average for SnAgCu solder. This small contribution of Mechanism I creep strain for SnAgCu solder joint is primarily due to very low creep rates at low stresses. Since the stress changes continuously during the cycle, the total creep strain is dominated by the contributions from higher stress region. Furthermore, since the creep resistance of SnAgCu solder at low stresses is much higher compared to SnPb solder, the solder joints made with this alloy can last a much longer time if the stresses are low.

Converting the above partitioned creep strains into damage using the life prediction models above, the damage contribution of low stress mechanism for SnAgCu is predicted to be less than 2% on the average. This is in direct contrast to damage contributions from each mechanism for SnPb solder, where the two mechanisms contributed almost the same amount of damage on the average. This indicates that while damage separation is required for SnPb solder, there is no need for such a separation for SnAgCu solder as almost all damage is caused by strain due to higher stress region for this solder. It should be noted, however, that the cases analyzed here are for accelerated test conditions with wide range of temperature change during a cycle. In real applications, the temperature range can be very small during mini cycles and contributions from low stress region can become prominent, requiring damage separation for more accurate life prediction for field cases.

**Total Accumulated Creep Strain:** Since the damage contribution for low stress region is very small for SnAgCu solder (at least for accelerated test cases), it is possible to use a simplified life prediction model based on total accumulated creep strain. This also simplifies the effort required in simulating the behavior of SnAgCu using ANSYS as there is no need to implement user defined creep law. The standard outputs from ANSYS (NL, CREQ & SEND, CREEP) provide the accumulated creep strain and creep energy density, which can be volume averaged by simple post-processing steps using ETABLES.

In order to determine the total accumulated creep strain (and energy density), the double power law model in Equation 1 was implemented using ANSYS’ standard implicit creep equation (TBOPT = 11 with \( C_3 = 0 \)). All 12 data points listed in Table 2 were then simulated. The accumulated creep strains for each element of solder joint were stored in NL, CREQ for every step of the temperature cycle, which were then post-processed.
to determine the volume averaged accumulated creep strain in the 25 microns thick layer of solder.

The total accumulated strain for the two solder alloys are compared in Figure 7, which shows that the total accumulated creep strain for SnAgCu solder joint can be very similar, higher, or lower than those for SnPb joint for the same package and test condition.

\[
y = 25.273x^{-0.9607} \\
R^2 = 0.9814
\]

![Figure 7: Comparison of accumulated creep strain in SnPb and SnAgCu solder joint.](image)

Figure 8 shows strain vs. life plot on a log-log scale, the typical format for such representation. Also shown is the fitted model relating mean life with volume averaged accumulated creep strain. Notice that the fitted model predicts the strain exponent as \(-0.9607\), a value very close to the theoretically derived exponent of \(-1.0\) discussed in earlier section. This shows that the fatigue life model given by Equation 6 is valid and data can be fitted with linear regression analysis.

Figure 9 shows the same data replotted on the log-log scale but with strain plotted against the inverse of life. The linear regression analysis with intercept = 0 of this representation shows even a better fit to data, resulting in life prediction model in the same form as Equation 6 with constant \(C' = 0.0468\). The life prediction model for SnAgCu thus becomes

\[
N_f = (0.0468 \varepsilon_{acc})^{-1}
\]

(14)

Notice that the constant for total creep strain based model, i.e., 0.0468, is very similar to the constant for Mechanism II of partitioned creep model (0.045). This is because the total accumulated creep strain is only slightly higher than accumulated creep strain due to “Mechanism II”.

Creep Strain Energy Density: Plastic or creep strain energy density (sometimes referred as plastic work) has also been used previously to predict the fatigue life of solder joints. Since the finite element simulations can calculate both accumulated creep strain and dissipated creep strain energy density from one analysis, life prediction models for SnAgCu are also determined using Creep Strain Energy Density.

\[
y = 674.08x^{-0.9229} \\
R^2 = 0.982
\]

![Figure 9: Inverse of Mean Life vs. Total Accumulated Creep Strain on log-log scale.](image)
Figure 10: Mean Life vs. Dissipated Creep Strain Energy Density on log-log scale.

Figure 10 shows the plot of measured mean fatigue life \( (N_f) \) vs. the creep strain energy density calculated using finite element simulation on a log-log scale. The fitted model in the figure also shows the energy density exponent of -0.9229, a value very close to theoretically derived value of -1.0 in Equation 7. This again proves the validity of the approach that the fatigue life exponent should be based on damage mechanism used to model the behavior of the material. The fitted model exponent so close to -1 again indicates that a linear regression analysis can be used for creep strain energy density based model as well.

