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DOI
10.1109/EuroSimE60745.2024.10491536

Publication date
2024

Document Version
Final published version

Published in
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Abstract

SnAgCu solder joint has oligocrystalline (few large grains) structure and due to body-centered tetragonal (BCT) structure, each grain shows strongly anisotropic behavior. Modelling anisotropic behavior of grain scale solder joints has been extensively researched by this group. In this paper, anisotropic grain-scale plasticity model is used to predict variability of solder joint fatigue durability under sine sweep vibration excitation. Solder experiences different levels of cyclic stress for different grain orientations. Stress-based high cycle fatigue (HCF) model (Basquin's model) and Miner's rule are used for determining the variability of vibration durability of solder joints for different orientations and compared with experimental results.

Keywords- *SAC305, oligocrystalline joint, sine sweep, vibration durability, grain-scale finite element model, multiscale analysis, Miner's rule, Basquin high-cycle fatigue model*

I. INTRODUCTION

Electronic products and thus interconnects are subjected to mechanical loading condition such as impact, vibration and bending as per application during its life cycle. Studies have been conducted on determining durability of SnAgCu (SAC) solder joint under harmonic or random vibration conditions [1-4]. Different clamping conditions and excitation levels are applied as per the application and there is also different ways []. Excitation level affects strain in solder joint per cycle and clamping conditions affect deformation modes in printed wiring board (PWB). Along with that effect of environmental factors such different isothermal and thermal cyclic conditions affect the durability of solder joint [5]. Conventionally for predicting the reliability of solder joint large number of tests are conducted and fatigue model constants are determined by correlating mean sweeps to failure (MSTF) and solder strain range, stress range or energy from simulation [2, 5]. SAC solder joints are modelled to be homogenous isotropic material during the simulation. Microstructure research on SAC solder alloys indicate that SAC solder joint consists of few large size grains (oligocrystalline) and within each grain is a composite of Body Centered tetragonal (BCT) Sn and Ag3Sn intermetallic compound (IMC). Higher percentage of B-Sn creates anisotropy in SAC305 solder joint. Grain orientation and other microstructural features affect the mechanical behavior of oligocrystalline solder joint [6,7]. Research has been conducted on modelling behavior of solder by considering SAC solder microstructure and anisotropy due to Sn [6, 8]. Variability in the behavior of anisotropic solder joint under multiaxial loading condition has been presented for thermomechanical cycling and cycling mechanical bending [9, 10]. In this article, this research has been extended by implementing grain scale anisotropic plastic properties on vibration durability test and comparing simulation results with experimental observation.

Experimental data from previous study is used modelling and determining confidence bounds on solder failure data. Brief explanation about the experiment is provided first which is followed by modelling approach to imitate the sine sweep vibration durability test. Objective of this article is to present high cycle vibration calibration method and use of anisotropic modelling to capture the observed variability is presented after modal harmonic global-local modelling approach. Fatigue modelling is done and variability is predicted based on simple anisotropic cases of solder joint. Conclusion and future work are presented in the end.

IV. SINE SWEEP DURABILITY EXPERIMENT AND MODELLING METHODOLOGY

Response of solder joints subjected to sine-sweep vibration loading conditions in prior tests [1] is analyzed with global-local finite element modeling scheme, to assess fatigue durability of solder joints. The tests used PWAs with 15 BGA components, mounted at four corners (Fig. 1). The model was calibrated using the tested fundamental frequency of the board (357±2Hz) and the tested response to the sine sweep excitation during the durability test (between 300-360Hz with sweep rate 5 octave/min, to excite only the fundamental response mode). The finite element model response history for solder joints of the components in the center column (U3, U8, U13) is combined with Basquin's HCF model, to determine the number of cycles to failure (fatigue durability). Durability results are compared with experiments (Fig. 2).

