Semi-analytical model for calculation of induced strains in solder joints of underfilled flip chip assemblies

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Abstract

In this paper, a simple but very practical analytical model is presented to calculate the induced strains in the solder joints of underfilled flip chip assemblies. This model is only a rough approximation of the real distribution in the solder joints, but the model explains very well how several design parameters influence the solder joint reliability and why an underfill with high elastic modulus and a CTE in the range of 15-25 ppm/°C is optimal for the solder joint reliability. It also proves that the solder joint reliability of underfilled assemblies is almost independent on the chip size. The distance between the outer joint and the chip edge is a influential parameter.
Key words

Flip chip assembly, underfill, solder joint reliability, analytical modeling, parameter study, thermo-mechanical induced failures

1. Introduction to flip chip assembly technology

Flip chip technology is considered to be an advanced form of surface mount technology, where a bare semiconductor chip processed with solder bumps on its surface is turned upside down and bonded directly to the substrate without requiring any intermediate chip packaging or lead frame mounting (Figure 1). The technology was originally invented by IBM in 1962, and focused on solid logic technology with silicon transistors mounted on thick-film substrates. Several years later, the concept of limiting the solder wettable area on the mating pads of the components was introduced, that is, the controlled collapse chip connection (C-4) technology [1]. The solder-bumped flip chip is aligned to the substrate, and all solder joints are made simultaneously by reflowing (= melting) the solder. Until recently, C-4 has been primarily a technology for mainframe computers and some niche applications in automotive sensors and ignition modules. Today the application of the concept of flip chip is extended to house large I/O count semiconductor chips.

The most well known interconnection material for flip chip is eutectic SnPb solder, but electrically conductive adhesives (isotropic conductive adhesives = ICA and anisotropic conductive adhesives = ACA) and thermocompression gold ball bonding are also used [2].

The flip chip offers several benefits compared to wire bonding, including high package density, high I/O number (area array), improved electrical performance (short interconnections) and improved thermal capabilities (mounting a heat sink on the free backside of the chip).

However, the flip chip also has drawbacks, such as limited availability of bumped ICs, increased process requirements, relative high cost and last but not least, a very low thermo-mechanical reliability when mounted on substrates with high CTE. Figure 2 depicts that the reliability for flip chip assemblies to an FR4 board is very low (N50% < 200 cycles). The data for Figure 2 is shown in Table 1.

For non-underfilled flip chip assemblies, the solder joints are very small (typically a diameter lower than 100 µm) and do not form a strong mechanical connection between the stiff chip and the substrate. During temperature cycling, the chip almost moves parallel to the substrate without a global bending effect. Therefore, "shear" is the main deformation of the solder joint. This involves that the induced strain is linearly dependent on the chip size (~ DNP) and on the CTE mismatch between the chip and substrate, and inversely proportional to the solder joint standoff height. The first two effects are also shown in Figure 2. Unless the CTE of the substrate matches the CTE of the chip (2.6 ppm/°C) or the chip size is very small, no acceptable thermo-mechanical reliability is achieved for flip chip assemblies. A solution to solve this problem is to fill the gap between the chip and the substrate with an epoxy material. Applying this so-called ‘underfill’, the flip chip assembly can even have a solder joint reliability, which is 10 times higher. However, a good attachment of the underfill to the chip and substrate is required. Often, underfill delamination is found on no-cleaned surfaces.
Figure 1. Schematic drawing for underfilled flip chip assembly.

Figure 2. Thermo-mechanical reliability for non-underfilled flip chip assemblies mounted on different substrate materials (estimated by finite element simulations). The solder joint stand-off height is 50 µm. The applied temperature cycle is –25°C to 125°C.

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Table 2. Material description of the silicon chip and the different substrates used in Figure 2.

