Evolution of Propensity for High Strain-Rate Damage Accrual in Doped and Undoped SnAgCu Lead-free Solders in Temperature Range of -65°C to +200°C after 1-Year Sustained High Temperatures Exposure

Pradeep Lall
Auburn University
NSF-CAVE3 Electronics Research Center
Department of Mechanical Engineering
Auburn, AL 36849
Email: lall@auburn.edu

Vishal Mehta
Auburn University
NSF-CAVE3 Electronics Research Center
Department of Mechanical Engineering
Auburn, AL 36849

Vikas Yadav
Auburn University
NSF-CAVE3 Electronics Research Center
Department of Mechanical Engineering
Auburn, AL 36849

Minmoy Saha
Auburn University
NSF-CAVE3 Electronics Research Center
Department of Mechanical Engineering
Auburn, AL 36849

Jeff Suhling
Auburn University
NSF-CAVE3 Electronics Research Center
Department of Mechanical Engineering
Auburn, AL 36849

Abstract—To ensure the reliability of high-performance electronics systems, constitutive models are crucial. Predictive models are particularly necessary for electronic equipment that operates in harsh environments, where extreme temperatures ranging from -65°C to +200°C may cause significant out-of-plane deformation in board assemblies due to shock, vibration, or transient loads. Automotive under-hood and aerospace electronics may require sustained exposure to high temperatures of 150-200°C and may go through random mechanical shock and vibration. Additionally, electronics may be stored in non-climate-controlled enclosures for prolonged periods before deployment.

In order to mitigate the adverse effects of sustained high-temperature exposure, the industry has experimented with adding dopants to SAC solders. This paper studies the effects of dopants, including Nickel and Bismuth, on doped alloys such as SAC-Q, SAC-R, M758, and SAC305 solder. The study examines the strain-rate range of 1-100 per second and the temperature range of -65°C to +200°C after one year of sustained exposure to 50°C and 100°C storage temperatures. The Anand model’s accuracy has been quantified by comparing experimentally measured data with predicted data computed using the model’s constants. Anand parameters have been computed and implemented in an FE analysis framework to simulate drop events for a ball-grid array package on a printed circuit board assembly, determining hysteresis loops of stress vs strains and plastic work density. The study also explores the evolution in hysteresis loops and PWD.

Keywords—Un-doped and doped Lead-Free Solders, High Strain Rates, Anand Viscoplasticity Model, Drop/shock FE analysis.

I. INTRODUCTION

Constitutive models are essential to ensure the dependability of high-reliability electronic systems used in harsh environments, particularly in the automotive underhood and aerospace electronics industries. These systems may be subjected to long periods of storage, low working temperatures, and high strain rates, which can cause negative operating temperatures ranging from 0°C to -65°C and significant out-of-plane deformation when subjected to rapid loads or vibration. Over the operational life of the electronic equipment, significant damage may accrue. Previous studies have revealed that electronic vehicle systems installed underhood, on the engine driver interior, and in the ECU box may experience operating temperatures ranging from -40°C to +200°C [1]. While SAC solders have shown to evolve mechanical properties at low strain rates after a moderate duration of sustained temperature exposure, determining the projected deterioration in mechanical performance, reliability, and constitutive models is necessary for ensuring good dependability.

In order to improve the mechanical integrity and properties of SnAgCu solders against sustained high-temperature exposure, solder companies have explored the use of various dopants. The material characterization of SAC solder alloys has been investigated in earlier investigations under thermal loads and in the range of strain rates 10^-6 to 10^4, as well as the impacts of thermal aging reported by several researchers [4]-[15]. Wong [17] found that 63Sn37Pb is less susceptible to strain rate compared to lead-free solder alloys. The authors’ earlier study [7]-[15] focused on the impact of thermal aging on the material behavior of several SAC materials under varied strain conditions. However, information on the mechanical performance, reliability, and constitutive models for many of the new formulations remains limited. There is also little data on the sustained exposure of high temperature on the high strain rate constitutive behavior. Previous evaluations of mechanical characteristics at various low strain rates have been limited to material test/experiment systems. The present study focuses on the evolution in hysteresis loops of stress vs strains and plastic work density.