Figure 11 shows the result of linear regression of the same data, replotted in different format (energy density vs. inverse of life), again showing a better fit than the one in Figure 9. The fitted model can be re-written in the same format as Equation 7 as

\[
N_f = (0.0015 \, w_{acc})^{-1}
\]  

Figure 11: Inverse of Mean Life vs. Dissipated Creep Strain Energy Density on log-log scale.

Life Prediction Models for Hyperbolic Sine Constitutive Equation

The life prediction models discussed above are determined when double power law was used to simulate the creep behavior of SnAgCu solder joints. Since a number of constitutive models are proposed for SnAgCu solder, the life prediction model parameters would depend on the constitutive equation used to simulate solder behavior. In order to investigate the effect of constitutive equation, the same 12 data points for SnAgCu solder were simulated using the hyperbolic sine relationship, given by Equation 2 in Table 1.

\[
\varepsilon_{CT} = A \left[ \sinh(\alpha \sigma) \right]^n \exp \left( \frac{-H_1}{kT} \right)
\]

This equation was implemented in ANSYS by using standard implicit creep equation (TBOPT = 8). The accumulated creep strain and dissipated creep strain energy density were calculated for each case and the life prediction model parameters were determined using linear regression analysis. Again a good fit was found for the data and the mean life can be predicted by using the following equations.

Acc. Creep Strain:

\[
N_f = (0.0513 \, \varepsilon_{acc})^{-1}
\]  

(16)

Creep Energy Density:

\[
N_f = (0.0019 \, w_{acc})^{-1}
\]  

(17)

Comparing above to the life prediction models for double power law creep constitutive equation, the exponents are again determined as -1 for both accumulated creep strain and creep strain energy density. The values of constants, however, are slightly different. This difference is due to the actual values of creep strain and energy density calculated from two constitutive models.

This shows that the life prediction model cannot be independent of deformation constants used to simulate the material behavior. This effect will be further discussed in detail in a separate paper.

Life prediction Models Validation and Comparison

The data used in above life prediction models development encompassed different substrate types, ball count and sizes, ball pitches, material sets, die sizes, board thickness, and temperature cycle conditions.

In order to further validate the model, a completely different package was simulated and tested. The package used is PS-etCSP™ (Package Stack—extremely thin CSP), which is a stack package design. The test and simulations were conducted for single and double sided assemblies, with and without package stacking. The details of this package and test data is described elsewhere [15].

Table 3 compares the measured life with the predicted life using four life prediction models. Of the four models, the accumulated creep strain model based on power law creep equation predicted life closest to the measured data. The accumulated creep strain based on hyperbolic sine creep

<table>
<thead>
<tr>
<th>Stack</th>
<th>Assembly</th>
<th>Measured Mean Life (cycles)</th>
<th>Predicted Lives (cycles)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td>Power Law</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Acc. Creep Energy Density</td>
</tr>
<tr>
<td>No</td>
<td>Single Sided</td>
<td>1225</td>
<td>1082</td>
</tr>
<tr>
<td>No</td>
<td>Double Sided</td>
<td>565</td>
<td>574</td>
</tr>
<tr>
<td>Yes</td>
<td>Single Sided</td>
<td>915</td>
<td>958</td>
</tr>
<tr>
<td>Yes</td>
<td>Double Sided</td>
<td>495</td>
<td>536</td>
</tr>
</tbody>
</table>

Table 3: Predicted vs. Measured life for Stack Package.
equation resulted in slightly higher predicted values. The energy density based models resulted in highest predicted values.

The same trends were observed for data in Table 2 and their respected predicted values. However, the energy density based models do seem to give the same trend as measured life when TC1 and TC2 test cycle data was compared, i.e., lower life for TC2.

**Characteristic and %BX life calculations**

The above life prediction models predict the mean life, not the characteristic life associated with 2 parameter Weibull distribution. The characteristic life (63.2%), however, can be easily calculated using the predicted mean life and the estimated slope ($\beta$) of Weibull distribution. This slope is typically around 10 for area array type packages, but can range between 6 and 20. In fact, the data shown in Table 2 has an average $\beta$ of about 11 for both SnAgCu and SnPb solder joints. Knowing the $\beta$ and the mean life, the characteristic life can be estimated using GAMMALN function in Excel spreadsheet by using the following equation

$$\text{Characteristic Life} = \frac{\text{Mean Life}}{\exp(GAMMALN(1+1/\beta))}$$

Using the $\beta$ of 10, the above equation results in the characteristic life to be about 1.05X of mean life. 