<table>
<thead>
<tr>
<th>Substrate</th>
<th>E-modulus (GPa)</th>
<th>CTE (ppm/°C)</th>
<th>Thickness</th>
</tr>
</thead>
<tbody>
<tr>
<td>FR4</td>
<td>15 GPa</td>
<td>17</td>
<td>1.6 mm</td>
</tr>
<tr>
<td>BT</td>
<td>20 GPa</td>
<td>14</td>
<td>0.4 mm</td>
</tr>
<tr>
<td>LCP</td>
<td>5 GPa</td>
<td>30</td>
<td>0.4 mm</td>
</tr>
<tr>
<td>Alumina</td>
<td>300 GPa</td>
<td>7</td>
<td>3.2 mm</td>
</tr>
<tr>
<td>Glass</td>
<td>66 GPa</td>
<td>4.5</td>
<td>0.7 mm</td>
</tr>
<tr>
<td><strong>Silicon</strong></td>
<td><strong>169 GPa</strong></td>
<td><strong>2.6</strong></td>
<td><strong>0.6 mm</strong></td>
</tr>
</tbody>
</table>

2. Principles of the semi-analytical modeling for underfilled flip chip assemblies

The use of “underfill” materials, which surround the connections and fill the space between the chip and substrate, has typically resulted in a significant improvement in reliability. The objective is to find an analytical approximation to calculate the induced strains in the solder joint, due to uniform temperature cycling.

A linear analytical model for non-underfilled peripheral and area array assemblies can be found in literature [3]. These calculations are based on elasticity theory. For underfilled assemblies, a linear analytical model would be complicated because the two components are connected to each other by a continuous medium (underfill) and several discrete (joint) connections. However, assuming that the discrete connections are relatively small and consequently have a low mechanical resistance, the model can be simplified to a tri-layer structure consisting of two components connected to each other using an adhesive (= underfill). This assumption is true for assemblies using solder connections because of the low yield stress of the solder, and consequently low mechanical strength. In this paper, an analytical approximation is derived for estimation of the induced strains in the solder joint. The schematic structure of the underfilled flip chip assembly is shown in Figure 3.

The principles for the analytical modeling are based on two assumptions. One, the solder joints are relatively small and have a low mechanical strength (even at small
deformation loads, the stress in the solder joint is above the yield stress). Therefore, the underfilled flip chip assembly behaves like a tri-layer structure (the underfill functions as an adhesive between the chip and the PCB). The stresses and strains induced in the underfill can be calculated using an analytical model described in literature.

The second assumption is that the solder joint has to follow the deformations of the underfill. Therefore, the induced strains in the underfill at the location of the joint need to be applied as an external deformation load to the solder joint, finally resulting in plastic deformations. The next sections describe how the induced strains in the solder joint are calculated based on these two assumptions.

Figure 3. Schematic drawing for underfilled flip chip assemblies.

3. Calculation of stresses in underfilled assemblies (tri-layer structure)

First, the stress/strain distribution in the underfill is calculated supposing a perfect tri-layer structure. The magnitude and the distribution of stresses in adhesively bonded assemblies, with consideration of the attachment compliance, was studied by Suhir [4]. In his model, the methods of structural mechanics are used to determine the normal and shear stresses acting in the bonded layer. A simplified version for Suhir’s model supposes that the adhesive is relatively thin compared to the chip and the substrate. Following formulae calculate for the adhesives the shear stresses $\tau(x)$ and the peeling stresses $\sigma_y(x)$.
Shear stress $\tau(x)$:

$$\tau(x) = k \cdot \frac{(\alpha_2 - \alpha_1) \Delta T}{\lambda \cdot \cosh(kL)} \cdot \sinh(kx)$$

with

$$k = \sqrt{\frac{\lambda}{\kappa}}$$

$$\lambda = \frac{1 - \nu_1}{E_1 h_1} + \frac{1 - \nu_2}{E_2 h_2} + \frac{(h_1 + h_2)^2}{4D}$$

