Measurement of Thermomechanical Behavior of Solder Joints under Power Cycling Condition Using Moire Interferometry

Se Young Yang, Ph.D. Candidate
Ilho Kim, Ph.D. Candidate
Soon-Bok Lee, Professor
Korea Advanced Institute of Science and Technology (KAIST)
373-1, Guseong-Dong, Yuseong-Gu, Daejon, 305-701, Korea

ABSTRACT
Failure mechanisms exposed by environmental accelerating testing methods such as thermal cycling or thermal shock test, may differ from those at the service operating conditions. While the device is heated up or cooled down evenly on its external surface during environmental testing, real operating powered devices experience temperature gradients caused by internal local heating, components’ different heat dissipation capability, and ambient temperature variation, etc. In this study, a power cycling technique is introduced to better approximate the field operating conditions by activating field failure modes. Power cycling test is performed with different solder joints, that is, lead contained and lead free, and the result is compared with environmental test results. Real time moiré interferometry is applied to measure the global/local thermomechanical behavior of different solder joints during power cycling excursion and compared with thermal cycling case. Effective damage parameter is extracted from the experiment and applied to account for the thermal fatigue life difference for different solder joint composition and accelerating testing conditions.

1. INTRODUCTION
Structural reliability of any product can be improved through understanding of the weakest link in a given design. Not to mention, improvements can be more effectively implemented if the capability of the weakest link is known in the early design stage[1]. In electronic packaging, undoubtedly, solder joint under repetitive thermal loading which leads to thermomechanical fatigue damage is considered as one of major weakest link. Thus, numerous efforts were dedicated to improve structural reliability of entire package by attempting to characterize mechanical behavior of solder[2-6] so that meaningful predictive modeling with numerical analysis should be possible and to develop fatigue reliability models through proper accelerated tests so that fatigue life of solder can be estimated.
While predicting the life with material based fatigue models, empirical models following Coffin-Manson relation and non-empirical (physics of failure) models adopting the fundamentals of fracture and damage mechanics, requires analyzing expense and time for adequate experimental procedure and numerical analysis for appropriate damage parameter extraction. Life estimation with accelerated environmental stress tests (ESTs) have merits for its simplicity and relatively low cost. The validity of ESTs, such as thermal cycling and thermal shock tests, lies on the assumption that the failure mechanisms active at the accelerated life test conditions are also dominant at the service operating conditions. However, the physical characteristic of service operating conditions are not sufficiently addressed by either thermal cycling or thermal shock tests[7]. The temperature of load in the vehicle stabilizes quickly and the entire package reaches a uniform temperature in the dwell portion of the cycle[8]. Thus, they cannot produce neither the temperature gradients, which can induce cyclic warpage[9,10], nor the transient conditions[11] resulting from power cycling. The physical characteristic of the power cycling better simulate the service operating conditions where the heat flows from the die into the package inducing temperature gradient during power-on and cooling cycles. According to these reasons, accelerated reliability estimation by accelerated test and numerical simulation under power cycling condition was performed by several researchers. Zhang and Baldwin[7] investigated the reliability problems of flip chip on organic board (FCOB) at first level interconnection while Qi[12] performed parametric study and failure analysis for both FC-PBGA (Plastic Ball Grid Array) and FC-CBGA (Ceramic Ball Grid Array) at second level solder joint under power cycling condition. Lenkkeri and Jaakola[13] conducted rapid power cycling with flip-chip and CSP and compared their result with Engelmaier’s[11] and Solomon’s[14] life prediction model. Lee et al.[18] constructed a power cycling module to mimic the operation condition in such a way that it can heat up and cool down the chip from its top surface. Tam et al.[8] and Towashiraporn et al.[15] attempted to find the correlation between thermal cycling and power cycling results of FC-PBGA and chip size package (CSP), respectively. Numerical simulation efforts were contributed by Hong and Yuan[16] considering the local temperature variations of CBGA applying computational fluid dynamics (CFD) and by Darveaux[17] adapting finite difference model to perform thermal analysis of multichip package.

As mentioned earlier, in order to acquire accurate parameter from numerical simulation, it requires time consuming endeavor to clearly characterize time/temperature dependent behavior of various non-linearly behaving materials in electronic packaging including solder, die adhesives, passivation layers, solder mask layers, and so on. Consequently, it is not too pessimistic to conclude that it is quite unattainable to verify exact properties of different materials under accelerating testing conditions where temperature varies from −55°C to +125°C and time rate effect can not be neglected. Situation becomes even worse when the size effect of materials are considered. In this respect, a critical need for experimental verification arises and high sensitivity moiré interferometry has been used as a feasible method to investigate deformation behavior of electronic packaging materials especially of solder joints[19-34]. Dishongh et al.[33] performed moiré experiment and measured accumulated residual shear strain at solder joints up to 100 consecutive thermal cycles. Ham et al.[34] tried to compare deformation behavior of solder joints occurring at different thermal loading conditions, i.e., temperature cycling and power cycling, highlighting the affects of temperature gradient and transient condition.