Finite element modeling has been extensively used in the design of solder joint attachments in electronic packaging. On order to capture the nonlinear behavior of solder alloys, various material models such as simple elastic, elastic-plastic, creep, and...
viscoplasticity have been employed by researchers. Among these models, the Anand model has been frequently used to describe the nonlinear behavior of solder materials ([4]-[15] and [18]-[20]). Amagai [20] suggested a modified Anand Constitutive model with Anand model constants for lead-free solders Sn3.5Ag0.75Cu and SAC105. Motalab’s research [6] indicated that long-term thermal aging of lead-free alloys’ mechanical properties can reveal thermal fatigue at lower strain rates.

The objective of this research is to investigate the characteristics of SAC305, SAC-Q, M758, and SAC-R alloys under extreme temperature conditions ranging from -65°C to 200°C and high strain rates, after undergoing varying periods of thermal aging up to 1 year at 50°C and 100°C. In order to comprehensively capture the material’s behavior across this wide temperature and strain rate range, the study has calculated the Anand Visco-plasticity model constants. Furthermore, the study has conducted a quantitative analysis of the model constants’ evolution during thermal storage at high temperatures. The validity of the model has been evaluated by comparing the observed material deformation behavior with the predicted behavior derived from the model constants.

II. FABRICATION OF TEST SAMPLES

EDX analysis was carried out for getting the chemical composition of solders, to find out the amount of dopants present in the alloy. It was found that no dopants like Bismuth or Nickel were present in SAC305 solder. SAC-Q solder has 4.9% of Bismuth, while SAC-R has 2.46% of Bismuth as a doping element. M758 solder has 4% of Bismuth and 0.2% of Nickel, as well. To create SAC solder specimens, small pieces of solder alloys were melted in a glass crucible tube. In this investigation, precise glass tubes having a rectangular cross-section and a vacuum suction pump were used to create rectangular samples. In order to be equivalent to the solder junction height for use in fine pitch electronics, the sample thickness is chosen as 0.5 mm. The glass tubes with the molten solder inside, are cooled using the water-quenching procedure. Once solidified, the specimen is reflowed in the nine-zone reflow oven Heller 1800EXL. Test samples were allowed to reach to room temperature and then transferred right to an isothermal oven for isothermal aging in order to lessen the impact of room temperature aging. Samples from SAC305 and M758 were aged at 100°C for up to a year. In contrast, 50°C storage temperature was kept for SAC-Q and SAC-R samples for the aging duration of up to 1 year. Test samples were carefully taken out of glass tubes, and x-ray images were obtained in order to look for a fault or damage prior to the tensile test. Sample preparation methodology and images are explained in detail in author’s previous publications [15].

III. EXPERIMENTAL TEST-SETUP AND TEST CONDITIONS

Using an impact hammer-based method, specimens were assessed with different standardized strain rates. Data on strain and deformation of the solder specimen were recorded by two high-speed cameras. Stress-strain data were measured by employing high strain rates and extreme testing temperatures (-65 to 200°C). To achieve low testing temperatures, a cooling chamber was integrated into the tensile test setup, and liquid nitrogen was circulated through it. The tensile test setup ensured a constant strain rate throughout the test while two high-speed cameras monitored the movement of the test sample and impact hammer. Two grips were employed to secure the test sample, and a load-cell was added to the upper grip to quantify the tensile load during testing. The authors have previously provided a comprehensive explanation of the sample fabrication and experimental setup in their publications [7]-[15].

Test samples prepared with SAC-Q and SAC-R solders were stored at 50°C in a heating oven for isothermal aging, for the durations up to 12 months. While SAC305 and M758 solder samples were stored at 100°C for the thermal aging for the durations up to 12 months. Un-aged and aged samples (for all aging durations) were uniaxially tested at the various test temperatures in the range of -65 to +200 °C (e.g. total 12 test temperatures), and for the strain rates 10, 35, 50, 75 sec⁻¹. For each test condition, at least five test samples were put to the test using the impact hammer-based tensile setup. Those five separate samples’ test results were averaged to create each stress-strain curve. The effects of low to high operating temperatures, high strain rates, and thermal aging conditions have been measured on the extracted materials’ characteristics.

