Reliability Simulation with the Finite Element Analysis (FEA) of Redistribution Layer in Fan-out Wafer Level Packaging

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1. Introduction of my study

2. Examining Critical Energy Release Rate \((G_c)\)

3. Analyzing Energy Release Rate \((G)\) by FEA

4. Discussion of Delamination Possibility \((G/G_c)\)

5. Conclusion of my results
Outline

1. Introduction of my study

2. Examining Critical Energy Release Rate ($G_c$)

3. Analyzing Energy Release Rate ($G$) by FEA

4. Discussion of Delamination Possibility ($G/G_c$)

5. Conclusion of my results
Introduction

Fig. 1 Fan-out PoP Package Illustration

Demand

- Smaller / Thinner
- High reliability
- Low cost

Solution

- Choosing best material
- Suitable structure
- Making R&D efficient
This Work

**Critical Energy Release Rate**

1. Peel test / Tensile test
2. Creating master curve
3. Calculating $G_c$

**Energy Release Rate**

1. Model / Temp. profile
2. Simulation by FEA
3. Calculating $G$

**Normalizing**

$$\frac{G}{G_c}$$

- $\geq 1.0 \Rightarrow$ Delamination occur
- $< 1.0 \Rightarrow$ the larger value is, the higher possibility of delamination
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Method of Calculation

**Critical Energy Release Rate (\(G_c\))**

\[
dU_{\text{ext}} = dU_t + dU_{\text{db}} + bG_c da
\]

- **External workload**
- **Deformation energy**
- **Delamination energy**

\[
G_c = \frac{P}{b} \left(1 + \varepsilon_a - \cos \theta \right) + h \int_0^{\varepsilon_a} \sigma \cdot d\varepsilon + \frac{1}{2} \left(E\varepsilon_y^2 h \right) \cdot f_1 (k_0)
\]

- **Tensile deformation**
- **Bonding deformation**

Obtained from peel test

Obtained from tensile test

\(k_0 = \theta_0 \cdot \frac{3}{4\varepsilon_y}\)

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ref). A.J. Kinloch et al., “The peeling of flexible laminates”, *International Journal of Fracture*, Vol. 66, No. 1, (1994), pp. 45-70.
Peel Test

\[ G_c = \frac{P}{b} \left( 1 + \varepsilon_a - \cos \theta \right) - h \int_0^{\varepsilon_a} \sigma \cdot d\varepsilon - \frac{1}{2} \left( E \varepsilon_y^2 h \right) \cdot f_1(k_0) \]

Obtained from Peel Test

Polymer

Copper

Silicon

Fig.2 Illustration of Peel Test Specimen

- \( P \): Delamination load
- \( \varepsilon_a \): Strain
- \( \theta \): Peel angle
- \( b \): Film width

Table 1 Condition of Peel Test

| Control system | Displacement control |
|----------------|----------------------|
| Peel angle [degree] | 180 |
| Displacement rate [mm/s] | 0.002 / 0.017 / 0.17 / 1.7 |
| Temperature [K] | 298 / 348 / 398 |

Fig.3 Peel Testing Machine
Tensile Test

\[ G_c = \frac{P}{b} (1 + \varepsilon_a - \cos \theta) - h \int_0^{\varepsilon_a} \sigma \cdot d\varepsilon - \frac{1}{2} \left( E \varepsilon_y^2 h \right) \cdot f_1(k_0) \]

Obtained from tensile test

\( \varepsilon_y \): Yield strain  
\( \sigma \): Stress  
\( E \): Elastic modulus  
\( h \): Film thickness  
\( \alpha \): Strain hardening coefficient

**Table.2 Condition of Tensile Test**

| Control system         | Displacement control |
|------------------------|----------------------|
| Displacement rate [mm/s]| 0.002 / 0.017 / 0.17 / 1.7 |
| Temperature [K]        | 298 / 348 / 398      |

Fig.4 Stress-strain Curve

瀣: Yield strain  
\( \sigma \): Stress  
\( E \): Elastic modulus  
\( h \): Film thickness  
\( \alpha \): Strain hardening coefficient
# Materials

## Table 3: Typical Properties of Polymer Materials

| Material          | PI-1         | PI-2         | PBO             | PH              |
|-------------------|--------------|--------------|-----------------|-----------------|
| Polymer           | Polyimide    | Polyimide    | Polybenzoxazole | Phenolic resin  |
| Cure Temp. [°C]   | 200          | 200          | 350             | 220             |
| Tg [°C]           | 200          | 220          | 300             | 230             |
| Elastic Modulus $E$ [GPa] | 3.2          | 4.0          | 2.4             | 3.5             |
| CTE $\alpha_1$ [ppm/K] | 60           | 50           | 45              | 36              |

![PI (Polyimide)](image1)

![PBO (Polybenzoxazole)](image2)

![PH (Phenolic resin)](image3)

PI (Polyimide)  
PBO (Polybenzoxazole)  
PH (Phenolic resin)
Critical Energy Release Rate ($G_c$)

Fig.5 Relationship between displacement rate and Critical energy release rate ($G_c$) in each temperature
Method of Creating Master Curve

Fig. 6 Relationship between displacement rate and Critical energy release rate ($G_c$) about PI-1

$\alpha_T = 3.04 \exp \left[13212 \left(\frac{1}{T} - \frac{1}{298}\right)\right]$
Fig. 7 Master curves of function of critical energy release rate $G_c$ and displacement rate $v$ about PI-1

$G_c = 155.0 v^{0.066}$

Fig. 8 Master curves of function of critical energy release rate $G_c$ and displacement rate $v$ about PI-2

$G_c = 175.9 v^{0.061}$
Master Curves of $Gc$

Fig. 9 Master curves of function of critical energy release rate $Gc$ and displacement rate $v$ about PBO