In this study, a power cycling technique is developed to better approximate and activate failure modes that may appear in real operating conditions introducing global warpage induced by thermal gradient and transient condition. Power cycling test is
performed with two different BGA solder joints, one with lead contained 63Sn/37Pb(SP) solder and the other with lead free Sn/4.0Ag/0.5Cu(SAC), and the thermal fatigue lives are compared. Real time moiré interferometry is applied to measure the global/local thermomechanical behavior of different solder joints during power cycling excursion and compared with thermal cycling case. Effective damage parameter, cyclic shear strain value, is extracted from the experiment and applied to account for the thermal fatigue life discrepancy for different solder joint composition and accelerating testing conditions. Visco-plastic finite element analysis is included for mutual verification of experimental and numerical approach.

2. EXPERIMENT

2.1 SPECIMEN DESIGN AND PREPARATION

In order to reduce the CTE mismatch between two adherends so that temperature gradient effect could be the main failure driving mechanism, the specimen is designed as in Fig.1 where two identical FR-4 PCBs of 2.0mm thickness are bonded by 36 solder joints. Fig.1 and Table 1 denote the specific dimensions and configurations of the specimen. The diameter and pitch of solder joints are 0.76 and 1.27mm, respectively. The joints are distributed forming 3×3 array at the corners of the PCB and daisy chained for assessment of the interconnect reliability. To obtain the thermal fatigue result in a limited time, which will be discussed shortly, the test condition is accelerated by means of increasing the specimen size and minimizing the number of joints.

The specimens are prepared for two different solder materials, SP and SAC, where they are reflowed in N₂ atmosphere with peak temperature of 230°C and 270°C, respectively. Power cycling thermal fatigue test is performed with as fabricated specimens whereas specimens are cross-sectioned and polished up to half of the solder of first row for moiré experiment.

2.2 MOIRE EXPERIMENT

Moiré interferometry is a whole-field in-plane displacement optical measurement technique with both high displacement sensitivity and high spatial resolution. It is especially effective for the non-uniform in-plane deformation measurements and has been used in the research and development of microelectronic packages to measure thermally induced displacement fields.

Table 1. Substrate configuration

<table>
<thead>
<tr>
<th></th>
<th>Upper</th>
<th>Lower</th>
</tr>
</thead>
<tbody>
<tr>
<td>Material</td>
<td>FR4</td>
<td>FR4</td>
</tr>
<tr>
<td>Surface Finish</td>
<td>Ni+Au</td>
<td>Ni+Au</td>
</tr>
<tr>
<td>Solder Mask</td>
<td>SMD</td>
<td>NSMD</td>
</tr>
</tbody>
</table>

Fig. 1. Specimen dimension
A thin cross line diffraction grating is replicated onto the cross section of interest and deforms with the sample. Interaction between two coherent laser beams with the deformed grating produces an interference pattern representative of the thermally induced displacement field. Based on a grating frequency of 1200 lines/mm, each interference fringe spacing represents 417nm relative displacement difference which explains the definition of sensitivity.[35]

Thermally induced strains can be extracted from the displacement fields by the following relationship,

\[
\varepsilon_{xx} = \frac{\partial U}{\partial x} = \frac{1}{f} \left[ \frac{\partial N_x}{\partial x} \right] \label{eq1}
\]

\[
\varepsilon_{yy} = \frac{\partial V}{\partial y} = \frac{1}{f} \left[ \frac{\partial N_y}{\partial y} \right] \label{eq2}
\]

\[
\gamma_{xy} = \frac{\partial U}{\partial y} + \frac{\partial V}{\partial x} = \frac{1}{f} \left[ \frac{\partial N_x}{\partial y} + \frac{\partial N_y}{\partial x} \right] \label{eq3}
\]

where \( N_x \) and \( N_y \) are the fringe orders in \( U \) and \( V \) fields, respectively.