Average material parameters, such as ultimate tensile strength and elastic modulus, were achieved from the stress-strain curves calculations. The experimental stress-strain curves were fitted using the nonlinear least squares fitting method, and the results were contrasted with the predicted stress-strain curve predicted by the Anand model. Nine Anand constants were derived for various SAC solders after the material data was fitted to the Anand Visco-plasticity model.

IV. ANAND VISCOPLASTIC CONSTITUTIVE MODEL

Anand model [18]-[20] is one of the most used models for nonlinear solder alloys. Anand’s model uses flow, evolution, and stress equations to describe the solder alloy’s rate-dependent plastic behavior. The stress equation for one-dimensional uni-axial tensile loading can be defined as:

\[
\sigma = \frac{1}{\xi} \sinh^{-1} \left[ \frac{\dot{e}_p}{A} \exp \left( \frac{Q}{RT} \right) \right] \\
\left[ \dot{s} \left[ \frac{\dot{e}_p}{A} \exp \left( \frac{Q}{RT} \right) \right] - \left( \frac{\dot{e}_p}{A} \exp \left( \frac{Q}{RT} \right) \right)^{n-1} \right] \cdot \left( \frac{\dot{e}_p}{A} \exp \left( \frac{Q}{RT} \right) \right)^{n-1} + \frac{\dot{e}_p}{A} \exp \left( \frac{Q}{RT} \right) \right] \\
(a-1) \left[ h_0 \left( \frac{\dot{e}_p}{A} \exp \left( \frac{Q}{RT} \right) \right)^n \right] \epsilon_r 
\]

Where, \( \sigma \) is stress, \( s \) is internal variable, and \( c \) is the function of strain rate, \( \dot{e}_p \) represents the Plastic Strain rate, \( \xi \) denotes the Stress Multiplier, \( T \) shows Temperature in Kelvin, \( A \) represents the pre-exponential factor, \( Q \) is the Activation Energy, \( R \) is the Universal Gas Constant, and \( m \) denotes the sensitivity of strain rate. Equation (1) comprises total 9-constants of material \( A, \xi, Q/R, h_0, m, s_0, S \) and \( a \). If we assume that the plastic strain \( \dot{e}_p \) approaches infinity, we can determine the ultimate tensile strength (UTS).
\[ \sigma^* = UTS = \sigma_{0,\text{sec}} \]  
\[ \therefore \sigma^* = \frac{\dot{\varepsilon}_0}{A^*} \exp \left( \frac{Q}{RT} \right) \sinh^{-1} \left( \frac{\dot{\varepsilon}_0}{A^*} \exp \left( \frac{Q}{RT} \right) \right) \]  

So, plugging this value back into equation (1) and rephrasing:

\[ \sigma = \sigma^* - \left[ (\sigma^* - c_s \cdot \varepsilon_0)^{\cdot n} + (a - 1) \cdot \left[ c_h (\sigma^*)^{\cdot n} \right] \right] \]  

Where, \( c \) is a function of strain rate:

\[ c = \left( \frac{\dot{\varepsilon}_0}{A^*} \right) \sinh^{-1} \left( \frac{\dot{\varepsilon}_0}{A^*} \exp \left( \frac{Q}{RT} \right) \right) \]  

For fitting the 9 constants (\( A, a, Q/R, \zeta, h_0, m, n, s_0 \)) of the Anand Viscoplasticity Model, multiple uniaxial tensile tests were conducted at various operating temperatures between -65 and 200°C and at various strain rates (10, 35, 50, and 75 per sec). The least-square nonlinear approach using MATLAB is then used to fit the experimental findings. Nine Anand parameters can be discovered using the procedure below:

(i) Equation (2) will be used to fit the experimental results of ultimate stress and strain, and the values of parameters \( A, Q/R, m, n, \) and \( \dot{s}/\xi \) will be obtained.

(ii) The value of \( \dot{s}/\xi \), obtained in the previous step, will be used to determine \( \zeta \) such that the \( s/\zeta \) ratio is less than unity. Subsequently, \( \delta \) will be calculated using the \( \dot{s}/\xi \) value obtained in the first step.

