EVOLUTION OF INTERNAL STATES IN A SN-PB SOLDER JOINT DURING RE-FLOW AND THERMAL CYCLES

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Abstract: Solder joint is one of the weakest links in an electronic PCB assembly, thus creating reliability concern. In this study, the deformation response of such assembly during solder re-flow and thermal cycling test is investigated. The objective is to examine the evolution characteristics of internal states in the solder joint. For this purpose, a test package with 92 solder joints arranged along the peripheral of a 24x24 solder array is analyzed using finite element method. Strain-rate-dependent plastic stress-strain curves define the viscoplastic response of the 60Sn-40Pb solder alloys. Results of the analysis show that the test package warps downward (with PCB on the bottom side) at room temperature with a magnitude of 93 µm following the re-flow process. In the critical solder joint, inelastic strain accumulates to 0.856 percent. Additional inelastic strains of 3.5 and 2.2 percent are accumulated in the solder after three temperature cycles at (-40 to 125 °C) and (-25 to 100 °C), respectively. Thermal shock loading (at 11.2 percent faster temperature ramp rate) accelerates the evolution of inelastic strain per cycle. However, the accumulated inelastic strain after three temperature cycles is 12 percent lower. A 10-minute dwell time at both extreme temperature levels is found to have small effect on the evolution of internal states in the solder joint.

INTRODUCTION

The relatively large thermal expansion mismatch between the electronic components and the printed circuit board (PCB) leads to package warpage and poor solder joint reliability. The reliability of these solder joints is determined by the combined effects of component design, assembly design and use environment. During solder re-flow process, intermetallic compounds are formed between the solder and electrical pads and gradually grow in service. Due to its brittle nature, the reliability of solder joints is expected to degenerate. In chip scale package (CSP), the shear stress due to thermal expansion mismatch prevailed over warpage of the package in causing solder ball cracking [Lee et al., 1998]. In addition, temperature fluctuations and in-circuit power on/off creates stress reversals and the accumulation of inelastic strain in the joints and interfaces. Thus, low cycle fatigue is a common failure mechanism in the packages.

Faster acquisition of reliability data could be achieved through accelerated thermal cycling tests where the solder joints are subjected to severe temperature cycling ranges, typically in the range from 125 to –40 °C. The evolution of stresses and strains throughout the temperature cycles determines the accumulation of fatigue damage in the solder alloy. The extent of accumulated damage, in turn, determines the fatigue life of the solder joint. Various parameters, often related to stress-strain behavior at a point in the joint over one cycle, have been proposed to estimate accumulated damage in solder joint. These include measurable physical quantity such as inelastic strain range, \( \Delta \varepsilon_{\text{in}} \), and the area of hysteresis loop, \( \Delta W \). Solder joint fracture occurs when the accumulated damage exceeds its critical level.

Numerical modeling by finite element analysis offers an effective means of understanding and predicting solder joint reliability. Numerical results provide insights of the internal states of the solder alloy when subjected to applied load cycles. Its success lies in appropriate representation of the package geometry with associated boundary condition, reproduction of temperature loading and the ability to accurately simulate the response of
package materials during thermal cycling or shock. In this respect, properties of solder alloy and their time and temperature variations within the range of interest must be empirically determined. Accurate description of solder alloy behavior accounts for both temperature and time-rate effects on the material as observed experimentally. The tensile strength of eutectic Sn-Pb solder decreases from about 50 to 30 MPa following 60 days of thermal aging [Kishimoto et al., 2001]. In addition, solder tensile properties can vary widely for different strain rates used in the tensile tests [Pang et al., 1998]. Thus, modeling of the solder with elastic or elastic-plastic (time-independent) behavior will lead to oversimplifying assumptions regarding the solder behavior.

Several different temperature cycling profiles (combinations of ramp rates, dwell times and temperature ranges) are employed for qualification of electronic products. The different ramp rates used in thermal cycling or shock are related to the strain rate effect of the solder mechanical properties. In this study, the deformation response of near-eutectic solder joints connecting packages to PCB during re-flow and subsequent thermal cycling test is investigated with the objective of examining the evolution characteristics of internal states in the solder joint. The relative effects of test temperature ranges, ramp rates and dwell time on deformation of the package are examined in terms of inelastic strain accumulation in the solder alloy.