Fig. 2 shows the power cycling moiré experiment setup which consists of moiré interferometer – PEMI (Portable Engineering Moiré Interferometer; Photomechanics co.), power cycling module, and image acquisition system. The schematic view of power cycling module is depicted in Fig.3. Specimen is placed on the module applying thermal grease and real operating condition, where power is self-generated from the lower substrate, is approximated by heat conduction from the underneath heater and water cooling from the channel. The design of the module is based on FEM thermal analysis to guarantee the uniform temperature on top surface of module[36]. Moiré fringe is captured by zoom tube which is capable of magnifying the field of view up to 3.0mm with 640 by 480 resolution CCD Camera.

A typical temperature profile at the top surface of lower and upper substrate during pseudo-power cycling test is shown in Fig.4(30°C~150°C case). Lower substrate was subjected to 3mins hold to add time dependent deformation effect, 3mins ramp, and 1.5mins cooling. Thermal deformation behavior of global warpage and of local solder are measured with moiré interferometer at corresponding times, A ~ F for 8 different cases listed in Table 2.
2.3 PSEUDO-POWER CYCLING THERMAL FATIGUE EXPERIMENT

Power cycling module mentioned above is extended to perform fatigue analysis as in Fig.5 where 14 specimens can be cycled simultaneously. The thermal excursion for each cycle is identical to that of Fig.4 except for the fact that $T_{\text{max}}$ is varied according to Table 3. Thermal fatigue life was acquired following the test schedule summarized in Table 3. During consecutive thermal cycles, failure was defined when there was an abrupt increase in resistance as in Fig.6. In addition, failure analysis with optical microscope clearly revealed that the dominant failure mode is solder joint fatigue at the IMC (Intermetallic Compound) layer(Fig.7).

2.4 FEM ANALYSIS

FEM analysis using ABAQUS version 6.2.1 is performed applying material properties listed in Table 4 adapted from Hong[36] and Lau's[37] work where 95.5Sn3.9Ag0.6Cu is selected for SAC due to lack of available material data. Quarter modeled FEM
3D mesh (20,112 elements and 25,595 nodes) is utilized to account for x and y symmetry condition (Fig. 8). Temperature history identical to power cycling test is designated to the top surface of upper and lower substrates. Both the global deformation of entire package and local behavior within a solder agree well with experimental results as reflected in Fig. 8 and 10.

![Fig. 6. Failure detection by resistance change](image1)

![Fig. 7. Solder joint fatigue failure](image2)

Table 4. Material properties for FEM

<table>
<thead>
<tr>
<th>Temperature (K)</th>
<th>Density (kg/m³)</th>
<th>Specific Heat (W/mK)</th>
<th>Thermal Conductivity (W/mK)</th>
<th>CTE (ppm/K)</th>
<th>Elastic Modulus (MPa)</th>
<th>Poisson Ratio</th>
<th>Yield Strength (MPa)</th>
</tr>
</thead>
<tbody>
<tr>
<td>63Sn37Pb</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>273</td>
<td>273</td>
<td>8470</td>
<td>150</td>
<td>51</td>
<td>25.2</td>
<td>0.360</td>
<td>36.4</td>
</tr>
<tr>
<td>323</td>
<td>26.1</td>
<td>12521</td>
<td>0.365</td>
<td>15.2</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>373</td>
<td>27.3</td>
<td>6909</td>
<td>0.378</td>
<td>9.6</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>95.5Sn4.0Ag0.5Cu</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>273</td>
<td>21.3</td>
<td>53000</td>
<td>0.3</td>
<td>16.0</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>323</td>
<td>22.15</td>
<td>49000</td>
<td>0.3</td>
<td>10.5</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>373</td>
<td>23</td>
<td>45000</td>
<td>0.3</td>
<td>10.5</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>423</td>
<td>41000</td>
<td>0.3</td>
<td>elastic</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>FR-4</td>
<td>298</td>
<td>1938</td>
<td>879</td>
<td>13</td>
<td>listed below</td>
<td>18200</td>
<td>0.25</td>
</tr>
<tr>
<td>Copper</td>
<td>298</td>
<td>8942</td>
<td>385</td>
<td>389</td>
<td>117000</td>
<td>0.34</td>
<td>69.0</td>
</tr>
</tbody>
</table>

Creep behavior = \( \varepsilon = A [\sinh (B\sigma)]^n \exp \left(-\frac{Q}{RT}\right) \)

<table>
<thead>
<tr>
<th>Temperature (K)</th>
<th>FR-4 CTE (ppm/K)</th>
<th>X</th>
<th>Y</th>
</tr>
</thead>
<tbody>
<tr>
<td>298</td>
<td>54.43</td>
<td></td>
<td></td>
</tr>
<tr>
<td>338</td>
<td>76.59</td>
<td></td>
<td></td>
</tr>
<tr>
<td>393</td>
<td>140.22</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
3. RESULTS AND DISCUSSIONS

