Failure prediction of the solder joints in the ball-grid-array package under thermal loading

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Abstract. This paper studies the numerical failure mechanism of the solder joints in the ball grid array (BGA) package under thermal reliability process. The package consists of the silicon die, the Flame Retardant 4 (FR-4) substrate and the FR-4 printed circuit board (PCB). A total of 64 95.5Sn-4.0Ag-0.5Cu (SAC405) solder joints with a diameter of 0.46 mm are arranged together in area array fashion with a pitch distance of 0.8 mm. Only a quarter-model of the package is simulated since all the geometry, loading and boundary conditions (BC) is symmetry at the centre of the package. The package is exposed with thermal loading, initially at the liquidus temperature of 220°C to room temperature (25°C). Then, it follows with 3 additional thermal cycles between 125°C and -40°C with a ramp rate of 11°C/min and 15 minutes dwell time, respectively. Unified inelastic strain model (Anand model) was used to compute the inelastic behaviour of the solder joints. Results show that the stress level at the critical solder joints and the corresponding inelastic strain are 39.91 MPa of 0.2083%, respectively after the end of the solder reflow cooling process. As predicted, the inelastic strains accumulate continuously in the solder joint throughout the temperature cycles. Additionally, in the critical solder joint, both high stress and inelastic strain gradients are localized near to the solder-IMC interfaces. Prolong the thermal cycles can extensively accumulate the inelastic strains which lead to fatigue crack and subsequently crack propagation in the solder joints. After the end of the FE simulation, the highest stress and inelastic strain predicted are 57.96 MPa and 0.5781%, respectively.

1. Introduction
Reliability of the solder joints is the core engineering problem in electronic industries because the solder joints are the weakest connections in the electronic package. Nowadays, the risk keeps increasing due to the demand for the smaller size and high computing performances of the chips. The size of the solder joints keeps decreasing but more inputs and outputs needed in the package. Thus, the mechanical integrity of the connections must be investigated due to high thermal generated during the electronic duty-cycle and has a high chance of creep failures occurs in the solder joints. In this respect, the numerical model of the ball-grid-array (BGA) package can be used to predict the inelastic behaviour of the solder joints under such loading. Accurate simulation may help the designer to interpret the mechanic behaviour in the electronic package, especially at the solder connections before finalizing the layout design. This may help the designer to design the electronic package faster with minimal design faulty.

Since 2003, the law had enforced all electronics industries to use lead-free solder as a substitution in solder joints connections [1]. In this respect, there have been numerous developments of leaded alternative solder alloys such as the combination between tin, silver, and copper (SAC). One of the most...
popular SAC solder material is 95.5Sn-4.0Ag-0.5Cu (SAC405). Although there is a fairly number of studies on lead-free solders, the research related to the numerical analysis of the solder joints failure in ball-grid-array (BGA) under thermal loading is quite limited. The numerical approach methodology such as Finite element (FE) modeling and analysis can be used to simulate the failures process in the solder joints. But the accurate prediction is necessary especially in the response of the solder material since the BGA packages experience high-temperature variations where creep is the dominant process. Thus, numerous temperature and strain-rate dependent experimental data of the solder alloys must be considered in developing the appropriate response of the solder material. In this study, the FE model and analysis is employed to examine the mechanic’s behavior and reliability of the solder joints in a typical BGA package using SAC405 solder joints. The results are explained in term of stress and inelastic evolutions in the critical solder joint.

2. Unified Constitutive Equations of Solder Material

The inelastic behaviour of SAC405 solder material under different temperatures and strain rates can be described using a unified inelastic strain model developed by Anand and Brown [2], [3]. In this model, the inelastic flow, $\dot{\varepsilon}_{in}$ as illustrated in equation (1) is depending on the internal state variable, $s$ which continuously evolved as depicted in equation (2). The advantage using Anand model are 1) no explicit yield condition is necessary to compute the inelastic behaviour of the material and 2) a single internal variable is enough to represent the isotropic resistance in inelastic flow. The details of the model can be illustrated in equation (1), equation (2) and equation (3).

Flow equation:

$$\dot{\varepsilon}_{in} = A \exp \left( -\frac{Q}{RT} \right) \left[ \sinh \left( \frac{Q}{RT} \right) \right]^{1/m} \tag{1}$$

Evolution of internal state variable, $s$:

$$\dot{s} = \left\{ \begin{array}{ll} h_0 & \left| 1 - \frac{s}{s^*} \right|^a \sign \left( 1 - \frac{s}{s^*} \right) \end{array} \right\} \dot{\varepsilon}_{in} \tag{2}$$

with:

$$s^* = \hat{s} \left[ \frac{\dot{\varepsilon}_{in}}{A} \exp \left( \frac{Q}{RT} \right) \right]^n \tag{3}$$

where $\sigma$ is equivalent inelastic stress and $T$ is the temperature in absolute scale. Table 1 shows the Anand model parameters and constants.