$$\kappa' = \frac{h_1}{3G_1} + \frac{h_2}{3G_2} + \frac{2h_{\text{fill}}}{3G_{\text{fill}}}$$

$$D_1 = \frac{E_1 h_1^3}{12(1 - \nu_1^2)}$$

$$D_2 = \frac{E_2 h_2^3}{12(1 - \nu_2^2)}$$

$$D = D_1 + D_2$$

Normal stress $\sigma_x(x)$:

$$\sigma_x(x) = \left( \alpha_{eq} - \alpha_{\text{fill}} \right) \Delta T \cdot \frac{E_{\text{fill}}}{h_{\text{fill}}}$$

with

$$\alpha_{eq} = \alpha_1 + \frac{(\alpha_2 - \alpha_1)}{h_1 E_1 \left( \frac{1}{h_1 E_1} + \frac{1}{h_2 E_2} \right)}$$

The stresses in the underfill as calculated by the analytical formulas are verified by a 2D plane strain FEM (Figure 4). The chosen geometry and material parameters are specified to:

**Top component ‘1’ (chip):**

$h_1 = 0.6 \text{ mm}$, $E_1 = 120000 \text{ MPa}$, $\alpha_1 = 2.6 \text{ ppm/}^\circ C$, $\nu_1 = 0.3$

**Bottom component ‘2’ (FR4):**

$h_2 = 1.58 \text{ mm}$, $E_2 = 15000 \text{ MPa}$, $\alpha_2 = 18 \text{ ppm/}^\circ C$, $\nu_2 = 0.3$

**Adhesive (=underfill):**

$h_{\text{fill}} = 0.075 \text{ mm}$, $E_{\text{fill}} = 10000 \text{ MPa}$, $\alpha_{\text{fill}} = 25 \text{ ppm/}^\circ C$, $\nu_{\text{fill}} = 0.3$

Chip size = 5.4mm (L = 2.7 mm)

$\Delta T = +180^\circ C$

Both the shear stress [$\tau(x)$] and normal stress [$\sigma_x(x)$] are well calculated by the analytical model. The shear stress increases with DNP,
Figure 4. Stresses in underfilled assembly (without solder joints) calculated by analytical model and by FEM.

Figure 5. By FEM simulated stresses in underfilled assembly for two cases: full underfill layer (Figure 4) and underfill layer with solder joint (at DNP = 2.4 mm).
and attains the maximum value at the edge. The normal stress \([\sigma_x(x)]\) is constant over the whole area, and only changes to zero near the edge. However, the model does not accurately calculate the peeling stress \([\sigma_y(x)]\).

To prove that the first assumption of this modeling strategy is correct, the underfill stresses are also calculated including a solder joint in the underfill at a DNP of 2.4 mm. Figure 5 shows that the presence of a solder joint almost has no influence on the underfill stresses.

Using the stress formulas defined above, the elastic strains in the underfill material are calculated using Hooke’s law:

\[
\varepsilon_{x,\text{fill}} = \frac{1}{E_{\text{fill}}} \left[ \sigma_x - \nu (\sigma_y + \sigma_z) \right]
\]

\[
\varepsilon_{y,\text{fill}} = \frac{1}{E_{\text{fill}}} \left[ \sigma_y - \nu (\sigma_x + \sigma_z) \right]
\]

\[
\gamma_{xy,\text{fill}} = \frac{\tau_{xy}}{G_{\text{fill}}}
\]

with

\[
\sigma_z = \nu (\sigma_x + \sigma_y)
\]

(plain strain consideration)

4. Estimation of mean strains in a solder joint

The second assumption is that the strains in the underfill are applied to the solder joints. The centre of the solder joint is located at a distance \([\text{ext}]\) from the edge (\(\text{ext} = \text{extension}\)). The induced strains at the location of the solder joint are calculated by filling in the value \([x = L-\text{ext}]\) into the formulae defined above. This approximation implies that only mean values for solder joint strains can be calculated (no local strain concentrations).