(iii) To calculate the values of parameters \( a, h_0 \) and \( S_\text{in} \), equation (3) will be used to fit the plastic strain at all temperatures and strain rates.

Table 1 lists the extracted Anand constants for SAC-Q materials tested in the ultimate tensile strength with the decrease in operating temperature to -65°C from +200°C. In addition, the UTS increased with the increase in the strain rate at any operating temperature measured in the test range of -65°C to +200°C.

<table>
<thead>
<tr>
<th>Anand Constant</th>
<th>UTS of SAC-Q (50°C Aged)</th>
<th>SAC-Q, Pristine, at Strain Rate = 50/sec</th>
<th>SAC-Q, Pristine, at Strain Rate = 50/sec</th>
</tr>
</thead>
<tbody>
<tr>
<td>( A )</td>
<td>5143</td>
<td>6005</td>
<td>6572</td>
</tr>
<tr>
<td>( \zeta )</td>
<td>4.28</td>
<td>4.28</td>
<td>4.28</td>
</tr>
<tr>
<td>( Q/R )</td>
<td>8444</td>
<td>8644</td>
<td>8644</td>
</tr>
<tr>
<td>( a )</td>
<td>1.2</td>
<td>1.2</td>
<td>1.3</td>
</tr>
<tr>
<td>( h_0 )</td>
<td>110353</td>
<td>100264</td>
<td>93765</td>
</tr>
<tr>
<td>( m )</td>
<td>0.59</td>
<td>0.52</td>
<td>0.47</td>
</tr>
<tr>
<td>( n )</td>
<td>0.0075</td>
<td>0.0059</td>
<td>0.0051</td>
</tr>
<tr>
<td>( \delta )</td>
<td>48.56</td>
<td>34.86</td>
<td>30.52</td>
</tr>
<tr>
<td>( s_0 )</td>
<td>1.99</td>
<td>1.75</td>
<td>1.7</td>
</tr>
</tbody>
</table>

The model constants included in Table 1 to Table 4 illustrate the behavior of all four materials at all test temperatures and strain rates for various aging durations. Fig. 1 to Fig. 4 compare experimental and model-predicted curves for the SAC305, SAC-Q, M758, and SAC-R, and they show a strong correlation. Each curve is the mean of five different curves. For model curves, the stress-strain data have been fitted using MATLAB using equations (2) and (3). Fig. 1 to Fig. 4 show curves with solid lines representing experimental data and dotted lines representing curves predicted by the Anand model. According to prior research [7]-[15], SAC solder materials are temperature and strain-rate-sensitive. Data shows that the
All of the solder alloys in the investigation exhibit the same patterns. The use of experimental results for a wide range of 12 operating temperatures and four strain rates used in computing the nine Anand parameters led to better prediction in the center range of temperatures, with the upper and lower temperatures showing a higher variation of the predicted stress-strain curve from the experimental data. In the center range of operating temperatures (50-125°C), less error was found for all solder materials. Particularly the Anand Model, predicts viscous plasticity. Both strain rate and temperature have an impact on material deformation behavior. According to the authors’ prior experience, it is possible to alter the model constants such that they are centered at the upper end or lower end of the operating temperatures to minimize deviation for those temperatures.

V. EFFECTS OF THERMAL AGING ON UTS AND E

The following section investigates how thermal aging affects different solder alloys. Two types of solder, SAC-Q and SAC-R, were aged at 50°C, while SAC305 and M758 were aged at 100°C for a maximum duration of one year. The impact of thermal aging on the ultimate tensile strength (UTS) and Young’s modulus (E) of all four solders is illustrated in Fig. 5 to Fig. 12. The results indicate that extended thermal aging deteriorates the mechanical characteristics of all four solders, across various strain rates and operating temperatures. Specifically, an increase in thermal aging time causes a decrease in both E and UTS values.