Once the characteristic life is determined, the life for any other cumulative failure rate can be determined by using 2 - parameter Weibull equation.

**Summary and Conclusions**

Thermal fatigue life prediction models are presented using double power law and hyperbolic sine constitutive equations for SnAgCu solder joints. Both accumulated creep strain and creep energy density approaches are used and the life prediction models are developed using damage mechanisms. The partitioning of creep strain shows that the contribution of low stress region is very small in total creep strain during an accelerated temperature cycle.

Since partitioning of creep strain is not required, the modeling approach can be easily implemented in ANSYS using standard features. The creep equations used are standard options in ANSYS and the accumulated creep strain and creep strain energy density are calculated by ANSYS directly. Post processing of results is required, however, to calculate volume averaged values in a 25 micron thick layer of solder. This can be easily accomplished using ETABLE commands in ANSYS. Although the model parameters are dependent on the finite element techniques used here, they can be used as long as 3-D modeling and volume averaging techniques are employed.

The constants of life prediction models were determined using actual test data and finite element simulations. These constants were calculated for both types of constitutive equations, showing slight difference in values.

All models show very good correlation with test data with predictions with 25% in most cases. Further validation on stacked package configuration shows life prediction approach using accumulated creep strain and double power law creep equation gives the closest results compared to experimental data.

**Acknowledgments**

The author would like to thank W J Kang, J Y Khim, Y J Kim, and Y H Ka at Amkor Technology, Korea for performing the reliability tests and data analysis used in this work.

**References**

10. Hua, F., Private Communications

---

**A Note to reader:** This paper was originally published in ECTC 2004 conference proceedings (pp 737 – 746), however, due to errors in data processing the constants for life prediction models published in the original paper were not accurate. These constants, along with associated figures, have been corrected here.
Accumulated Creep Strain and Energy Density Based Thermal Fatigue Life Prediction Models for SnAgCu Solder Joints

Ahmer Syed
asyed@amkor.com

Presented at 54th Electronic Components & Technology Conference June 3, 2004
Life Prediction Models for SnAgCu Solder

- **Why Predict**
  - Industry is fast migrating to SnAgCu solder alloys
  - Reduced design cycle time limits the use of testing to evaluate reliability
  - Life prediction models are needed to assess reliability at the design stage

- **Four factors governing life prediction**
  - Material behavior
  - Simulation techniques
  - Life prediction methodology
  - Test data
1. Material Behavior

- Constitutive equations for SnAgCu solder joints
  - Double Power Law
    - Wiese et al (Sn4.0Ag0.5Cu)
      \[ \varepsilon_{cr} = A_1 \exp \left( -\frac{H_1}{kT} \right) \left( \frac{\sigma}{\sigma_n} \right)^{n_1} + A_2 \exp \left( -\frac{H_2}{kT} \right) \left( \frac{\sigma}{\sigma_n} \right)^{n_2} \]
    - Morris et al (Sn3.0Ag0.5Cu)
  - Hyperbolic Sine
    - Schubert et al (Sn3.8Ag0.7Cu, Sn3.5Ag0.75Cu, Sn3.5Ag0.5Cu, CASTIN™)
      \[ \varepsilon_{cr} = A_1 \sinh (\alpha \sigma) \exp \left( -\frac{H_1}{kT} \right) \]
    - Zhang et al (Sn3.9Ag0.6Cu)

\[
A_1 = 4 \times 10^{-7} \text{ s}^{-1} \\
H_1/k = 3223 \\
n_1 = 3.0 \\
A_2 = 1 \times 10^{-12} \text{ s}^{-1} \\
H_2/k = 7348 \\
n_2 = 12.0
\]

\[
A_1 = 277984 \text{ s}^{-1} \\
a = 0.02447 \text{ MPa}^{-1} \\
n = 6.41 \\
H_1/k = 6500 \\
E(\text{MPa}) = 61251 - 58.5T(\text{oK}) \\
\text{CTE} = 20.0 \text{ ppm/K,} \\
\text{Poisson’s ratio} = 0.36
\]
1. Material Behavior

- **Steady State Creep Rate Prediction**
  - SnAgCu solder is significantly more creep resistant at low stresses compared to SnPb solder
  - Similar creep behavior from 3 models at stresses below 30 MPa
    - Models diverge at high stresses

![Steady-State Creep Rate Graph]