Both the horizontal normal strain and the shear strain in the solder joint need to be equal to the underfill strain at location \(x = L - \text{ext}\):

\[
\varepsilon_{x,\text{solder}} = \varepsilon_{x,\text{fill}}; \quad \gamma_{xy,\text{solder}} = \gamma_{xy,\text{fill}}
\]

In the vertical deformation, there is also an effect of the mismatch in thermal deformation between the underfill and the solder joint. The total strain (= elastic + thermal strain) in the underfill must be equal to the total strain in the solder joint:

\[
\varepsilon_{y,\text{solder}} + \Delta T \alpha_{\text{solder}} = \varepsilon_{y,\text{fill}} + \Delta T \alpha_{\text{fill}}
\]

Consequently, the mean vertical normal strain induced in the solder joint is:

\[
\varepsilon_{y,\text{solder}} = \varepsilon_{y,\text{fill}} + \Delta T \left( \alpha_{\text{fill}} - \alpha_{\text{solder}} \right)
\]

The equivalent strain is calculated by:

\[
\varepsilon_{\text{eq, solder}} = \frac{2}{3} \left( \varepsilon_{x,\text{solder}}^2 + \varepsilon_{y,\text{solder}}^2 + \gamma_{xy,\text{solder}}^2 \right)
\]

Assuming this equivalent strain is much higher than the maximum allowed elastic strain \((\sim \sigma_y/\text{Esolder})\), this strain is supposed to be the induced plastic strain.

Verification of the semi-analytical model by FEM and parameter sensitivity analysis

The trends found in several parameter sensitivity analysis is verified by a 2D plane strain non-linear FEM (with a rectangular
Table 2. Comparison between solder strain calculated by analytical model and by FEM for 4 different underfill material combinations (strain is averaged over the joint).

<table>
<thead>
<tr>
<th>$E_{\text{fill}}$ (MPa)</th>
<th>$\alpha_{f/\text{fill}}$ (ppm/°C)</th>
<th>Normal strain $\varepsilon_{x,\text{solder}}$</th>
<th>Analytical</th>
<th>FEM</th>
</tr>
</thead>
<tbody>
<tr>
<td>5000</td>
<td>25</td>
<td>-0.30 %</td>
<td>-0.32 %</td>
<td></td>
</tr>
<tr>
<td>5000</td>
<td>50</td>
<td>-0.71 %</td>
<td>-0.76 %</td>
<td></td>
</tr>
<tr>
<td>10000</td>
<td>25</td>
<td>-0.30 %</td>
<td>-0.36 %</td>
<td></td>
</tr>
<tr>
<td>10000</td>
<td>50</td>
<td>-0.71 %</td>
<td>-0.82 %</td>
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</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>$E_{\text{fill}}$ (MPa)</th>
<th>$\alpha_{f/\text{fill}}$ (ppm/°C)</th>
<th>Shear strain $\varepsilon_{y,\text{solder}}$</th>
<th>Analytical</th>
<th>FEM</th>
</tr>
</thead>
<tbody>
<tr>
<td>5000</td>
<td>25</td>
<td>0.12 %</td>
<td>0.26 %</td>
<td></td>
</tr>
<tr>
<td>5000</td>
<td>50</td>
<td>0.74 %</td>
<td>0.74 %</td>
<td></td>
</tr>
<tr>
<td>10000</td>
<td>25</td>
<td>0.12 %</td>
<td>0.29 %</td>
<td></td>
</tr>
<tr>
<td>10000</td>
<td>50</td>
<td>0.75 %</td>
<td>0.79 %</td>
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</tr>
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</table>

