Experiment-Based Computational Investigation of Thermomechanical Stresses in Flip Chip BGA Using the ATC4.2 Test Vehicle†

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ABSTRACT
Stress measurement test chips were flip chip assembled to organic BGA substrates containing micro-vias and epoxy build-up interconnect layers. Mechanical degradation observed during temperature cycling was correlated to a damage theory developed based on 3D finite element method analysis. Degradation included die cracking, edge delamination and radial fillet cracking.

KEY WORDS
flip chip, piezoresistor stress measurement, die stresses

INTRODUCTION
Flip Chip on Board (FCOB) assemblies are generally under a high degree of thermomechanical stress due to large differences in coefficient of temperature expansion (CTE) between the Si die and organic substrate. Underfill is used to minimize cyclic strain imposed on C4 solder interconnects and maximize solder ball fatigue life during thermal excursions that accompany power cycling and changing environmental conditions. Often, the weak link in such a system is considered to be the adhesive bonds at the die-to-underfill and the underfill-to-substrate interfaces. Analytical calculations of stress distributions in FCOB assemblies show normal forces (peel stress) that increase exponentially approaching die edges and these stresses are thought to be involved in delamination or "unzipping" of the die-to-underfill interface. As a result, numerous studies have been undertaken to evaluate and improve the bonding of underfill materials to typical dielectric interfaces such as polyimide, benzocyclobutene (BCB), and silicon nitride along with solder mask and non-solder mask coated organic substrate surfaces. However, temperature cycling reliability studies conducted here and elsewhere generally have not supported a correlation between underfill interfacial adhesion strength and edge delamination. Interestingly, 3D finite element method (FEM) stress calculations performed on FCOB assemblies show the die-to-underfill interface to be in a state of increasing compressive rather than tensile stress approaching the die edge due to the effects of the underfill edge fillet and substrate bending.

In previous work [1], we reported the prediction and measurement of thermomechanical stresses in 1000 I/O 250 μm pitch ATC4.2 test chips assembled to 35 mm BGA substrates. These parts underwent temperature cycling during which three principal failure modes were observed (die cracking, edge delamination and radial fillet cracking) that were subsequently linked to shifting of thermomechanical stresses caused by debonding of the underfill fillet-to-die edge interface. In this work, we complete the analysis of edge fillet-related die cracking and delamination including results from failure analysis of test vehicles and very high resolution 3D FEM stress calculations. 3D FEM calculations were also used in a viscoelastic non-linear constitutive solder fatigue model that provided an estimate of thermal cycles to failure.

EXPERIMENTAL
Test Vehicle Description
The ATC4.2 Flip Chip Test Chip is a redistributed area array version of the ATC04 Assembly Test Chip that is 11.56 mm on an edge in the 2x2 QUAD form containing 100 addressable stress sensing cells, ring oscillators, and heaters described in detail elsewhere [2]. The QUAD layout of the basic ATC04 is shown in Figure 1. The peripheral design is converted to a 1004 I/O flip chip area array by the addition of redistribution and bumping layers shown in Figure 2.

The redistribution layer provides access to stress measurement circuitry in the active IC, chip side daisy chain links, and connections for Kelvin and van der Pauw test structures. Redistribution and bumping was provided by two suppliers (Bmp1 and Bmp2) with slightly different bump technologies, although both used BCB for dielectric and Cu for interconnect layers. Due to a design incompatibility only one of two bump suppliers (Bmp2) furnished die electrically capable of providing stress measurements.

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The BGA substrate design incorporates three perimeter rows of off-grid die pads on 250 μm pitch using a "clamshell" technique, first described by Gasparini and Bhattacharyya, maximizing escape routing of an area array with a minimum number of layers [3]. The actual layout was furnished by Zuken-Redac as part of a voluntary contribution to this work. The first layer die pad layout and escape routing for this design is shown in Figure 3.

Figure 1. Layout of 1 of 4 die in an ATC4 QUAD prior to redistribution and solder bumping showing location of stress sensing rosettes.