Temperature = 60 C

- SnPb Wong]
- SnAgCu [Wiese]
- SnAgCu Schubert]
- SnAgCu [Zhang]
- SnAgCu [Morris]
2. Finite Element Analysis

- Same approach as SnPb solder
  - Step 1: Build 3D Model
    - Simple representation of solder joints
    - Perform linear analysis to determine the location of critical joint
  - Step 2: Substructuring
    - Lump all elements with linear, temperature independent properties into a superelement
    - Perform superelement analysis for 1°C change in temperature
  - Step 3: Build Critical Joint Model
    - Attach Superelement from Step 2
    - Model Viscoelastic and temperature dependent behavior of solder
    - Perform nonlinear analysis
- Detailed approach in ECTC’01
2. Finite Element Analysis

• Solder joint response calculation
  – Inelastic strain and energy density calculated by volume averaging
    ▪ 25 micron thick layers of solder at package and board side
    ▪ Each layer has two elements across the thickness
  – Life prediction model parameters are only valid for this thickness
  – Besides 3-D modeling, this is the only requirement for life prediction model
    ▪ Substructuring only to improve efficiency
2. Solder Joint Response

- **Effect of Time Independent Plasticity**
  - Wiese’s Model *(Creep only VS Creep + Plasticity)*
  - Ceramic BGA on FR4
  - -55 <> 125 C cycle, fast ramps (highest stress condition)

  Plastic strain and Energy Density contributions are insignificant in total inelastic response

- **No need to model time independent plasticity for Thermal Cycle simulations**
3. Life Prediction Model Development

- Solder joint life is governed by Creep
- Thermal Cycle Fatigue ➔ Cyclic Creep Rupture
  - Creep due to sequence of loading, repeated in a cyclic manner
  - Monkmann-Grant Equation & Time Fraction Rule
    \[
    t_r = \frac{C}{\dot{\varepsilon}_{cr}} \quad N_f \left( \frac{\sum_{i=1}^{n} \Delta t_i}{t_{ri}} \right)_{one\ cycle} = 1 \quad \Delta t_i = \text{time spent at stress level } \sigma_i \text{ within a cycle, and}
    \]
    \[
    t_{ri} = \text{rupture time for stress level } \sigma_i.
    \]
  - Combine
    \[
    N_f = (C'\varepsilon_{acc})^{-1} \quad N_f = (W' w_{acc})^{-1}
    \]
- For two mechanisms (double power law creep)
  \[
  N_f = \left( C_I \varepsilon_{acc}^I + C_{II} \varepsilon_{acc}^{II} \right)^{-1} \quad N_f = \left( W_I w_{acc}^I + W_{II} w_{acc}^{II} \right)^{-1}
  \]
- Constants to be determined by relating mean life (test) with solder joint response (simulations)
- Same approach has been successfully used for SnPb solder for 8+ years
4. Fatigue Test Data

- Thermal cycle tests conducted on various packages with different substrate types, body sizes, ball pitches, land sizes

