

3-D Corner Delamination Analysis for Fan-Out Chip Scale Package

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Abstract

The problem of a corner delamination in a fan-out chip scale package under thermomechanical load is investigated. The fracture mechanics parameters, including the stress intensity factors and the strain energy release rate, for a quarter-circular corner delamination between silicon die and fan-out redistribution polyimide layer are obtained by using numerical finite element approach with 3-D virtual crack closure technique (VCCT). Results of the analysis indicated that contact between crack faces occurs under temperature cycling condition. The delamination driving forces are mode-II and -III dominant. In addition, the strain energy release rate is highest near the location where the delamination crack front intersects die-to-molding compound interface. Parametric study is also conducted to investigate the effects of material properties and geometrical dimensions on the delamination driving forces. The calculated fracture mechanics parameters may be combined with the experimental data on the resistance to interface fracture for predicting reliability of the package.

Keywords: delamination, fan-out package, stress intensity factor, and virtual crack closure technique (VCCT)

Introduction

Driven by the need for electrical performance improvement and system integration, the interconnection between silicon die and its package has become one key area for packaging technology development. One of the interconnection schemes received a lot of attention lately is the die surface fan-out redistribution interconnect [1, 2]. In a fan-out package the silicon die is first encapsulated in molding compound except its top surface. A metal-polymer redistribution layer is then fabricated on top for interconnection between die-level bond pads and BGA pads. This type of interconnect involves structures in thin-layered configuration and materials having high coefficients of thermal expansion (CTEs). As a result, the structure is susceptible to interfacial delamination during package assembly or under service condition. To ensure reliability of the fan-out package, it is therefore important to understand the interaction of materials and geometry and their effects on the delamination driving forces.

In a plastic package the delamination defect typically initiates from the corner of die where the thermomechanical stress is the most significant. The corner defect would propagate in a three-dimensional (3-D) fashion [3]. Since the analytical solutions for 3-D delamination problem are limited to cases that has very simple geometry, numerical finite element approach is preferred for investigating the delamination growth in a complex structure such as the fan-out package.

Within the scope of linear elastic fracture mechanics, the parameters that characterize the fracture driving forces at the interface crack front are the stress intensity factors and the strain energy release rate. In this study the virtual crack closure technique (VCCT) is applied to obtain the fracture mechanics parameters for the corner delamination in a fan-out package. Advantage of the VCCT approach for calculating fracture mechanics parameters is that the results are determined by post-processing finite element solutions. It does not require special finite element formulation, and, as a result, can be implemented in any finite element software.

In the following sections, a brief description is first given for the definitions of fracture mechanics parameters in interface fracture and the 3-D VCCT technique used for calculating these parameters. The 3-D VCCT is then applied to determine the fracture mechanics parameters along a realistic curvilinear corner delamination crack front in a fan-out package under uniform cooling from 125°C to -40°C. The effects of materials, package dimension, and crack shape on the delamination driving forces are also discussed.

Fracture Mechanics Parameters

The asymptotic stress field at the crack tip of an interface crack between two dissimilar isotropic materials can be expressed as

$$\sigma_{ij}(r, \theta) = \frac{1}{\sqrt{2\pi r}} \left\{ \text{Re}[Kr^{i\epsilon}] \tilde{\sigma}_{ij}^I(\theta, \epsilon) + \text{Im}[Kr^{i\epsilon}] \tilde{\sigma}_{ij}^{II}(\theta, \epsilon) + K_{III} \tilde{\sigma}_{ij}^{III}(\theta) \right\}, \quad (1)$$

where r and θ are the in-plane coordinates of the plane normal to the crack front, K is the complex stress intensity factor, $K = K_I + iK_{II}$, $\tilde{\sigma}_{ij}^I, \tilde{\sigma}_{ij}^{II}, \tilde{\sigma}_{ij}^{III}$ are the angular variations of stress components for each mode. The bimaterial constant ϵ is given by

$$\epsilon = \frac{1}{2\pi} \ln \left(\frac{1-\beta}{1+\beta} \right), \quad (2)$$

where

$$\beta = \frac{\mu_1(\kappa_2 - 1) - \mu_2(\kappa_1 - 1)}{\mu_1(\kappa_2 + 1) + \mu_2(\kappa_1 + 1)}, \quad (3)$$