At a temperature of -65°C and a strain rate of 75 per sec, the highest values for UTS and E were observed as depicted in Fig. 5 and Fig. 6 for SAC-Q. Conversely, the lowest values were recorded at +200°C and 10 per sec. Thermal aging resulted in linear degradation of both mechanical properties. As the aging period increased from 0 to 360 days, the properties of SAC305 declined similarly to SAC-Q. The UTS and E values exhibited a decreasing trend after thermal aging. Fig. 7 and Fig. 8 depict the decline in UTS and E values at different strain rates for thermally aged SAC305 as the test temperature increased. The effects of aging on UTS and E for M758 and SAC-R solder are illustrated in Fig. 9 to Fig. 12 for up to one year of aging and operating temperatures ranging from -65 to +200°C at 10 to 75 per sec strain rates. Similar aging patterns were observed in all four SAC solder materials.
Observations have shown that SAC solder with bismuth content is less sensitive to thermal aging durations and operating temperatures, when compared to traditional SAC305 solder. Material properties values are higher for M758 and SAC-Q solder alloys in comparison to SAC305 and SAC-R. Among different solder alloys, M758 performed better in various aging conditions, possibly due to the presence of nickel and bismuth content in the alloy. Researchers Wu [21] and Hassan [22] reported that the microstructure of SAC-Q solder alloy experienced growth during aging in various durations. In comparison to SAC305’s particle increment of 300%, an increase in average particle diameter of over 100% was observed for SAC-Q during aging, but SAC-Q’s IMC particle coarsening was significantly mitigated compared to SAC305. Bismuth was observed in the beta-Sn dendrites and in the rich intermetallic regions between dendrites during aging.

Bismuth presence in SAC-Q base increases diffusion resistance to the Ag3Sn IMC particles [21]. The elastic modulus and the ultimate tensile strength of the SAC-R solder degrades to a lesser degree in comparison with the graph envelope for SAC305 over the same operating temperature conditions in the range of -65°C to +200°C. In addition, the temperature dependence of SAC-R constitutive behavior vs. SAC305 is lower at all strain rates in the range of 1-100s⁻¹ and exposure durations of time-temperature sustained exposure. The muted dependence of elastic modulus can be readily seen in the lower spread of the curves in Fig. 12. The resistance to aging and increases in mechanical properties were found to be directly proportional to the amount of Bismuth present in the SAC+X alloy [22].
VI. DROP TESTING

In order to show the capabilities of the measured Anand constitutive model, a drop event simulation based on finite element analysis (FEA) was carried out using ANSYSTM. From a drop event generated by FEA, hysteresis loops, and plastic work were extracted using the input-G method. The plastic work per cycle must be assessed in order to construct a damage model that accurately forecasts time to failure. The Anand parameters and other material characteristics utilized in the simulation were determined at the CAVE3 facility for pristine and aged SAC solders at high strain rates and elevated temperatures. In order to evaluate the damage trend in each solder connection, the hysteresis loop and plastic work density were retrieved. Fig. 13 depicts a test vehicle with a center-mounted PBGA324 package. The test board has the following measurements: 132 mm x 77 mm x 1.5 mm. It features a 1 mm pitch and 324 I/O counts for solder balls.

Fig. 13. Test Board with PBGA324 Package.

Fig. 14 depicts the ANSYS model for the test vehicle for the drop event. VISCO107 elements represent four critical/corner solder balls while the remaining solder junctions are represented by Timoshenko beam elements represented by BEAM188 components. The PCB and the other components in the package are SOLID45 components. The package assembly mainly consists of solder joints, Mold compound, silicon die, die attach, BT substrate, copper pad and PCB. The Poisson’s Ratio for each part ranges from 0.28 to 0.39 and the density for each part ranges from 8.82E-09 to 1.65E-09. The E values for solder joints has been taken from the Experimental data for the particular condition and strain rate where E values for other parts of the package assembly ranges from 2760 MPa to 162000 MPa, which are taken from previously published literatures.

Fig. 14. Modeled PCB- PBGA324 Package assembly.

Fig. 15. Cut-Section view of package.