$Gc = 34.2 v^{0.202}$

Fig. 10 Master curves of function of critical energy release rate $Gc$ and displacement rate $v$ about PH

$Gc = 101.0 v^{0.036}$
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Finite Element Analysis

Fig.11 FEA Model
## Materials

### Table 4 Typical Properties of FEA Model Components

| Materials | Property | Modulus [GPa] | CTE [ppm/K] | Poisson's ratio |
|-----------|----------|---------------|-------------|----------------|
| Cu        |          | 129.8         | 17          | 0.34           |
| FR-4      |          | 22            | T-dependent | 0.28           |
| SR        | Elasticity | 2.6          | T-dependent | 0.29           |
| UBM       |          | 199.5         | 13.1        | 0.3            |
| Si        |          | 168           | 2.6         | 0.35           |
| Solder    | Creep    | $76.087 - 0.109T$ | 0.3 | 0.3 |

Creep constitutive equation of solder; Garofalo’s rule

$$\dot{\varepsilon}_{ss} = 5.75 \times 10^6 \left[ \sinh (0.03 \sigma) \right]^{7.8} \exp \left( -\frac{70000}{RT} \right) \dot{\varepsilon}_{ss}$$

$\dot{\varepsilon}_{ss}$: Creep strain rate

$\sigma$: Stress

$R$: Gas constant

$T$: Temperature
Temperature Profile

Fig. 12 Temperature profile for thermal cycle

- $T_{\text{max}} = 398$ K
- $T_{\text{min}} = 233$ K
- $T_{r} = 298$ K

Fig. 13 Temperature profile for reflow process

- $T_{r} = 523$ K
- Birth (Solder)
- Death (Solder)
- $\Delta T = 5$ K/s
Effects of $E$ and $\alpha$ on $G$

Table 5 Levels and Magnifications of each Factors

|                 | level         |
|-----------------|---------------|
| Elastic modulus, $E$ | $\times 0.5$  | $\times 1$  | $\times 1.5$ |
| Thermal expansion coefficient, $\alpha$ | $\times 0.7$  | $\times 1$  | $\times 1.3$ |

Fig. 14 Relationship between temperature and $E$

Fig. 15 Relationship between temperature and $\alpha$
Interaction Effect of $E$ and $\alpha$

Thermal Cycle (398K→233K)

- Energy release rate, $\mathcal{G}$, J m$^{-2}$
- Elastic modulus, $E$, and CTE, $\alpha$

Smallest

Large

Small

Fig. 16 Interaction Effect of $E$ and $\alpha$ on $\mathcal{G}$ in thermal cycle (398K→233K)

Reflow Process

- Energy release rate, $\mathcal{G}$, J m$^{-2}$
- Elastic modulus, $E$, and CTE, $\alpha$

Large Angle

Smallest

Small Angle

Fig. 17 Interaction Effect of $E$ and $\alpha$ on $\mathcal{G}$ in reflow process (523K→233K)
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Table 6 Relative Parameters of $G_c$, $E$ and $\alpha$

|                         | PI-1       | PI-2       | PBO        | PH         |
|-------------------------|------------|------------|------------|------------|
| Critical energy release rate, $G_c$ | OHigh     | OHigh      | $\times$ Low | $\Delta$ Middle |
| Elastic modulus, $E$    | High       | High       | Low        | High       |
| Thermal expansion coefficient, $\alpha$ | $\times$ High | $\Delta$ Middle | $\Delta$ Middle | OLow       |
Fig. 18 $G/G_c$ normalized in the thermal cycle

![Diagram showing energy release rate and material layers (PI, PBO, PH, Cu-RDL, UBM) with normalized $G/G_c$ for different thermal cycles: 233K→398K and 398K→233K.](image-url)
Normalized Energy Release Rate, \( \frac{G}{G_c} \) in the Thermal Cycle

Fig. 19: \( \frac{G}{G_c} \) normalized in the thermal cycle (without PBO)

- Solder side
- Si side

- Temperature range: 398K to 233K

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Fig. 20 \( \frac{G}{G_c} \) normalized in the reflow process.
**G/Gc Normalized in the Reflow Process**

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**Figure 21**

- **Normalized Energy Release Rate, G/Gc**
- **Solder side**
- **Si side**
- **523K → 298K**

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**Graph**

- **Normalized Energy Release Rate, G/Gc**
- **Solder Side**
- **Polymer**
- **Si Side**
- **PI-1**
- **PI-2**
- **PH**

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**Text**

- **Normalized Energy Release Rate, G/Gc normalized in the reflow process (without PBO)**

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**Additional Information**

- **Device Packaging 2020 - Fountain Hills, AZ USA - March 2-5, 2020**
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Conclusion

✔ This study has made it possible to simulate the delamination possibility of Cu/Polymer interface at arbitrary temperatures and displacement rates from basic material data and FEA analysis of the FOWLP structure.

✔ This knowledge can be used to develop polymer materials with high reliability

✔ More importantly, we can know the reliability under arbitrary conditions in advance about various materials and various package structures.
Future Works

✓ We have been attempting integrated simulation of delamination and material fracture by combining this study with the Fatigue Crack Propagation Test of materials.

✓ If these two can be integrated, it is possible to discriminate between the case of delamination occurring and the case of material fracture occurring according to differences in materials and package structures.

✓ We can be expected to select an optimal material for the designed package structure, and/or to be used as a design guide for a high reliability package structure.
Creating for Tomorrow

The commitment of the Asahi Kasei Group:
To do all that we can in every era to help the people of the world make the most of life and attain fulfillment in living.
Since our founding, we have always been deeply committed to contributing to the development of society, boldly anticipating the emergence of new needs.
This is what we mean by “Creating for Tomorrow.”