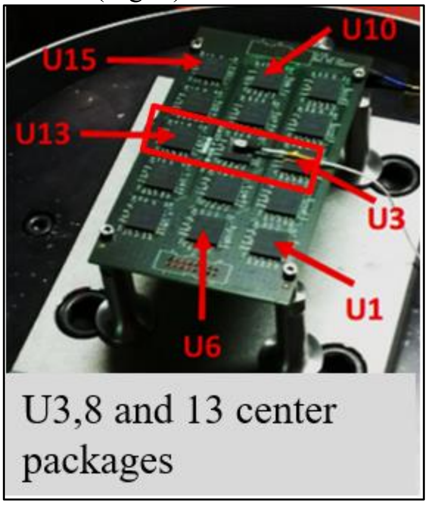

Figure 1: Test Setup for Sine Sweep [1]

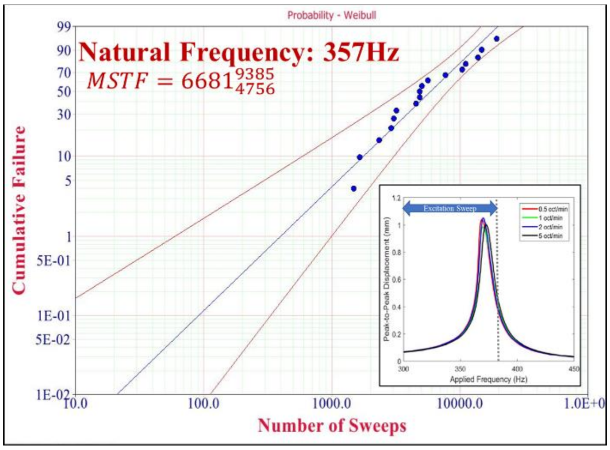

Figure 2: Weibull Distribution of Failed Center Packages [1]

PWB harmonic simulations are conducted using a global FEA model the consists of shell elements with linear elastic anisotropic properties. Mass of the accelerometer and components and the stiffening effect of components are included in this model, using methods described elsewhere [11]. The stiffening factor for the modeled BGA is found to be 3.25. Modal harmonic analysis is conducted by discretizing the sine-sweep excitation into five different frequencies in the given range. The response is predominantly in the fundamental mode (Fig.1).

The response of the global FEA model for each frequency is transferred to a detailed quasi-static elastic-plastic local model of the BGA package in the center of the PWB, using a quarter-package model due to the symmetry of the package and the deformation mode. Four fatigue cycles were modeled and the highest stress amplitudes (in the corner solder joint) were recorded**.** Solder joint dimensions are shown in Fig. 3. Interface region between solder and copper pad experiences the highest stress so the stress response amplitude in this critical region is considered for fatigue modeling and calibration at each frequency.