<table>
<thead>
<tr>
<th>$E_{\text{fill}}$ (MPa)</th>
<th>$\alpha_{f/\text{fill}}$ (ppm/°C)</th>
<th>Normal strain $\varepsilon_{x,y,\text{solder}}$</th>
<th>Analytical</th>
<th>FEM</th>
</tr>
</thead>
<tbody>
<tr>
<td>5000</td>
<td>25</td>
<td>-0.73 %</td>
<td>-1.24 %</td>
<td></td>
</tr>
<tr>
<td>5000</td>
<td>50</td>
<td>-0.73 %</td>
<td>-1.34 %</td>
<td></td>
</tr>
<tr>
<td>10000</td>
<td>25</td>
<td>-0.38 %</td>
<td>-0.84 %</td>
<td></td>
</tr>
<tr>
<td>10000</td>
<td>50</td>
<td>-0.38 %</td>
<td>-0.96 %</td>
<td></td>
</tr>
</tbody>
</table>
solder joint shape). In this parameter sensitivity analysis, a silicon chip

\[ L = 2.5 \text{ mm} \]
\[ h_1 = 0.6 \text{ mm} \]
\[ E_1 = 120000 \text{ MPa} \]
\[ \alpha_1 = 2.6 \text{ ppm/°C} \]

is flip chip mounted to a FR4 PCB

\[ h_2 = 1.58 \text{ mm} \]
\[ E_2 = 15000 \text{ MPa} \]
\[ \alpha_2 = 18 \text{ ppm/°C} \]

The solder joint parameters are:

\[ h_c = h_{\text{fill}} = 0.075 \text{ mm} \]
\[ E_c = 30000 \text{ MPa} \]
\[ \alpha_c = 25 \text{ ppm/°C} \]
\[ \sigma_y = 30 \text{ MPa} \]
\[ \text{ext} = 0.3 \text{ mm} \]

The load is a uniform temperature increase of 180°C.

5. Optimal material properties

An optimal choice of the underfill material is of high importance for the flip chip reliability. The induced solder joint strains for four different combinations of elastic modulus and CTE for the underfill is shown in Table 2.

The comparison to the FEM results shows that the analytical model is able to simulate the same trends. The normal strains are relatively accurate while the shear strain is underestimated by the analytical model (Table 2 already indicated that the analytical model is underestimating the shear stress).

Figure 5 shows that the best underfill has 10000 MPa and 25 ppm/°C as material properties. In this case, the lowest \( \varepsilon_y \) and \( \varepsilon_{xy} \) are achieved. The influence of elastic modulus and CTE of the underfill is described as follows:

The elastic modulus of the underfill only influences the shear strain \( \varepsilon_{xy} \), not the normal strains \( \varepsilon_x \) and \( \varepsilon_y \). It is found that the higher \( E_{\text{fill}} \), the lower the induced shear strain in the solder joint. The shear stress in the underfill is mainly induced by the two components, which the underfill is connecting, while \( \tau_{xy} \) is almost not influenced by the underfill material properties (Eq. 1). The induced shear strain in the underfill is equal to the shear stress divided by the shear modulus \( \sim E_{\text{fill}} \) (Eq. 4). Consequently, the higher the underfill elastic modulus, the lower the induced strain in the underfill and the lower the strain in the solder joint.

The CTE of the underfill only influences the normal strains \( \varepsilon_{x,\text{solder}} \) and \( \varepsilon_{y,\text{solder}} \). The FEM results also show a small effect on the \( \varepsilon_{xy,\text{solder}} \). Principally, the thermal expansion of the underfill has little effect on the induced shear stress in the underfill. However, the normal stress \( \sigma_x \) in the underfill is determined by the difference between \( \alpha_{eq} \) and \( \alpha_{\text{fill}} \) where \( \alpha_{eq} \) is determined by the chip and the substrate properties (Eq. 3). In this particular case, \( \alpha_{eq} = 6.5 \text{ ppm/°C} \) and therefore, the induced stress \( \sigma_x \) in the underfill is smaller when \( \alpha_{\text{fill}} \) is closer to this value. This is also true for the induced strain \( \varepsilon_{x,\text{solder}} \).