<table>
<thead>
<tr>
<th>Data Point</th>
<th>Package Type</th>
<th>Substrate Type</th>
<th>Body Size</th>
<th>I/O Pitch</th>
<th>Die Size</th>
<th>Pad Type</th>
<th>Pad Size</th>
<th>Ball Dia</th>
<th>Test Type</th>
<th>Board Thickness</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>CABGA</td>
<td>Laminate</td>
<td>15 x 15</td>
<td>208</td>
<td>0.8</td>
<td>8.5 x 8.5 x 0.265</td>
<td>SMD</td>
<td>0.4</td>
<td>0.46</td>
<td>TC1</td>
</tr>
<tr>
<td>2</td>
<td>CABGA</td>
<td>Laminate</td>
<td>15 x 15</td>
<td>256</td>
<td>0.65</td>
<td>10 x 10 x 0.265</td>
<td>SMD</td>
<td>0.32</td>
<td>0.4</td>
<td>TC2</td>
</tr>
<tr>
<td>3</td>
<td>CABGA</td>
<td>Laminate</td>
<td>8 x 8</td>
<td>64</td>
<td>0.8</td>
<td>4.8 x 4.8 x 0.29</td>
<td>SMD</td>
<td>0.4</td>
<td>0.46</td>
<td>TC3</td>
</tr>
<tr>
<td>4</td>
<td>CABGA</td>
<td>Laminate</td>
<td>8 x 8</td>
<td>64</td>
<td>0.8</td>
<td>4.8 x 4.8 x 0.29</td>
<td>SMD</td>
<td>0.4</td>
<td>0.46</td>
<td>TC2</td>
</tr>
<tr>
<td>5</td>
<td>Ceramic BGA</td>
<td>Ceramic</td>
<td>8 x 8</td>
<td>64</td>
<td>0.8</td>
<td>None</td>
<td>SMD</td>
<td>0.4</td>
<td>0.46</td>
<td>TC1</td>
</tr>
<tr>
<td>6</td>
<td>Ceramic BGA</td>
<td>Ceramic</td>
<td>8 x 8</td>
<td>64</td>
<td>0.8</td>
<td>None</td>
<td>SMD</td>
<td>0.4</td>
<td>0.46</td>
<td>TC3</td>
</tr>
<tr>
<td>7</td>
<td>CVBGA</td>
<td>Laminate</td>
<td>12 x 12</td>
<td>288</td>
<td>0.5</td>
<td>7.1 x 7.1 x 0.175</td>
<td>SMD</td>
<td>0.25</td>
<td>0.3</td>
<td>TC1</td>
</tr>
<tr>
<td>8</td>
<td>fleXBGA</td>
<td>Tape</td>
<td>12 x 12</td>
<td>144</td>
<td>0.8</td>
<td>6.4 x 6.4 x 0.3</td>
<td>SMD</td>
<td>0.3</td>
<td>0.46</td>
<td>TC3</td>
</tr>
<tr>
<td>9</td>
<td>fleXBGA</td>
<td>Tape</td>
<td>12 x 12</td>
<td>144</td>
<td>0.8</td>
<td>6.4 x 6.4 x 0.3</td>
<td>SMD</td>
<td>0.3</td>
<td>0.46</td>
<td>TC3</td>
</tr>
<tr>
<td>10</td>
<td>fleXBGA</td>
<td>Tape</td>
<td>12 x 12</td>
<td>144</td>
<td>0.8</td>
<td>6.4 x 6.4 x 0.3</td>
<td>SMD</td>
<td>0.3</td>
<td>0.46</td>
<td>TC3</td>
</tr>
<tr>
<td>11</td>
<td>PBGA</td>
<td>Laminate</td>
<td>27 x 27</td>
<td>256</td>
<td>1.27</td>
<td>10 x 10 x 0.30</td>
<td>SMD</td>
<td>0.65</td>
<td>0.76</td>
<td>TC2</td>
</tr>
<tr>
<td>12</td>
<td>TSCSP</td>
<td>Tape</td>
<td>12 x 12</td>
<td>288</td>
<td>0.5</td>
<td>top: 5.08 x 5.08 x 0.15 btm: 10.16 x 10.16 x 0.15</td>
<td>SMD</td>
<td>0.24</td>
<td>0.3</td>
<td>TC2</td>
</tr>
</tbody>
</table>

- Three test conditions
  - TC1: -40<>125°C, 15 minutes ramps and dwells, 1 cycle/hr
  - TC2: -55 <> 125°C, 2 minutes ramps, 13 minutes dwells, 2 cycles/hr
  - TC3: 0 <> 100°C, 10 minute ramps, 5 minutes dwells, 2 cycles/hr