Fig. 15 shows a meshed cut-view of a test vehicle component. Four mass components that were five orders of magnitude heavier than the test board’s real weight were constructed at the center of the PCB screw holes and then mounted to the PCB using a stiff element to employ the input-G method. The input acceleration has been applied to the mass node. The input force was calculated as the product of the mass of the mass node and the input acceleration. A shock pulse of 1500g and 0.5ms was employed to simulate the drop event. The tabular force data was used as a boundary condition to apply the proper acceleration to the mass elements in the test board. The preconditioned gradient solution was used to resolve the shock-impact problem.
A. Stress Distribution

The stress distribution for the critical solder joint was established using FEA-based modeling. A crucial solder connection can be observed near the corner of the package. The simulation has yielded the stresses and strains for the important solder connection. The critical solder junction of a package is shown in Fig. 16 as a stress contour plot in the y-direction (σ_y). The solder connection and the copper pad had the highest observed stress.

![Fig. 16. Contour plot of stress distribution in critical solder joint](image)

B. Stress-Strain Hysteresis Loops and Accumulated Plastic Work

Plastic work densities and stress-strain results of critical solder ball were retrieved using FEA-based simulation employing the volume average technique, which may help reduce the impact of mesh density on finite element results. The average plastic work values are calculated using the top layer of the essential solder ball.

![Fig. 17. Stress-Strain Hysteresis Curves for pristine and 360 days aged SAC-Q Solder Alloy: (a) -65°C, (b) at 200°C](image)

![Fig. 18. Stress-Strain Hysteresis Curves for pristine and 360 days aged SAC305: (a) -65°C, (b) at 200°C](image)

For the critical solder ball layer shown in Fig. 16 the stress-strain data are extracted in the y direction to represent the hysteresis loop for SAC solder alloys at extreme operating temperatures of -65°C and 200°C as shown in Fig. 17 to Fig. 20. According to results, peak stress levels fall as operational temperatures rise. The hysteresis loop area increased for all solder alloy as the aging duration increased from pristine to up to one year.

![Fig. 19. Stress-Strain Hysteresis Curves for Pristine and 360 days aged M758: (a) -65°C, (b) at 200°C](image)

![Fig. 20. Stress-Strain Hysteresis Curves for Pristine and 60 days aged SAC-R Solder for: (a) at -65°C, (b) at 200°C](image)

VII. SUMMARY AND CONCLUSIONS

This study aims to investigate how low working temperatures and high strain rates affect the mechanical properties of un-doped solder SAC305 and doped solders like SAC-Q, M758, and SAC-R, both in unaged and isothermally aged samples over a prolonged period of up to one year. The study conducted high-strain rate tensile tests at temperatures ranging from -65 to 200 °C to establish stress-strain relationships. The results indicate that the elastic modulus and ultimate tensile strength of all SAC solders depend on the strain rate and increase with it. The study also found that all the SAC solders exhibit increased mechanical characteristics when the temperature decreases to -65 °C. The study further explored the impact of thermal aging on the mechanical properties of SAC305, SAC-Q, SAC-R, and M758 solders at extreme working temperatures. The findings suggest that compared to traditional SAC-R and SAC305 solders, the isothermal aging has less impact on the material characteristics of M758 and SAC-Q solders. Moreover, the study discovered that thermal aging had less impact than operating temperature for all the solder alloys examined in the research. In order to forecast the stress-strain curves, the research extracted nine Anand
parameters from the stress-strain data. The Anand Viscoplasticity constants were subsequently used to match the experimental material data using MATLAB's nonlinear least squares technique. The experimentally achieved stress-strain data correlates well with stress-strain curves derived from Anand Model constants. ANSYS™ was utilized to simulate a drop/shock event through FE analysis, with the extracted Anand constants and other experimental material parameters used to model the PCB-Package assembly. The simulation revealed that the solder joint and copper pad were most stressed during the drop event. Furthermore, plastic work in the solder joints was evaluated by performing an FEA-based drop simulation at 1500g under extremely high and low ambient temperatures. The hysteresis loop evolution and plastic work density were determined for various thermal aging durations.

ACKNOWLEDGMENTS
The research results presented in this paper have been supported by a grant from the National Science Foundation and members of NSF-CAVE3 Electronics Research Center.

REFERENCES