The effect of \( \alpha_{\text{fill}} \) on the normal strain \( \sigma_{y,\text{fill}} \) is more complicated. The strain in the underfill is the summation of the thermal strain \( \alpha_{\text{fill}} \Delta T \) and the out-of-plane expansion \( (-\nu \frac{\sigma_x + \sigma_y}{E_{\text{fill}}}) \). If this \( \varepsilon_{y,\text{fill}} \) strain is equal to the thermal expansion of the solder \( \alpha_{\text{solder}} \Delta T \), the normal strain \( \varepsilon_{y,\text{solder}} \) would be zero. In this particular case, the optimal \( \alpha_{\text{fill}} \) is found for:

\[ \varepsilon_{y,\text{fill}} + \Delta T (\alpha_{\text{fill}} - \alpha_{\text{solder}}) = 0 \] (9)
Supposing that \( \sigma_y \) is zero, \( \varepsilon_{y,fill} \) can be formulated as:

\[
\varepsilon_{y,fill} = \frac{1}{E_{fill}} \left[ \sigma_y - \nu \left( \sigma_x + \sigma_z \right) \right]
\]

\[
= \frac{1}{E_{fill}} \left[ 0 - \nu \left( \sigma_x + \nu \sigma_x \right) \right]
\]

\[
= \frac{\sigma_x}{E_{fill}} \left[ - \nu - \nu^2 \right]
\]

\[
= \frac{(\alpha_{eq} - \alpha_{fill})E_{fill}}{E_{fill}} \Delta T \left[ - \nu - \nu^2 \right]
\]

\[
= (\alpha_{eq} - \alpha_{fill}) \Delta T \left[ - \nu - \nu^2 \right]
\]

Inserting (Eq. 10) into (Eq. 9), the vertical normal strain \( \varepsilon_{y,solder} \) is zero when:

\[
\alpha_{fill} = \alpha_{solder} - \frac{(\alpha_{eq} - \alpha_{fill}) \Delta T \left[ - \nu - \nu^2 \right]}{\Delta T}
\]

\[
= \alpha_{solder} - \left( \alpha_{eq} - \alpha_{fill} \right) \left[ - \nu - \nu^2 \right]
\]

\[
\Rightarrow \alpha_{fill} = \frac{\alpha_{eq} \left( \nu + \nu^2 \right) + \alpha_{solder}}{1 + \nu + \nu^2}
\]

Substituting the values for

\( \nu (= 0.3) \),

\( \alpha_{solder} (= 25 \text{ ppm/}^\circ\text{C}) \) and

\( \alpha_{eq} (= 6.5 \text{ ppm/}^\circ\text{C}) \),

\( \varepsilon_{y,solder} = 0 \) for \( \alpha_{fill} = 19 \text{ ppm/}^\circ\text{C} \).
Figure 7. Induced plastic strains in solder joint versus chip size (calculated by analytical model and FEM; the strain is averaged over the whole joint).

The previous calculation only optimizes the $\varepsilon_{y,\text{solder}}$. A general optimization would optimize the total of the three strains. Figure 6 shows the full parameter sensitivity analysis varying $E_{\text{fill}}$ between 5000 and 10000 MPa, and $\alpha_{\text{fill}}$ between 0 and 50 ppm/°C. The optimal CTE found by the analytical model is around 15 ppm/°C. This CTE value is in between 6.5 ppm/°C ($\varepsilon_x = 0$) and 19 ppm/°C ($\varepsilon_y = 0$). An analytical formula for the general optimal $\alpha_{\text{fill}}$ is extracted optimizing the equivalent strain (Eq. 8). Because $\alpha_{\text{fill}}$ has no influence on $\gamma_{xy,\text{solder}}$, the optimization can rewritten as

$$\min(\varepsilon_{eq,\text{solder}})$$

$$= \min \left( \frac{2}{3} \left( \varepsilon_{x,\text{solder}}^2 + \varepsilon_{y,\text{solder}}^2 + \frac{\gamma_{xy,\text{solder}}^2}{2} \right) \right)$$

$$= \min \left( \varepsilon_{x,\text{solder}}^2 + \varepsilon_{y,\text{solder}}^2 \right)$$