- Various board thickness’
4. Fatigue Test Data

- SnAgCu vs. SnPb solder measured fatigue life

<table>
<thead>
<tr>
<th>Data Point</th>
<th>Package Type</th>
<th>Body Size</th>
<th>I/O</th>
<th>1st Failure</th>
<th>Weibull Slope</th>
<th>Weibull Char. Life (Cycles)</th>
<th>Mean Life (Cycles)</th>
<th>1st Failure</th>
<th>Weibull Slope</th>
<th>Weibull Char. Life (Cycles)</th>
<th>Mean Life (Cycles)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>CABGA</td>
<td>15 x 15</td>
<td>208</td>
<td>2491</td>
<td>8.92</td>
<td>3717</td>
<td>3520</td>
<td>2539</td>
<td>10</td>
<td>3450</td>
<td>3281</td>
</tr>
<tr>
<td>2</td>
<td>CABGA</td>
<td>15 x 15</td>
<td>256</td>
<td>3380</td>
<td>15.4</td>
<td>4096</td>
<td>3960</td>
<td>1856</td>
<td>7.4</td>
<td>2725</td>
<td>2557</td>
</tr>
<tr>
<td>3</td>
<td>CABGA</td>
<td>8 x 8</td>
<td>64</td>
<td>3463</td>
<td>8.36</td>
<td>4843</td>
<td>4570</td>
<td>2445</td>
<td>11.76</td>
<td>3212</td>
<td>3076</td>
</tr>
<tr>
<td>4</td>
<td>CABGA</td>
<td>8 x 8</td>
<td>64</td>
<td>2493</td>
<td>9.81</td>
<td>3263</td>
<td>3103</td>
<td>2205</td>
<td>13.76</td>
<td>2664</td>
<td>2565</td>
</tr>
<tr>
<td>5</td>
<td>Ceramic BGA</td>
<td>8 x 8</td>
<td>64</td>
<td>318</td>
<td>7.08</td>
<td>445</td>
<td>417</td>
<td>340</td>
<td>10</td>
<td>437</td>
<td>416</td>
</tr>
<tr>
<td>6</td>
<td>Ceramic BGA</td>
<td>8 x 8</td>
<td>64</td>
<td>853</td>
<td>9.55</td>
<td>1103</td>
<td>1047</td>
<td>982</td>
<td>8.96</td>
<td>1246</td>
<td></td>
</tr>
<tr>
<td>7</td>
<td>CVBGA</td>
<td>12 x 12</td>
<td>288</td>
<td>1332</td>
<td>5.81</td>
<td>2005</td>
<td>1890</td>
<td>1700</td>
<td>9.26</td>
<td>2217</td>
<td></td>
</tr>
<tr>
<td>8</td>
<td>fleXBGA</td>
<td>12 x 12</td>
<td>144</td>
<td>2580</td>
<td>19.06</td>
<td>2948</td>
<td>2868</td>
<td>2369</td>
<td>10.4</td>
<td>3164</td>
<td>3015</td>
</tr>
<tr>
<td>9</td>
<td>fleXBGA</td>
<td>12 x 12</td>
<td>144</td>
<td>2351</td>
<td>20.4</td>
<td>2792</td>
<td>2720</td>
<td>1902</td>
<td>15.2</td>
<td>2140</td>
<td>2327</td>
</tr>
<tr>
<td>10</td>
<td>fleXBGA</td>
<td>12 x 12</td>
<td>144</td>
<td>8939</td>
<td>15.7</td>
<td>10370</td>
<td>10027</td>
<td>5042</td>
<td>12.95</td>
<td>6195</td>
<td>5953</td>
</tr>
<tr>
<td>11</td>
<td>PBGA</td>
<td>27 x 27</td>
<td>256</td>
<td>4651</td>
<td>7.2</td>
<td>6812</td>
<td>6381</td>
<td>3656</td>
<td>13.92</td>
<td>4544</td>
<td>4378</td>
</tr>
<tr>
<td>12</td>
<td>TSCSP</td>
<td>12 x 12</td>
<td>288</td>
<td>175</td>
<td>6</td>
<td>296</td>
<td>275</td>
<td>NA</td>
<td>NA</td>
<td>NA</td>
<td>NA</td>
</tr>
</tbody>
</table>

- Life for SnAgCu solder joints is longer, but not for every case
- Acceleration factors between test conditions are not the same
Life Prediction for SnPb Joints

\[ \varepsilon_{cr} = B_1 \exp\left( \frac{-H}{kT} \right) \left( \frac{\sigma}{E(T)} \right)^{n_1} + B_{II} \exp\left( \frac{-H}{kT} \right) \left( \frac{\sigma}{E(T)} \right)^{n_2} \]

\[ N_f = \left( 0.02\varepsilon_{acc}^{I} + 0.063\varepsilon_{acc}^{II} \right)^{-1} \]

- Provides confidence in properties used for package and board materials
- Failure location is correctly predicted

Prediction Accuracy: ± 25%
SnAgCu Solder Life Prediction

• 5 life prediction models attempted depending on the constitutive equation for SnAgCu solder

• Double power law creep (Wiese et al)
  – Creep Strain Partitioning
  – Total Accumulated Creep Strain
  – Total Accumulated Creep Strain Energy Density

• Hyperbolic sine creep (Schubert et al)
  – Total Accumulated Creep Strain
  – Total Accumulated Creep Strain Energy Density
ANSYS Implementation

- **Creep Model Implementation in ANSYS**
  - **Double Power Law Model**
    \[ \varepsilon_{cr} = A_1 \exp \left( \frac{-H_1}{kT} \right) \left( \frac{\sigma}{\sigma_n} \right)^{n_1} + A_2 \exp \left( \frac{-H_2}{kT} \right) \left( \frac{\sigma}{\sigma_n} \right)^{n_2} \]
    