Table 1 contains material properties for the substrate and underfill experimental splits used in the assembly of the ATC4.2 test vehicles. The property data received from the SubA vendor appear to be in error, as the 3D FEM simulations resulted in stresses and out-of-plane deformations that disagreed significantly with experimental measurements of in situ stress and back side curvature, and also disagreed with analytical calculations based on direct measurements of overall CTE and bending modulus. (The latter are contained in Table 2.) Properties for Si in Table 1 are averages of the minimum and maximum anisotropic values in the [100] and [110] directions. Underfill and substrate properties were obtained from respective vendors.

Figure 2. Layout of ATC4.2 showing locations of "clamshell" design peripheral bumps and redistribution of ATC4.2 pads shown in Figure 1.

The Zuken-Redac design was used by two suppliers of PC boards to fabricate BGA substrates, designated SubA and SubB in Figures 4 and 5, respectively. Both substrates use fiberglass reinforced cores and epoxy build-up (B/U) layers containing micro-vias for layer-to-layer interconnection. SubA has a thinner core with three B/U layers and SubB has a thicker core with two B/U layers.

Figure 3. Top layer layout of the 35 mm ATC4.2 BGA substrate.
Table 1: Material Properties used in FEM calculations

<table>
<thead>
<tr>
<th>Material</th>
<th>E (GPa)</th>
<th>Tg (°C)</th>
<th>α1 (10⁻⁶/°C)</th>
<th>α2 (10⁻⁶/°C)</th>
<th>ν</th>
</tr>
</thead>
<tbody>
<tr>
<td>Silicon</td>
<td>120</td>
<td>n/a</td>
<td>2.6</td>
<td>n/a</td>
<td>0.34</td>
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<tr>
<td>Copper</td>
<td>107.6</td>
<td>n/a</td>
<td>16.1</td>
<td>n/a</td>
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<tr>
<td>UF1</td>
<td>5.8</td>
<td>145</td>
<td>40</td>
<td>unk</td>
<td>0.3</td>
</tr>
<tr>
<td>UF2</td>
<td>8.5</td>
<td>140</td>
<td>26</td>
<td>87</td>
<td>0.3</td>
</tr>
<tr>
<td>UF3</td>
<td>11</td>
<td>125</td>
<td>31</td>
<td>89</td>
<td>0.3</td>
</tr>
<tr>
<td>Solder Mask A</td>
<td>0.25</td>
<td>105</td>
<td>60</td>
<td>160</td>
<td>0.25</td>
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<tr>
<td>Solder Mask B</td>
<td>5.8</td>
<td>132</td>
<td>49</td>
<td>120</td>
<td>0.25</td>
</tr>
<tr>
<td>Build-upA</td>
<td>5.8</td>
<td>190</td>
<td>70</td>
<td>n/a</td>
<td>0.3</td>
</tr>
<tr>
<td>Build-upB</td>
<td>3.1</td>
<td>119</td>
<td>78</td>
<td>176</td>
<td>0.3</td>
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<tr>
<td>CoreA</td>
<td>2.45</td>
<td>190</td>
<td>14</td>
<td>n/a</td>
<td>0.2</td>
</tr>
<tr>
<td>CoreB</td>
<td>16.4</td>
<td>170</td>
<td>14.7</td>
<td>unk</td>
<td>0.2</td>
</tr>
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Table 2: Laminate properties used in analytical calculations

<table>
<thead>
<tr>
<th></th>
<th>E (GPa)</th>
<th>α1 (10⁻⁶/°C)</th>
<th>ν</th>
<th>Thickness (µm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>SubA</td>
<td>8.8</td>
<td>21.8</td>
<td>0.25</td>
<td>680</td>
</tr>
<tr>
<td>SubB</td>
<td>10.9</td>
<td>19.3</td>
<td>0.25</td>
<td>940</td>
</tr>
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</table>