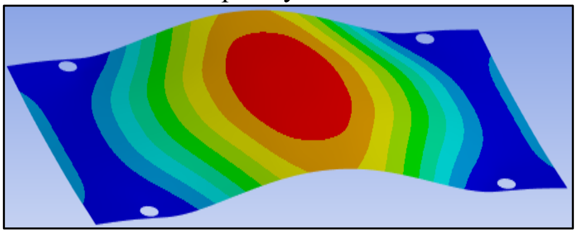

Figure 3: Deformation Profile in First Mode of Vibration

A (μm)	350
b (μm)	15
c(μm)	41
d (μm)	306
e(μm)	450

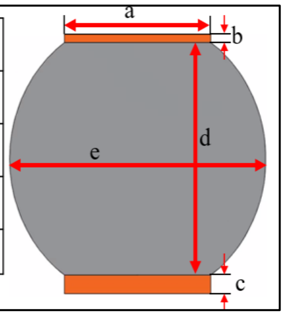

Figure 3: Solder Ball Dimensions

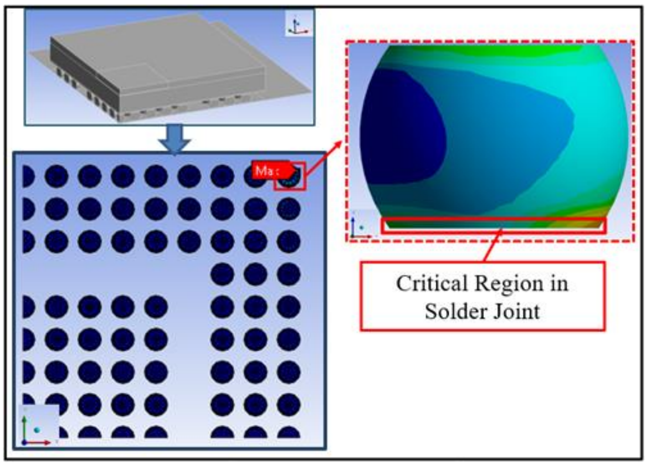

Figure 4: Quarter Model and Critical Solder Joint

III. Time to Failure Modelling

Cyclic fatigue damage due to each modeled frequency is considered, for modeling the sine-sweep vibration durability test. The PWA experiences the same number of cycles at each frequency during sine-sweep due to the sweep rate scheme used in the test. Time to failure is estimated with Basquin high-cycle fatigue model (Eq. 1) and Miner's rule (Eq. 2) :

$$\Delta\sigma_{eq} = \sigma_f \left(2N_f\right)^b \qquad 1$$

$$\sum_{i=1}^{5} \frac{n_i}{N_i} = 1 \qquad 2$$

Where, $\Delta\boldsymbol{\sigma}_{eq}$: Equivalent stress range
σ_f : Fatigue strength coefficient
b : Fatigue strength exponent
n_i: Actual cycles at i[th] frequency
N_i: Cycles to failure at i[th] frequency

The fatigue model constants in Basquin'e HCF model (Eq. 1) are determined by using the stress range predicted by the FEA global-local model, the damage accumulation model (Miner's rule) in Eq. 2, and the mean cycles to failure (MCTF) measured from mean sweeps to failure (MSTF) in the test. Corner region near PWB is a high stress concentration region. Average stress in the first element layer of stress concentration region is used to determine high cycle fatigue model constants. Resulting Model constants are shown in table 1.

Table 1: Basquin Constant

$\boldsymbol{\sigma_f}$	b
62.92	-0.071

IV. Prediction of Variability

Cross polarized microscopy is conducted on sample BGA solder joints to analyze the grain morphology in SAC solder joints. Fig. 5 shows that solder joint contains either single grain, or a few large grains.

Figure 5: Single and Oligocrystalline Solder Joint

To predict the variability due to different grain structures, grain scale anisotropic model is implemented on single crystal and tri-crystal solder joint morphologies in the critical (corner) solder joint. Total number of cases with all different normal orientations and single, bi-crystal and tri-crystal grains are twenty-seven. Based on cyclic mechanical bending study only two corner cases of anisotropy are considered (Fig. 6) and compared with upper and lower bounds obtained from 95% confidence interval of experimental data.

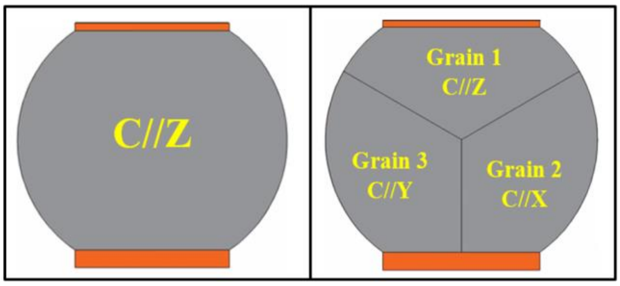

Figure 6: Anisotropic Grain Morphologies for Critical Solder Joint

Anisotropic elastic properties of SAC305 solder joint [6] are shown in table 2. All values are in GPa