The optimum is found for:

$$\frac{\partial}{\partial \alpha_{\text{fill}}} \left[ \left( \alpha_{eq} - \alpha_{\text{fill}} \right) \left( 1 - \nu^2 \right) \right] + \left[ \left( \alpha_{eq} - \alpha_{\text{fill}} \right) \left( - \nu - \nu^2 \right) + \gamma_{xy,\text{solder}}^2 \right] = 0$$
Figure 8. Induced plastic strains in solder joint versus chip size (calculated by analytical model and FEM; the strain is averaged over the whole joint).

The solution for this equation is:

$$\alpha_{\text{fill}} = \frac{\alpha_{\text{solder}} (1 + \nu + \nu^2) + \alpha_{\text{eq}} [(1 + \nu) (1 + \nu + \nu^2) + (1 - \nu^2)]}{(1 - \nu^2)^2 + (1 + \nu + \nu^2)^2}$$

In this particular case, the optimal underfill CTE would be 16 ppm/°C. Figure 6 confirms this optimal CTE. The optimal CTE for the FEM results is about 5 ppm/°C lower. There are two reasons for this. First, the shear strain also increases slightly with increasing underfill CTE. Second, the solder joint has at lower $\alpha_{\text{fill}}$ more hydrostatic stress ($\sigma_x$ and $\sigma_y$ have the same sign) and therefore, the solder joint is at higher stress before it starts to yield.

Chip size

Figure 7 shows that the induced solder joint strains are almost independent on the chip size. This is in contradiction to what was found with non-underfilled flip chip assemblies. All the stresses in the underfill, inclusive the maximum shear stress at the edge, are almost
independent on the chip size. Consequently, the induced solder joint strains are not increasing when the chip size is growing. This trend is also found in the FEM results (Figure 7). Reference [5] confirms these simulation results by experimental data (experiments show the same reliability for flip chip assemblies for 10x10 up to 40x40 mm²).

Distance from the edge

In Figure 8, this parameter is defined as ‘ext’. As both the ‘peeling’ stress $\sigma_y$ and the shear stress $\tau_{xy}$ in the underfill are increasing to a maximum at the edge, the induced solder joint strains are lower if the solder joint is located further away from the edge. In the curve calculated by FEM, there is even a maximum at 0.2 mm. This is caused by the peeling stress $\sigma_y$ that is maximum at 0.2 mm. This effect is not found in the analytical model due to the worse calculation of the peeling stress.

Solder joint stand-off height

The stresses are almost independent on the underfill thickness, and therefore, the solder joint strains are independent on the solder joint standoff height. In reality, a better solder joint reliability is found for larger standoff height due to the effect of solder resist.

6. Conclusions

Finally, we can conclude that the analytical estimation already gives good insight in the origin of the solder joint strains in underfilled flip chip assemblies and is able to roughly estimate the average strains. The model is based on the assumption that the underfilled structure behaves as a trilayer structure, with the underfill as adhesive. The strains inside the underfill are applied to the solder joints as external load. The analytical model is limited due to inaccuracy in stress calculation (limitation in Suhir’s model), the method of transforming underfill strain into solder joint plastic strains and the simplification of the structure (considering no local strain concentrations). However, the model is suitable for parameter sensitivity analysis and these trends have been verified by finite element modeling. It is found that the optimal underfill properties are a high elastic modulus and a CTE in the range of 15 to 25 ppm/°C. It is shown that the solder joint reliability for underfilled flip chip assemblies is independent on the chip size. The induced strains are increasing when the solder joint is located closer to the edge.

References


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