FINITE ELEMENT MODELING

The finite element method has been employed to examine the evolution characteristics of internal states in Sn-Pb solder joints during re-flow and subsequent thermal cycles. Model of the test package consists of 92 solder joints arranged along the peripheral of a 24x24 solder array. The diameter, height and pitch distance of the solders is 760 µm, 600 µm and 1.0 mm, respectively. Due to symmetrical nature of the package, only one-quarter of the 3-D model is analyzed. Exploded view of the model and cut-out section of a solder joint is illustrated in Figure 1. The various different materials considered in the simulation are Si-die, near eutectic solder joints, Cu-traces, Cu₆Sn₅ intermetallics, FR-4 substrate and PCB. Thermal analysis performed on the test package indicates that the transient effect is negligible, thus thermal boundary condition is not imposed in the stress analysis.

![Fig. 1: Exploded view of the test package (quarter model). The inset figure shows detail cross-section view of a solder joint.](image)

Temperature dependent material properties of Si, solder alloy, Cu-traces and FR-4 employed in the analysis are extracted from published literature [Adams,1986; Amagai,1999; Auersperg,1997; Pang et al.,2002]. Strain-rate-dependent plastic stress-strain curves define the viscoplastic response of the 60Sn-40Pb solder alloys while other materials are assumed to behave elastically throughout the analysis. In addition, orthotropic behavior of FR-4 substrate and PCB is considered. Thermal loading of the test package consists of an initial cooling down from re-flow temperature at 183 °C to room temperature, followed by thermal cycling between –40 to 125 °C (See Figure 6). The effects of different temperature range, dwell time at extreme temperature levels and temperature ramp rates on the evolution characteristics of stresses and strains in the solder joints are examined using load cases as shown in Table 1. Each load case consists of three temperature cycles following solder re-flow process.
Table 1  Different temperature cycles employed in the study.

<table>
<thead>
<tr>
<th>Load Case</th>
<th>$\Delta T$ (°C)</th>
<th>Ramp rate (°C/min)</th>
<th>$t_{dwell}$ (mins)</th>
</tr>
</thead>
<tbody>
<tr>
<td>TC1 (ref.)</td>
<td>-40 to 125</td>
<td>33</td>
<td>-</td>
</tr>
<tr>
<td>TC2</td>
<td>-25 to 100</td>
<td>33</td>
<td>-</td>
</tr>
<tr>
<td>TD1</td>
<td>-40 to 125</td>
<td>33</td>
<td>10</td>
</tr>
<tr>
<td>TR1</td>
<td>-40 to 125</td>
<td>370</td>
<td>-</td>
</tr>
</tbody>
</table>

**RESULTS AND DISCUSSION**

**Re-flow Process (Cool-down)**

Results of the finite element analysis show that the test package warps downward (with PCB on the bottom side) at room temperature (25 °C) with a magnitude of 93 µm following the re-flow process. At this temperature, the solder joint located at the symmetry line that is parallel with the longer side of the Si-die is the most critically strained solder. The evolution of von Mises stresses and the corresponding equivalent inelastic strains in this critical solder joint throughout the re-flow process is illustrated in Figure 2. It is noted that inelastic strains developed early following cooling down of the package from 183 °C. Although the stress level induced by coefficient of thermal expansion (CTE) mismatch is low, yield strength of the solder is also relatively low at high temperature. In addition, at this high homologous temperature, creep strain rate of the solder alloy is significant. Typical yield strength of 60Sn-40Pb solder alloys is 8 and 52 MPa at 125 and –55 °C, respectively when strained at $1.67\times10^{-4}$ per second [Adams, 1986]. The stress is brought to the yield surface with the continuously accumulated inelastic strains. The von Mises stress reaches 24.0 MPa with the corresponding inelastic strain of 0.856 percent at room temperature.

In the critical solder joint, a high stress gradient develops along the interface between the solder and the Cu$_6$Sn$_5$ intermetallic owing to both thermal expansion mismatches between the two materials and the severe geometric discontinuities. Typical calculated von Mises stress and the corresponding equivalent inelastic strain distribution in the critical solder at 25 °C is shown in Figure 3. It is worth noting that the region of high stress occurs only to a small depth from the surface of the solder while the bulk of the solder remains elastic. The location underneath the edges of the chip (or intermetallic phase) is experiencing the maximum stress and strain hysteresis during subsequent thermal cycles. Consequently, extensive accumulation of cyclic inelastic strains is likely to initiate fatigue crack along the solder /intermetallic interfaces. Crack initiation in the solder corresponds to the location of the maximum creep and plastic strain [Sarihan, 1999]. In addition, solder fatigue cracking has been observed to initiate and propagate from similar location in chip scale packages [Amagai, 1999; Lee et al., 1998]. Catastrophic propagation of such crack is governed by fatigue and fracture parameters including stress level, fracture toughness and threshold stress intensity factor range.
Fig. 3: von Mises stress and equivalent inelastic strain distribution in the critical solder joint at 25 °C, following the re-flow process.