Table 3: Splits in the experimental matrix

<table>
<thead>
<tr>
<th>Split</th>
<th>Solder bump supplier</th>
<th>Substrate supplier</th>
<th>Underfill supplier</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Bmp1</td>
<td>SubA</td>
<td>UF1</td>
</tr>
<tr>
<td>2</td>
<td>Bmp1</td>
<td>SubA</td>
<td>UF2</td>
</tr>
<tr>
<td>3</td>
<td>Bmp1</td>
<td>SubA</td>
<td>UF3</td>
</tr>
<tr>
<td>4</td>
<td>Bmp1</td>
<td>SubB</td>
<td>UF1</td>
</tr>
<tr>
<td>5</td>
<td>Bmp1</td>
<td>SubB</td>
<td>UF2</td>
</tr>
<tr>
<td>6</td>
<td>Bmp1</td>
<td>SubB</td>
<td>UF3</td>
</tr>
<tr>
<td>7</td>
<td>Bmp2</td>
<td>SubA</td>
<td>UF1</td>
</tr>
<tr>
<td>8</td>
<td>Bmp2</td>
<td>SubA</td>
<td>UF2</td>
</tr>
<tr>
<td>9</td>
<td>Bmp2</td>
<td>SubA</td>
<td>UF3</td>
</tr>
</tbody>
</table>

Experimental Procedure

ATC4.2 die solder bumped by two bump suppliers, Bmp1 and Bmp2, were flip chip assembled to SubA and SubB substrates using three underfills, UF1, UF2, and UF3. Bmp1 die were assembled to both substrate splits but Bmp2 die were only assembled to SubA splits. This resulted in a total of 9 experimental legs (see Table 3). Since Bmp2 die were assembled only to SubA substrates, in situ stress data were only available for parts in this leg. Assemblies were classified as Level 3 moisture sensitive at National Semiconductor using Test Method A112-A of EIA/JEDEC Standard 22. All parts in the 9 experimental legs underwent JEDEC preconditioning and temperature cycling (T/C) from -45 to +125 °C. Electrical tests and C-mode Scanning Acoustic Microscopy (C-SAM) inspection were performed at 0, 100, 200, 300, 500, 1500, and 2000 T/C intervals. Electrical tests included 4-point resistance measurements of corner solder balls, microvias and van der Pauw sheet resistance structures, daisy chain continuity and piezoresistor measurements. C-SAM images of the underfill
interface were used to detect and monitor failures in the die-
to-substrate interface.

At the completion of temperature cycling, destructive failure
analysis was performed on parts selected from each leg of the
experimental matrix in order to verify damage observed in
C-SAM images and assess the condition of C4 solder
connections. These results along with theoretical
explanations for the observed behavior will be discussed in
the experimental matrix in order to verify damage observed
to-substrate interface.

2D Theoretical Stress Analysis
Radius of curvature and the distribution of in and out-of-
plane stresses were estimated using the tri-material form of
Suhir’s model described in [4] with improvements for out-
of-plane shear and peel stress calculation in [5]. Although
this model does not take into account the effect of the flip
chip edge fillet, it provides a good prediction of stress
maximums and die deflection. Die and underfill properties
were taken from Table 1 and substrate properties from
Table 2. Radius of curvature data were converted to die
deflections over a 7.14 mm arc so that they could be more
easily compared to measured and 3D calculated deflections.
These results are contained in Table 4. Analytical and FEM
calculations are very dependent on estimations of the stress-
free temperature. For this work, it was assumed to be the Tg
of the underfill listed in Table 1 so that ΔT = Tg − 25°C.

Table 4: Calculations of maximum σyy, σzz, and τyz and
deflection from Suhir

<table>
<thead>
<tr>
<th>Experimental Split</th>
<th>σyy max (MPa)</th>
<th>σzz max (MPa)</th>
<th>τyz max (MPa)</th>
<th>Deflection (μm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>SubA/UF1</td>
<td>-108</td>
<td>7.3</td>
<td>17.5</td>
<td>9.3</td>
</tr>
<tr>
<td>SubA/UF2</td>
<td>-102</td>
<td>6.2</td>
<td>16.9</td>
<td>8.8</td>
</tr>
<tr>
<td>SubA/UF3</td>
<td>-93</td>
<td>4.9</td>
<td>16.8</td>
<td>8.0</td>
</tr>
<tr>
<td>SubB/UF1</td>
<td>-104</td>
<td>-0.01</td>
<td>15.6</td>
<td>8.9</td>
</tr>
<tr>
<td>SubB/UF2</td>
<td>-98</td>
<td>-0.3</td>
<td>15.1</td>
<td>8.5</td>
</tr>
<tr>
<td>SubB/UF3</td>
<td>-88</td>
<td>-0.3</td>
<td>14.9</td>
<td>7.6</td>
</tr>
</tbody>
</table>