Table 2: Elastic Constants for SAC305 Solder

C11	C22	C33	C44	C55	C66	C12	C13	C23
73.2	73.5	89.3	22.3	22.3	24.2	59.6	36.3	36.4

Hill potential for anisotropic plasticity is combined with Ramberg Osgood (RO) flow model for modelling anisotropic plasticity. Eqs. 3 and 4 indicate Hill potential and RO model.

$$\sigma_{Hill} = \sqrt{\begin{matrix} \boldsymbol{F}(\sigma_{22}-\sigma_{33})^2 + \boldsymbol{G}(\sigma_{33}-\sigma_{11})^2 + \boldsymbol{F}(\sigma_{11}-\sigma_{22})^2 \\ +2\boldsymbol{L}\sigma_{23}{}^2 + 2\boldsymbol{M}\sigma_{13}{}^2 + 2\boldsymbol{N}\sigma_{12}{}^2 \end{matrix}} \qquad 3$$

Where, σ_{Hill}: Hill Stress
F, G, H, L, M and N: Hill constants

$$\boldsymbol{\sigma = K\varepsilon_p{}^n} \qquad 4$$

Where, σ : Effective Hill Stress
ε_p: Effective Hill Plastic strain
K: Strength Coefficient
n: Strain hardening exponent

Table 2: Hill-RO Model Constants for Single SAC305 Solder Crystal [6], stresses are in MPa

Hill Constants				RO Constants	
F=G	H	L=M	N	K	n
0.5	0.95	1.2	1.29	88	0.225

Deformation in solder joint for different grain morphologies are determined based on Hill-RO model constants [6]. Dimensions of BGA solder joint are given in Fig. 3. Grain boundaries acts as a barrier for dislocation motion during plastic deformation. Hall-Petch equation is used to scale the solder grain properties (RO model constants) based on its size, when modelling tri-crystal joints. Hill constants are kept constant, assuming degree of anisotropy will remain the same for a given material.

The stress-strain curve in Fig. 7 reveals that the highest yield strength occurs for the small grain tri-crystal structure and the lowest for a single crystal joint. Isotropic solder plastic curve is in between these two corner cases.

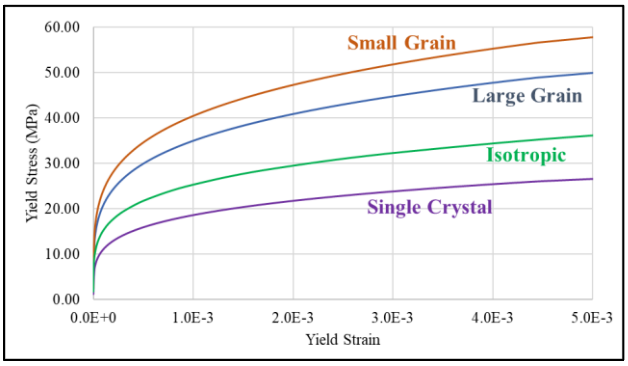

Figure7: Grain Scale Properties of Solder Joint and Comparison with Isotropic Properties

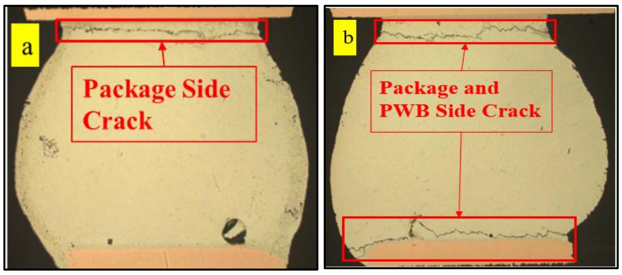

Figure 8 Different Failure Modes in Solder Joint under Vibration Testing

Failure analysis of the solder joint indicates competing failure sites at the top and bottom interfaces (Fig. 8a and Fig. 8b), with the grain morphology often deciding which interface is more vulnerable Modelling solder joint as an isotropic homogenous material will result in only one failure mode (failure near PWB side). Simulation indicated that single crystal solder joint showed stress concentration near PWB side where as tri-crystal solder joint showed high stress concentration near the package side. So, anisotropic grain scale plastic modeling of solder joints is able to explain both observed failure modes (Fig. 9). Solder joint durability for each grain morphology is assessed by averaging the stress over one layer of elements at the critical interface.