| Table 1. Model parameters for unified inelastic strain model for SAC405 solder material |
|---------------------------------|------------------|
| Anand model parameters          | Values           |
| Initial value of state variable, $s_0$ (MPa) | 47.86            |
| Activation energy term, $Q/R$ (1/K) | 9840             |
| Pre-exponential factor, $A$ (1/sec) | 2254             |
| Stress multiplier, $\xi$        | 36.70            |
| Strain rate sensitivity of stress, $m$ | 1.2893          |
| Hardening coefficient, $h_0$ (MPa) | 5421475         |
| Coefficient for deformation resistance saturation value, $\hat{s}$ (MPa) | 92.14            |
| Strain rate sensitivity of the saturation value, $n$ | -0.009117        |
| Strain rate sensitivity of the hardening coefficient, $a$ | 3.667            |

These model parameter values listed in table 1 are determined using published SAC405 experimental data [4] tested at various temperatures (25 °C to 150 °C) and different inelastic strain rates ($10^{-5}$ s$^{-1}$ to
The parameters were obtained by implementing the non-linear optimization techniques (particle swarm and Nelder-Mead algorithm) and non-linear least square method. The parameters obtained from the optimization techniques were compared with the experimental data to validate the numerical prediction of inelastic strain and flow stress response. Figure 1, figure 2 and figure 3 show the comparison between predicted responses of SAC45 solder using table 1 model parameter values and experimental data [4] at different temperatures and inelastic strain rates. The result shows that a prediction model can capture a good correlation with experimental data. These model parameters are then employed in the BGA package simulation subjected to reflow cooling and temperature cycling for numerically predicted the deformation behavior of the solder material.

![Figure 1](image1.png)

**Figure 1.** Comparison of stress-inelastic strain curves between predicted and experimental data for SAC405 at temperature 25 °C with different strain rates [4].

![Figure 2](image2.png)

**Figure 2.** Comparison of stress-inelastic strain curves between predicted and experimental data for SAC405 at temperature 75 °C with different strain rates [4].

### 3. Finite Element Model and Analysis

A typical BGA package consists of a silicon die (4.8 mm x 4.8 mm x 0.29 mm), a flame retardant (FR-4) substrate (10 mm x 10 mm x 0.26 mm) and FR-4 printed circuit board (PCB) (20 mm x 20 mm x 1.6 mm) [5]. A total of 64 solder joints are arranged in area array fashion with pitch distance between them is 0.8 mm. Each solder joint has a diameter of 0.46 mm and stand-off height 0.3 mm. The final geometry of the solder joints after the reflowed cooling process is computed using Surface Evolver software [6]. In this simulation, 2 µm of Cu₅Sn₆ intermetallics (IMC) layer is assumed to have developed between the solder/copper pad interface [7]. Since all the geometries, loads and boundary conditions are symmetry at the cutting planes as shown in figure 4, only a quarter-model is considered. A total number of 242708 continua three-dimensional linear hexahedral with incompatible modes, C3D8I is generated. All contact surfaces are assumed to be perfectly bonded throughout the simulation. A preliminary run of the model indicates that the
solder joint underneath the top corner of the die is the critical solder joint label as D1 solder joint illustrates in figure 5.

![Solder joint](image)

**Figure 3.** Comparison of stress-inelastic strain curves between predicted and experimental data for SAC405 at temperature 150 °C with different strain rates [4].

![Finite element model](image)

**Figure 4.** Finite element (FE) model of the quarter BGA package assembly.

![Finite element detail](image)

**Figure 5.** Detail of the finite element (FE) model of the solder joints. Critical solder joint located at the D1 solder joint.

In this analysis, the symmetry boundary conditions were applied along the cutting planes (X = 0 and Y = 0) label as Y-Symmetry and X-Symmetry as shown in figure 4. A node in the center point was fixed (Ux = Uy = Uz = 0) to prevent rigid body motion. The thermal load profile consists of a two-stage thermal process which are solder joint reflow cooling and thermal cycles. The solder reflow process is subjected
to temperature from 220 °C to 25 °C at a cooling rate of 80 °C/min. Meanwhile, the cyclic temperature ranging between 125 °C and -40 °C at 11°C/min with 15 minutes dwell time at each peak temperature levels [8]. The detail of the temperature profile is summarized in figure 6.

Figure 6. Temperature loading profile. Reflow cooling profile at the beginning and continue with 3 thermal cycles profile.

The solder material inelastic response is described using unified inelastic strain theory as proposed in equation (1), equation (2) and equation (3). Other materials are assumed to behave elastically throughout the simulation. Detail of the material properties is depicted in table 2.