3D Theoretical Stress Analysis
A 3D finite element model (FEM) was applied to predict the
stress, strain, and deformation response of the ATC4.2 test
vehicle due to 1) cool down to room temperature from the
soldering temperature prior to underfill, and 2) due to cool
down to room temperature from the cure temperature
following underfill. The finite element idealization utilizes
two planes of symmetry resulting in one quarter of the
package being simulated using a high resolution 500,000
element model. This includes 441 solder interconnects
modeled using three eight-node brick elements per solder
ball.

The solder was assumed to respond as an isotropic
temperature dependent elastic/plastic material with power
law hardening. This model neglects the time dependent
(creep) and microstructural dependent response known to
occur in eutectic SnPb solder. The underfill was assumed to
respond as an isotropic temperature dependent linear elastic
material which neglects time dependent effects known to
occur in polymers. The Si die was assumed to respond as an
isotropic linear elastic material and the FR-4 substrate was
assumed to respond as a temperature dependent, isotropic,
linear elastic material.

In the first computation, it was assumed that the assembly
prior to underfill was stress free at 180°C and subsequently
cooled to 25°C. In the second computation, the assembly
after underfill was assumed to be stress free at 160°C and
the temperature was uniformly lowered to 25°C. The
thermomechanical response was computed as a function of
temperature using the Sandia proprietary finite element code
JASS3D and respective properties contained in Table 1. Estimated die deflections along a 7.14 mm arc and stress
maximums along the centerline half-length of the die
surface are contained in Table 5.

Table 5: FEM calculations of maximum σyy, σzz, and τyz
along the centerline half-length of the die surface and
deflection over a 7.14 mm arc. Maximum σyy is located
at die center, maximum σzz and τyz are at die edge. (NF
stands for no edge fillet.)

<table>
<thead>
<tr>
<th>Experimental Split</th>
<th>σyy max (MPa)</th>
<th>σzz max (MPa)</th>
<th>τyz max (MPa)</th>
<th>Deflection (μm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>SubB/UF1</td>
<td>-103</td>
<td>-24</td>
<td>24</td>
<td>9.3</td>
</tr>
<tr>
<td>SubB/UF2</td>
<td>-101</td>
<td>-15</td>
<td>21</td>
<td>9.1</td>
</tr>
<tr>
<td>SubB/UF3</td>
<td>-102</td>
<td>-28</td>
<td>27</td>
<td>9.0</td>
</tr>
<tr>
<td>SubB/UF2/NF</td>
<td>-101</td>
<td>33</td>
<td>17</td>
<td>9.1</td>
</tr>
</tbody>
</table>

Deflection Measurements
Die curvature at room temperature were measured along the
x-axis and y-axis of the die backside using a Mahr S8P
profilometer with a Focodyn laser stylus. Parts were aligned
in a machined fixture to ensure repeatable measurements
along the die centerline in both directions. Data were
collected along a 10 mm path straddling the geometric die
center and vertical deflections were calculated for a 7.14
mm segment of this path. The average of the x and y
deflection measurements were calculated for each part.
Table 6 contains measurements taken at the 200 T/C
inspection interval.

Table 6: Measurements of die curvature over a 7.14 mm
arc

<table>
<thead>
<tr>
<th>Experimental Split (Nr. parts)</th>
<th>Average Deflection (μm)</th>
<th>Standard Deviation (μm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bmp1/SubA/UF1 (9)</td>
<td>9.1</td>
<td>0.2</td>
</tr>
<tr>
<td>Bmp1/SubA/UF2 (9)</td>
<td>8.5</td>
<td>0.1</td>
</tr>
<tr>
<td>Bmp1/SubA/UF3 (9)</td>
<td>9.0</td>
<td>0.1</td>
</tr>
<tr>
<td>Bmp1/SubB/UF1 (9)</td>
<td>8.0</td>
<td>0.2</td>
</tr>
<tr>
<td>Bmp1/SubB/UF2 (9)</td>
<td>8.0</td>
<td>0.1</td>
</tr>
<tr>
<td>Bmp1/SubB/UF3 (9)</td>
<td>8.1</td>
<td>0.1</td>
</tr>
<tr>
<td>Bmp2/SubA/UF1 (4)</td>
<td>8.7</td>
<td>0.1</td>
</tr>
<tr>
<td>Bmp2/SubA/UF2 (4)</td>
<td>8.4</td>
<td>0.2</td>
</tr>
<tr>
<td>Bmp2/SubA/UF3 (4)</td>
<td>8.7</td>
<td>0.2</td>
</tr>
</tbody>
</table>
Experimental Stress Measurements