**Thermal Cycles**

The evolution characteristics of internal states in the critical solder joint during the application of temperature cycles are presented and discussed in terms of inelastic strains. Figure 4 compares the predicted inelastic strains at identical location in the critical solder joint for the different load cases considered. Comparing load cases TC1 (ΔT = 165 °C) and TC2 (ΔT = 125 °C), faster evolution rate (per cycle) of strains is calculated for higher temperature range as reflected in higher slope of the curve for TC1. Higher ΔT, therefore, is expected to result in earlier solder joint failure by low cycle fatigue mechanism as commonly modeled using Coffin-Manson equation. An additional inelastic strains of 3.5 and 2.2 percent is accumulated at the end of 3 thermal cycles following re-flow process for load case TC1 and TC2, respectively.

Results for the load case with a 10-minute dwell time at both extreme temperature levels (load case TD1) is superimposed on curve TC1 in Figure 4. The 10-minute dwell time has minimal effect on the accumulated inelastic strains in the solder joint. It is noted that minute amount of inelastic strains is accumulated during dwell-time period of the temperature cycle. As a result, similar magnitude of inelastic strains is acquired after each temperature cycle for both load cases TC1 and TD1. The calculated viscoplastic strains in the solder alloys are primarily creep strains. Work by Shiratori and Yu (1997) showed that creep deformation is significant during the earlier part of the dwell period and diminishes when stress relaxation occurs. In addition, the creep curve of the solder alloys showed negligible transient creep [Ishikawa et al., 1996].
Fig. 5: Effect of temperature ramp rates on the evolution of inelastic strain in the critical solder joint

In view of fatigue life prediction of solder joint, the cyclic stress-strain hysteresis response of the solder alloy is examined in this study. The shear stress-strain hysteresis loops display the largest strain ranges compared to other stress-strain components. The large relative displacement within the solder /intermetallic interface attenuates the cyclic interfacial shear stress and strains resulting in crack initiation, as often observed experimentally. The shear stress-strain hysteresis loops for the first three temperature cycles (TC1) following the re-flow process are illustrated in Figure 6. Points a through k correspond to the thermal cycles profile (see inset figure). Path a-b represents cooling down from the assumed stress-free re-flow temperature to room temperature. Stresses in the solder decrease and increase upon heating and cooling part of the thermal cycle, respectively. The predicted shear stress range is 34.0 MPa. It is worth mentioning that although the shear stress range is larger (41.0 MPa) for faster ramp rate (TR1), the resulting shear strain range is similar at 0.8 percent. For comparative purpose, a typical fatigue life of eutectic solder (with cycling frequency of 10 mins./cycle) at a plastic strain range of 1.0 percent is about 5000 cycles [Hua et al., 1998]. Several low cycle fatigue parameters including unified plastic work Darveaux et al. (1995) and plastic strain variation Solomon (1995) have been utilized in predicting fatigue life of bulk solder.

CONCLUSIONS

Viscoplastic finite element analysis of a surface mount test package has been performed. The evolution characteristics of stresses and strains in the Sn-Pb solder joint during re-flow and subsequent thermal cycles have been investigated. Results show that:

- The package warps downwards at 25 °C following the re-flow process with a magnitude of 93 μm. The accumulated inelastic strain is 0.856 percent.
- Additional inelastic strain of 3.5 and 2.2 percent evolved during the 3 temperature cycles at (-40 to 125 °C) and (-25 to 100 °C), respectively.
- A 10-minute dwell time at peak temperature levels has minimal effect on the evolution of internal states in the solder joint.
- Faster temperature ramp rate (370 versus 33 °C/min) accelerates the inelastic strain evolution per temperature cycle. However, the strain magnitude is 12 percent lower after three cycles.

- Shear stress-strain hysteresis loops displayed the largest strain range at 0.8 percent when compared to other stress-strain components.

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