    - Standard Implicit Creep Model, TBOPT = 11 with C3 = 0.0
    - Creep strain partitioning in POST PROCESS, if needed
    - No need for USER SUBROUTINE
    - Post Processing text file can be provided.
  - **Hyperbolic Sine Model**
    \[ \varepsilon_{cr} = A_1 \left[ \sinh (\alpha \sigma) \right]^n \exp \left( \frac{-H_1}{kT} \right) \]
    
    - Standard Implicit Creep Model, TBOPT = 8

- **Output Parameters**
  - NL, CREQ = Accumulated Creep Strain
  - SEND, CREEP = Creep Strain Energy Density
**Cyclic stability**

- SnPb solder joints show cyclic stability after 1\textsuperscript{st} cycle
- SnAgCu solder joints show stability after 2\textsuperscript{nd} cycles
  - 20 to 30\% reduction after 1\textsuperscript{st} cycle

**Life prediction model parameters in the paper are based on 1\textsuperscript{st} cycle values due to post processing error and are not correct**
SnAgCu Solder Life Prediction

- **Double Power Law Creep**
  - Creep Strain Partitioning
    - More scatter in low stress creep for SnAgCu solder
    - % contribution of low stress creep is < 10%
    - Significantly different response compared to SnPb Solder
- Creep strain partitioning not needed for SnAgCu solder joints

\[
\varepsilon_{cr} = A_1 \exp\left(\frac{-H_1}{kT}\right)\left(\frac{\sigma}{\sigma_n}\right)^3 + A_2 \exp\left(\frac{-H_2}{kT}\right)\left(\frac{\sigma}{\sigma_n}\right)^{12}
\]

\[
N_f = \left(\frac{C_I \varepsilon_{acc}^I + C_{II} \varepsilon_{acc}^{II}}{C_{III} \varepsilon_{acc}^{III}}\right)^{-1}
\]
SnAgCu Solder Life Prediction

- **Double Power Law Creep**
  - Total accumulated creep strain & energy density approach
  - Std curve fit
    - Mean Life Vs Strain
    - Mean Life Vs Energy density
  - Curve fit for both show fatigue life exponent to be very close to 1.0

\[
\varepsilon_{cr} = A_1 \exp\left(\frac{-H_1}{kT}\right) \left(\frac{\sigma}{\sigma_n}\right)^3 + A_2 \exp\left(\frac{-H_2}{kT}\right) \left(\frac{\sigma}{\sigma_n}\right)^{12}
\]

![Graph showing mean life vs accumulated creep strain and energy density with equations and R² values.](image-url)
SnAgCu Solder Life Prediction

- **Double Power Law Creep**
  - Total creep and energy density

\[
N_f = (C' \varepsilon_{acc})^{-1}
\]

\[
N_f = (W' w_{acc})^{-1}
\]

- Constants determined by relating solder joint response with measured life

\[
C' = 0.0468
\]

\[
W' = 0.0015
\]

- Acc. creep strain model seems to provide better fit at high life numbers

\[
\varepsilon_{cr} = A_1 \exp \left( \frac{-H_1}{kT} \right) \left( \frac{\sigma}{\sigma_n} \right)^3 + A_2 \exp \left( \frac{-H_2}{kT} \right) \left( \frac{\sigma}{\sigma_n} \right)^{12}
\]
SnAgCu Solder Life Prediction

- Hyperbolic Sine Creep
  - Similar model but different constants
    
    \[ N_f = \left(0.0513 \varepsilon_{acc}\right)^{-1} \]
    \[ N_f = \left(0.0019 \, w_{acc}\right)^{-1} \]
  
  - Energy density based model provides better fit at higher life numbers
  
  - Acc. Strain based model provides conservative estimate

\[
\varepsilon_{cr} = A_1 [\sinh(\alpha \sigma)]^n \exp\left(\frac{-H_1}{kT}\right)
\]
SnAgCu Solder Life Prediction

• Which method is better?