A second independent measure of die stress was based on piezoresistor data from the 100 rosettes distributed across each ATC4.2 die shown in Figure 1. Piezoresistors formed on CMOS [100] are sensitive to in-plane compressive and shear components of the stress tensor, but cannot detect out-of-plane components that are generally of the most interest in terms of packaging reliability. However, in-plane data can validate out-of-plane calculations through comparison to in-plane analytical and FEM calculations. The stress distribution (compressive stress normal to the y-plane acting in the y-direction) along the centerline of the die surface can be used in this way and is shown in Figure 6 for the Bmp2/SubA/UF2 split. (Since valid 3D FEM calculations for the SubA splits were not available due to faulty material property data, Figure 6 contains FEM data for SubB for reference.)

![Figure 6](image)

**Figure 6.** Plot of $\sigma_{yy}$ distribution (compressive stress normal to y-plane acting in the y-direction) along the normalized centerline half-length of the die surface. Symbols denote experimental data for one part in the Bmp2/SubA/UF2 split. Dashed line is Suhir calculation that neglects edge fillet effects and solid line is from FEM calculation that includes the edge fillet.

RESULTS/DISCUSSION

In the preceding section we described the test vehicle, test matrix, 2D and 3D methods for predicting stress and deformation of the test vehicle, and method for validating 3D FEM calculations using experimental measurements of die deflection and in situ stress. In this section we analyze the 2D and 3D predictions and experimental measurements, followed by a discussion of three dominant stress-related failure modes observed in the test vehicles during thermal cycling.

Stress Analysis

In the Experimental section we showed estimates of stress and deflection based on 2D analytical theory and 3D FEM, the former not accounting for edge effects or underfill fillet and the latter accounting for these effects. A ranking of the underfills and substrates in terms of their effect on stress and strain has been extracted from Tables 4, 5, and 6 and summarized in Table 7. The 2D calculations show the same ranking of underfills for all of the stress components of interest and for overall deflection of the assembly. The 3D calculations predict the same deflection order but, interestingly, different orders for the three stress components. 3D calculations were not completed on the SubA case for reasons previously discussed, so substrate ranking is shown based on 2D calculations and physical measurements of backside deflection.

The SubA groups averaged 11%, 6.2%, and 13.7% greater measured deflections for UF3, UF2, and UF1, respectively, than the corresponding SubB groups. This measurement was done at the 200 T/C point at which time underfill-to-die edge interfaces of the entire SubA/UF2 appeared to have debonded. It is likely that the deflection difference of 6.2% between SubB/UF2 and SubA/UF1 would have been higher without the stress relief brought about by fillet debonding in this group.

<table>
<thead>
<tr>
<th>Method</th>
<th>$\sigma_{yy}$ max</th>
<th>$\sigma_{zz}$ max</th>
<th>$\tau_{yc}$ max</th>
<th>Deflection</th>
</tr>
</thead>
<tbody>
<tr>
<td>2D (UF)</td>
<td>3&lt;2&lt;1</td>
<td>3&lt;2&lt;1</td>
<td>3&lt;2&lt;1</td>
<td>3&lt;2&lt;1</td>
</tr>
<tr>
<td>3D (UF)</td>
<td>2&lt;2&lt;1</td>
<td>2&lt;2&lt;1</td>
<td>2&lt;2&lt;1</td>
<td>2&lt;2&lt;1</td>
</tr>
<tr>
<td>2D (Sub)</td>
<td>B&lt;A</td>
<td>B&gt;A</td>
<td>B&lt;A</td>
<td>B&lt;A</td>
</tr>
<tr>
<td>Deflection</td>
<td>—</td>
<td>—</td>
<td>—</td>
<td>—</td>
</tr>
</tbody>
</table>