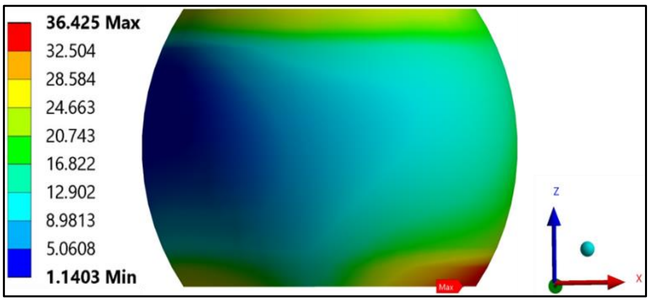

Figure 9a: Single Crystal Solder Joint with Grain Orientation C||Z

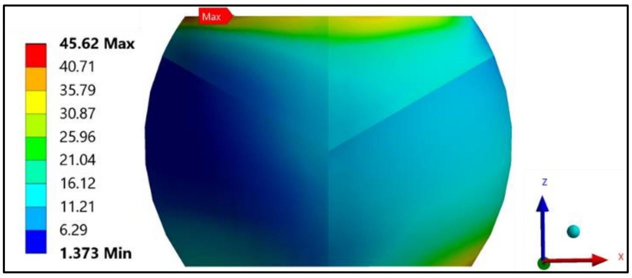

Figure 9b: Tri-Crystals Solder Joint with ZXY as Grain Orientation

Life of solder joint with different orientations resulted in different average equivalent stress values and model constants from Table 1 are used to determine fatigue durability. Equivalent stress is Hill stress (Eq. 3) in case of anisotropic modelling and von Mises' stress in case of isotropic modeling. Predicted life for single crystal solder joint with z-axis of solder joint parallel to global Z-axis is 2792 sweeps and 22329 sweeps for ZXY tri-crystal SAC305 solder joint. Anisotropic grain scale modelling of solder joint resulted in wider bounds, compared to values obtained from experiment (Fig. 10). The upper and lower bounds for the experiments are determined from 97.5% and 2.5% confidence intervals.

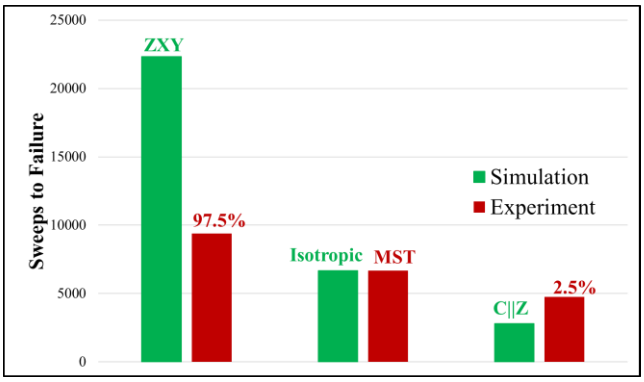

Figure 10: Comparison between Simulation and Experimental Results

IV. CONCLUSION

Objectives of this study are to demonstrate the global local modelling technique for harmonic vibration analysis using ANSYS workbench and analyze the variability captured by grain scale anisotropic modelling of SAC305 solder joint. Failure modes observed in simulation are compared with experiment and regions of stress concentration are found to matching with crack sites seen in the experiments. Limited number of extreme grain morphologies are modeled here, for illustrative purposes. This study can be improved by modeling other intermediate grain orientations of oligocrystalline solder joints. Grain orientation and size of grains have been used to conduct anisotropic grain scale simulation on solder joints to predict the observed variability in fatigue durability.

Aknowledgement

This work is sponsored by the members of the CALCE Electronic Products and Systems Consortium at the University of Maryland, College Park.

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