<table>
<thead>
<tr>
<th>Package</th>
<th>SnAgCu Mean Life (Test)</th>
<th>Prediction Accuracy</th>
<th>Double Power Law</th>
<th>Hyperbolic Sine</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Acc. Creep Strain</td>
<td>Energy Density</td>
<td>Acc. Creep Strain</td>
</tr>
<tr>
<td>15mm-208 CABGA</td>
<td>3519</td>
<td>0%</td>
<td>15%</td>
<td>-24%</td>
</tr>
<tr>
<td>15mm-256 CABGA</td>
<td>3960</td>
<td>3%</td>
<td>-6%</td>
<td>-16%</td>
</tr>
<tr>
<td>8mm-64CABGA - TC1</td>
<td>4570</td>
<td>-31%</td>
<td>-16%</td>
<td>-45%</td>
</tr>
<tr>
<td>8mm-64CABGA - TC2</td>
<td>3101</td>
<td>8%</td>
<td>4%</td>
<td>-10%</td>
</tr>
<tr>
<td>8mm-64 CBGA TC1</td>
<td>417</td>
<td>0%</td>
<td>0%</td>
<td>5%</td>
</tr>
<tr>
<td>8mm-64 CBGA TC3</td>
<td>1047</td>
<td>-7%</td>
<td>2%</td>
<td>-8%</td>
</tr>
<tr>
<td>12mm-288CVBGA</td>
<td>1890</td>
<td>7%</td>
<td>20%</td>
<td>-27%</td>
</tr>
<tr>
<td>12mm-144 XBGA TC1</td>
<td>2866</td>
<td>-5%</td>
<td>11%</td>
<td>-27%</td>
</tr>
<tr>
<td>12mm-144 XBGA TC2</td>
<td>2720</td>
<td>21%</td>
<td>18%</td>
<td>-5%</td>
</tr>
<tr>
<td>12mm-144 XBGA TC3</td>
<td>10027</td>
<td>22%</td>
<td>65%</td>
<td>-44%</td>
</tr>
<tr>
<td>27mm-256PBGA - TC2</td>
<td>6381</td>
<td>14%</td>
<td>18%</td>
<td>-18%</td>
</tr>
<tr>
<td>12mm-288TSCSP</td>
<td>275</td>
<td>1%</td>
<td>1%</td>
<td>1%</td>
</tr>
</tbody>
</table>

• Models based on Power law creep equation provide better accuracy
  – Accumulated creep strain based model slightly better
2. Solder Joint Response

- **Creep Strain**
  - Accumulated vs. range
  - Most accumulation during ramps, some during dwell times at low and high temperatures

- **Strain Energy Density (Creep)**
  - Significant accumulation during low temperature dwell
    - High stresses at low temp
  - Almost no accumulation during high temp dwell
SnAgCu Solder Life Prediction

- Trend Predictions
  - 3 test conditions, 12mm-144 fleXBGA package
  - Predictions show same trend as actual test data
  - Acceleration factors are different for SnPb and SnAgCu

```
<table>
<thead>
<tr>
<th>Condition</th>
<th>SnPb - Test</th>
<th>SnPb - Predictions</th>
<th>SnAgCu - Test</th>
<th>SnAgCu - Predictions</th>
</tr>
</thead>
<tbody>
<tr>
<td>TC1</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>TC2</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>TC3</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
```

Mean Life (cycles)
Model Validation

- 12mm-320 etCSP package – with and without stacking
  - Single sided
  - Double sided

<table>
<thead>
<tr>
<th>Stacked?</th>
<th>Assembly</th>
<th>Measured Life</th>
<th>Predicted (Power law)</th>
<th>Predicted (Hyp Sine)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td>Strain</td>
<td>Ener Den</td>
</tr>
<tr>
<td>No</td>
<td>Single Sided</td>
<td>1148</td>
<td>1082</td>
<td>1173</td>
</tr>
<tr>
<td>No</td>
<td>Double Sided</td>
<td>563</td>
<td>574</td>
<td>600</td>
</tr>
<tr>
<td>Yes</td>
<td>Single Sided</td>
<td>884</td>
<td>958</td>
<td>1031</td>
</tr>
<tr>
<td>Yes</td>
<td>Double Sided</td>
<td>495</td>
<td>536</td>
<td>557</td>
</tr>
</tbody>
</table>

- Strain based approach resulted in conservative predictions
SnAgCu Solder Life Prediction

- Prediction Accuracy = $\pm 25\%$
  - 18 data points

![Graph showing Mean Cycles to Failure (Test) vs. Mean Cycles to Failure (Prediction) for various packages.]
SnAgCu Solder Life Prediction

• Conclusions
  – Creep strain partitioning not needed for SnAgCu solder joints life prediction
  – Better prediction accuracy achieved by using double power law constitutive equation
  – Either accumulated creep strain or energy density can be used for life prediction
    ▪ Creep strain provides better prediction accuracy
    ▪ Energy density captures high stress effects better