Edge Delamination

The edge fillet significantly affects the magnitude of the peel stress component $\sigma_{zz}$. According to FEM simulations, this stress is highly compressive at the die perimeter with a fully bonded edge fillet and becomes tensile with a debonded edge fillet. This is evident in Table 5 and can be seen graphically in Figure 7 where the distribution of $\sigma_{zz}$ FEM calculations with fully bonded and 100% debonded fillet are plotted. The debonded fillet case results in tensile conditions at the edge while the presence of the fillet tends to "squeeze" the edge of die into the substrate due to the CTE mismatch between it and the Si die.

Significant edge delamination occurred in all 9 parts in the Bmp1/SubA/UF2 split during T/C. Figure 8 contains C-SAM images of one part in this group taken after preconditioning and at the 100, 300, and 1500 T/C off-line testing interval. A low voltage SEM inspection of this part at 200 T/C showed debonding of the edge fillet around the entire perimeter. It is assumed that the remaining parts in
this split contain similar debonding. Although it is unclear why only this group experienced complete edge fillet debonding early in temperature cycling, the resulting edge delamination is consistent with peel stress reversal discussed in the previous paragraph.

Radial Fillet Cracking

Radial cracks emanating from die corners were evident in every part in all experimental groups in early phases of temperature cycling. These cracks became progressively longer extending past the underfill edge fillet into the substrate with increasing T/Cs. This can be seen in Figure 9 which contains an optical micrograph of part S/N 104 after 2000 T/Cs. The length and frequency of these cracks were considerably greater in the SubA experimental groups and the underfill dependency generally showed the relation UF1<UF2<UF3 in terms of severity. The substrate relationship is consistent with stress calculations and measurements discussed in the first section showing SubA to be under greater residual stress than SubB. However, these calculations and measurements conflict if used to predict functional dependency of radial crack growth on underfill. The observed dependency might be less a function of residual stress and more a result of differences in physical properties that could affect crack propagation. For example, the elastic modulus of the three underfills contained in Table 1 show the same UF1<UF2<UF3 relation in terms of increasing modulus and decreasing flexibility.

Figure 7. Plot of $\sigma_{zz}$ peel stress distribution along the normalized centerline half-length of the die surface. Dashed line is FEM for SubB/UF2 case for fully bonded fillet, solid line is for fully debonded fillet.

Figure 9. Micrograph of Bmp2/SubA/UF3 part S/N 104 top view after 2000 T/C illustrating typical radial crack emanating from die corner through underfill edge fillet and into BGA substrate during thermal cycling. Approximate locations of cut lines are indicated as reference for cross-sections shown in Figure 11.

Figure 10. SEM micrograph of die corner top view in Figure 9 showing underfill-to-die edge debonding.
result in slippage between the fillet and die edge. Slippage will cause the hoop stress shown in Figure 12 to redistribute and concentrate in the corners and eventually result in cohesive failure of the fillet. The stress distribution at this point would favor radial crack propagation from the corner.

Figure 11. SEM micrograph of cross-section through radial crack shown in Figures 9 and 10.

Figure 12. Surface plot of maximum normal stress in edge fillet near corner for SubB/UF2 case. Region illustrated is similar to that shown in Figure 10 but slightly tilted and with the die removed.

Edge debonding of the underfill fillet is apparent in Figure 10 which contains a SEM close-up of the corner shown in Figure 9. This particular radial crack extends completely through the top build-up layers stopping at the glass woven core, as shown in Figure 11. Radial crack initiation can be explained by considering the stress-strain field of a fully bonded edge fillet. In this case, the "hoop" stress within the fillet is relatively constant around the perimeter, as shown in Figure 12, due to the adhesive joint along the fillet-to-die edge interface. The shear forces developed in this interface that act to maintain the adhesive bond are zero at the midpoints of the die edge and increase to a maximum at each corner. Debonding of the interface would be expected to begin at the corners, where this stress is greatest, and

Figure 13. C-SAM images of S/N 104 after 100, 200, 300 and 500 T/C showing first sign of cracking at midpoint of left side after 100 T/C.