Table 2. Material properties used for this study where \( T \) is the temperature in °C [4], [9]–[12].

| Material | \( E \) (GPa) | \( G \) (GPa) | \( v \) | CTE (ppm/°C) |
|----------|---------------|---------------|--------|---------------|
| SAC405   | 44.7-0.146\( T \) | -             | 0.36   | 20            |
| Silicon  | 132.46-0.00954\( T \) | -             | 0.28   | 2.113+0.00235\( T \) |
| Copper   | 141.92-0.04427\( T \) | -             | 0.35   | 15.64+0.0041\( T \) |
| Cu6Sn5   | 85.6          | -             | 0.31   | 16            |
| FR-4     | In plane: 17.823-0.037\( T \) 8.0409-0.0167\( T \) | 0.11   | 16       |
|          | Out of plane: 7.836-0.016\( T \) 3.5071-0.0073\( T \) | 0.39   | 84       |

4. Results and Discussion
The finite element results are presented and discussed in terms of the evolution of stresses and inelastic strains distributions in the critical solder (label as D1 in figure 5) during reflowed cooling and continue with three temperature cycling.

4.1. Stress and inelastic strain distributions during the solder reflow process
The evolution of von Mises stresses and the corresponding equivalent inelastic strains in the critical solder joint throughout the thermal loading is illustrated in figure 7 and figure 8. The stress scale is in MPa. Label A in figure 7 and figure 8 indicated the stress and inelastic strain distribution of critical solder after the end of the reflow cooling process (25°C). The solder joint is deforming at the beginning of the reflowed process even though the stress level in the solder joint is in the lower state value. This deformation is due to the creep deformation at the high-temperature region. Additionally, a high-stress gradient develops at the edge of the solder near the solder intermetallic interface indicating the mismatches of thermal expansion between the solder material, copper pad and Cu6Sn5 intermetallic resulting in severe geometry discontinuities. Such a high-stress region yields the solder material to permanently deformed. At the end of the solder reflow cooling process, the von Mises stress reaches 39.91 MPa with the corresponding inelastic strain of 2.08% at 25°C.
4.2. Stress and inelastic strain distributions during thermal cycles

The results of equivalent stress and inelastic strain for 3 temperature cycles are depicted in figure 7 and figure 8. Each label in figure 7 and figure 8 indicating thermal state during thermal cycles. The details of each thermal state can be referring to figure 6. The results of the first, second and third cycles are labelled from A to F, F to K and K to P, respectively. For each cycle, the temperature starts from 25°C (label A, F, and K) and increased linearly until reached temperature 125°C (label B, G, and L). Then, the temperature maintains at 125°C about 15 minutes (label C, H, and M). The temperature decreased linearly from 125°C to temperature -40°C (label D, I and N). And it continues with soak temperature at -40°C (label E, J, and O) in 15 minutes. Lastly, the temperature increased linearly from -40°C to 25°C (label F, K, and P).

In the early of the first cycle, the distribution of von Mises stress reduced from average 35 MPa (label A) to 10 MPa (label B). This is due to the rising temperature from 25°C to 125°C, release its internal stress developed inside the solder joint. At soak temperature 125°C, the stress increased slowly (label C) in the solder joint because of the deformation due to the creep deformation in critical solder. When the solder was cooled from 125°C to -40°C, internal stress developed (label D) inside the critical solder joint and reached up to 57.18 MPa. This is the state where the highest stress predicted in each cycle. It is noted that the high-stress gradient manifests between solder interfaces at the PCB and component side, respectively. As discussed earlier in section 4.1, the high-stress region near solder interfaces is due to the mismatched of thermal expansion between different materials in the package. There are minor changed of stress distribution (label E) after the solder joint maintained at -40°C. Since, no rapid cooling at this point, the solder joint is in the relaxing process (stress relief). In the last part of the first temperature cycle, the stress distribution of the solder joint reduced from high-stress condition to the average stress distribution of 25 MPa (label F). For the second (label F to K) and the third (label K to P) thermal cycles, the stress level in the critical solder joint are almost identical with the first cycle but differs in term of stress magnitude. Results show that the highest stress values computed for first, second and third cycles are 57.18 MPa (label D), 57.67 MPa (label I) and 57.96 MPa (label N), respectively. Meanwhile, for its corresponding inelastic strain, the calculated values were 0.4195% (label D), 0.5084% (label I) and 0.5781% (label N), respectively. The increase in stress magnitude is accompanied by the accumulation of inelastic strains due to the creep mechanism. Further thermal cycles will eventually lead to extensive accumulation of inelastic strains resulting in crack initiation and subsequent crack propagation near to solder/IMC interfaces.

Figure 7. Evolution of von Mises stress distribution at critical solder joint.
5. Conclusions
The response of a BGA assembly with SAC405 solder joints during solder reflowed and thermal cycles have been examined using finite element (FE) simulation. Results show that the computed residual von Mises stress reach up to 39.91 MPa and its corresponding inelastic strain of 0.2083% after the end of the solder reflowed process. In the critical solder joint, both high stress and inelastic strain gradients are localized in a small edge region at the solder-IMC interfaces. During thermal cycles, the highest predicted stress at the critical solder joint is 57.96 MPa. The accumulated inelastic strain after the first, second and third thermal cycle is 0.4195%, 0.5084%, and 0.5781%, respectively. The subsequent cycles may lead to crack initiation and propagation near to solder/IMC interfaces.

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