Fig. 8. (a) FEM 3D modeling (b) U & (c) V field of case 2 of Table 2 at point ‘F’ from Fig.4. (0.417µm/fringe)

Fig. 9. Outermost solder ball, case 2 & 6 of Table 2; (a) U field & (b) V of case 2; (c) U & (d) V of case 6

Fig. 10. Global deformation, case 2 & 6 of Table 2; (a) U & (b) V of case 2; (c) U & (d) V of case 6

3. RESULTS AND DISCUSSIONS

Fig.10 shows the global U and V deformation fields of the specimen at point ‘F’ in Fig.4 for both SAC and SP. Deformation fields are measured after three cycles to obtain stabilized behavior of the materials and compared with FEM result obtained at identical state. Deformation field of outermost solder ball is magnified using a zoom tube which enables accurate strain analysis with enhanced spatial resolution(Fig.9). Additionally, thermal deformation field during isothermal cycling condition is acquired for direct comparison with power cycling case. Test is performed for case 6 of Table 2 with a convective chamber[28] which comprises of an optical window so that laser beam from the interferometer can be applied. From U and V deformation fields it was apparent that global warpage as well as shear strain in solder are reduced(Fig.11). Total strain values, $\gamma_{xy}$, $\varepsilon_{xx}$, and $\varepsilon_{yy}$ at the outermost solder ball are calculated using Eqn.(1)~(3) for all cases of experiments and summarized in Fig.13(a). Average total strain values extracted from FEM analysis is included for comparison(Fig.13(b)). Discrepancy between
experiment and numerical simulation may have arisen from the fact that the specimens used in experiments inherit manufacturing tolerance such as slight misalignment in solder joints which is apparently manifested in Fig.9. Moreover, residual stress or deformation effect induced during manufacturing process which is not considered in numerical simulation, inexact material property selection for SAC, and simplified temperature boundary condition designation in FEM analysis can be another sources of difference. Abrupt increase of shear strain above 125°C for both experiment and FEM is observed for SAC leading to an assumption that it is more likely to be damaged at high temperature region. Physical mechanism to certain behavior may be carefully postulated to be the effect of sudden increase in intrinsic creep and stress relaxation behavior of SAC, a topic requiring additional intensive further studies.

Fig.11. Thermal cycling, case 6 of Table 2; (a) U field (b) U at outermost solder (c) V at outermost solder

Fig.12. Weibull plot for power cycling thermal fatigue test result; (a) SP (b) SAC

Fig.13. Average total strain values for outermost solder; (a) From moiré experiment, SAC vs. SP (b) Moiré vs. FEM for SAC

Power cycling thermal fatigue test results are summarized and represented in Weibull plot as denoted in Fig.12. Mean time to failure (MTTF) which refers to 63.2% of life, is chosen for the representative fatigue life for a given $T_{\text{max}}$. Infant failures are excluded in order to maintain single failure mechanism. $T_{\text{max}}$ vs. life cycle curve is plotted in Fig.14 where there exists a cross line behavior between SAC and SP as $T_{\text{max}}$ reaches higher value, coinciding with the assumption drawn from moiré experiment.
CONCLUSION

1. Power cycling modules for real time moiré measurement and thermal fatigue test are developed in order to better approximate and activate failure modes that may appear in real operating conditions.

2. Thermomechanical behavior of the specimens with different solder materials is measured using moiré interferometer under power cycling and thermal cycling condition. Apparent distinction in local deformation behavior with respect to different solder composition suggests extensive work on material characterization of newly adapted lead free solders. Difference in global deformation between power cycling and thermal cycling conditions reveals that fatigue damage in solder interconnection can be accelerated by different driving force.

3. Power cycling thermal fatigue test is performed and $T_{\text{max}}$ vs. life relationship is obtained. Thermal fatigue lives of SAC and SP delineate cross line behavior, that is, life of SAC is higher than SP in relatively low temperature regime whereas it becomes lower as the temperature increases.

4. Average total strain values obtained by moiré measurement can be an effective parameter to predict the overall operation life for solder joints as its behavior coincides with estimated life from thermal fatigue experiment.

![Fig.14. Thermal Fatigue life; $T_{\text{max}}$ vs. Life cycles](image)

REFERENCE


[36] Hong, Bor Zen, Thermal Fatigue Analysis of a CBGA Package with Lead-free Solder Fillets, InterSociety Conference on Thermal Phenomena, pp.205-211, 1998