Figure 14. C-SAM image of S/N 104 after 2000 T/C showing edge delamination and in-plane die crack.

Die Cracking
Evidence of in-plane die cracking was present in C-SAM images as early as the first 100 T/C inspection point in some of the experimental splits. Once initiated, these cracks appeared to increase in area in C-SAM images taken at subsequent temperature cycle intervals. Figures 13 and 14 show signs of two cracks that first appeared along the left side after 100 T/Cs and merged to form a single large crack eventually encompassing the entire upper left quadrant. A
cross-section of this part along the diagonal in Figure 14 is contained in Figure 15. The left-hand side of the figure (really the upper left corner of the die) is expanded in Figure 16 to reveal a fully debonded edge fillet.

![Figure 15. SEM micrograph of S/N 104 cross-section showing blow-ups of die crack.](image)

![Figure 16. Blow-up of left-hand side of Figure 15 showing fully debonded edge fillet.](image)

Die cracking is clearly related to overall deformation or bending of the assembly caused by residual thermal stress. Only one of 27 parts in the three SubB underfill groups showed signs of die cracking in C-SAM and it appears to be due to handling. The die split in half along the vertical centerline. On the other hand, 24 of 26 parts in the six SubA groups showed evidence of cracking on or before 2000 T/Cs. This correlates with predictions and measurements in Tables 4, 6, and 7 that show higher stress in the SubA parts. For instance, back side deflections averaged 6–14% greater for SubA parts.

Though the driving force for cracking is associated with overall residual stress, and can probably be ameliorated by proper choice of substrate and underfill material properties, it appears that partial debonding of the edge fillet can trigger cracking in an otherwise stable assembly. Support for this idea is found in 3D FEM calculations in Figure 17, where the normal stress in the z-direction along a vertical path on the die edge is plotted for the three underfills and SubB on the left side of the chart. (3D FEM was not performed on SubA due to errors in material properties obtained from the vendor.) These three plots show similar compressive behavior—the die is being “squeezed” into the substrate by the fillet. Simulations of various debond length are also contained in this figure for the UF2 case only. These plots show a tensile stress concentration that coincides with the debond tip that increases in magnitude with increasing debond length along the die edge top to bottom. Given conditions of critical residual stress, the intersection of such a stress riser with edge damage from wafer dicing could initiate an in-plane crack.

![Figure 17. Plot of normal stress in the z-direction (normalized) along the y-face (edge) of the die at the die corner for UF1, 2 and 3. Also shown are the stress distributions for the UF2 case with varying degrees of underfill fillet-to-die edge debonding showing formation of tensile stress concentration at debond tip.](image)

If the edge fillet debond becomes complete without initiating a crack, there are still two hazards remaining for the assembly. First, edge delamination (described above) will develop as a reversal in the peel stress \(\tau_{zz}\) from compressive to tensile at the underfill-to-die interface. This is evident in Figure 7. The delamination zone will move inward during temperature cycling until all stress is relieved, progressively encompassing solder ball interconnections that will then be subjected to large cyclic shear strains. Second, the tip of the delamination zone will contain a stress riser similar to that shown in Figure 17 for the edge fillet region that could initiate a die crack away from the edge but within the plane of the die. The die crack shown in Figures 13, 14, and 15 might have originated in this way.
Conclusions
Partial and complete debonding of the fillet-to-die edge interface were observed in flip chip BGA parts that exhibited die cracking and underfill-to-die interfacial edge delamination during temperature cycling. Die cracking is more likely in assemblies under greater stress and in combination with rough or dicing-saw damaged edges, but appears to be triggered by stress risers at the tip of a partially debonded edge fillet. Edge delamination, on the other hand, requires complete debonding of the edge fillet in order to initiate.

Cracks emanating from die corners through the edge fillet and proceeding radially into and along the surface of the solder mask and build-up dielectric were associated with the same debonding of the fillet-to-die edge interface. FEM simulations show relatively uniform tensile stresses in the edge fillet when bonded that become concentrated at the die corner after debonding.

The critical role of the edge fillet in preventing delamination within the underfill region raises questions about the reliability of fillet-less wafer level processes currently under development.

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REFERENCES