μ is the shear modulus, $\kappa = 3 - 4\nu$ for plane strain, ν is the Poisson's ratio, and the subscripts = 1 and 2 refer to the materials above and below the crack plane, respectively. It may be seen from (1) that the complex stress intensity factor K has a unit of (stress) $\times$ (length)^{1/2-i ϵ} . This oscillating nature makes characterizing the stress intensity factors difficult. To overcome this issue, Rice [4] suggested an alternative definition of stress intensity factors for the interface crack

$$\hat{K} = K_I + iK_{II} = KL^{i\epsilon}, \quad (4)$$

where L is a certain material length, invariant to crack length or other geometric dimensions in different applications. It may be seen that $\hat{K}$ has a unit of (stress) $\times$ (length), which is the same as that of the classical stress intensity factor. The in-plane and antiplane crack opening displacements at a small

distance r behind the crack tip are given, respectively, by

$$\begin{aligned} \delta_2 + i\delta_1 &= \frac{c_1 + c_2}{2\sqrt{2\pi}(1 + 2i\epsilon)\cosh(\pi\epsilon)} \hat{K} r^{1/2} \left(\frac{r}{L} \right)^{i\epsilon}, \\ \delta_3 &= \sqrt{\frac{2}{\pi}} \left(\frac{1}{\mu_1} + \frac{1}{\mu_2} \right) K_{III} r^{1/2}, \\ c_1 &= \frac{\kappa_1 + 1}{\mu_1}, \quad c_2 = \frac{\kappa_2 + 1}{\mu_2}. \end{aligned} \quad (5)$$

The virtual crack closure technique is based on the hypothesis that crack growth is self-similar and the released strain energy during crack growth is the same as the amount of work required to close the crack. Therefore, the strain energy release rate G for a crack to extend by an infinitesimal distance Δ can be expressed as

$$\begin{aligned} G &= G_I + G_{II} + G_{III}, \\ G_I &= \frac{1}{2\Delta} \int_0^\Delta \sigma_{22}(r, 0) \delta_2(\Delta - r) dr, \\ G_{II} &= \frac{1}{2\Delta} \int_0^\Delta \sigma_{12}(r, 0) \delta_1(\Delta - r) dr, \\ G_{III} &= \frac{1}{2\Delta} \int_0^\Delta \sigma_{23}(r, 0) \delta_3(\Delta - r) dr. \end{aligned} \quad (6)$$

It may be seen from (1), (5) and (6) that G_I and G_{II} are coupled functions of K_I and K_{II} . To obtain the mode-I and II stress intensity factors, Chow and Atluri [5] introduced an integral, given by

$$\begin{aligned} G_{I-II} &= \frac{1}{2\Delta} \int_0^\Delta [\sigma_{22}(r, 0) \delta_1(\Delta - r) \\ &\quad + \sigma_{12}(r, 0) \delta_2(\Delta - r)] dr. \end{aligned} \quad (7)$$

By substituting (1) and (5) into (6) and (7), it can be shown that, for an "opening" crack tip, the stress intensity factors can be obtained from the following equations:

$$\begin{aligned} K_I^2 &= \frac{8\cosh^2(\pi\epsilon)}{c_1 + c_2} \{ (G_I + G_{II}) \\ &\quad + \text{Re}[A_1](G_I - G_{II}) - \text{Im}[A_1]G_{I-II} \}, \end{aligned} \quad (8)$$

$$\begin{aligned} K_{II}^2 &= \frac{8\cosh^2(\pi\epsilon)}{c_1 + c_2} \{ (G_I + G_{II}) \\ &\quad - \text{Re}[A_1](G_I - G_{II}) + \text{Im}[A_1]G_{I-II} \}, \end{aligned} \quad (9)$$

$$K_{III}^2 = \frac{4\mu_1\mu_2}{\mu_1 + \mu_2} G_{III}, \quad (10)$$

where

$$A_1 = I(\varepsilon) \left(\frac{L}{\Delta} \right)^{2i\varepsilon}, \quad (11)$$

$$I = \frac{1}{2} (1 + 2i\varepsilon)^2 B(1 + 2i\varepsilon, 1/2 - i\varepsilon),$$

and B is the Beta function. Note that the signs of the stress intensity factors can be determined by inspecting the signs of the crack tip opening displacements. Dundurs [6] showed that, for an interface crack between two dissimilar isotropic materials, the absolute value of ε is not more than $(1/2\pi)\ln 3$. Therefore, the Beta function in (11) can be approximated by using a Taylor series such that

$$I \approx (1 - 12.6787\varepsilon^2 + 61.6693\varepsilon^4 - 254.670\varepsilon^6 + 1023.29\varepsilon^8) + i(4.77258\varepsilon - 29.3447\varepsilon^3 + 126.458\varepsilon^5 - 511.275\varepsilon^7). \quad (12)$$

Note that the error of the approximation for I given in (12) is less than 0.05%.

When large-scale frictionless contact occurs between crack faces, the crack opening displacement δ_2 equals to zero for the closed crack tip. From (6), it can be seen that K_I is zero when the crack tip is closed. The relationship between K_{II} and G_{II} can be expressed as

$$K_{II}^2 = \frac{16}{(c_1 + c_2)(1 - \beta^2)} G_{II}. \quad (13)$$

The relationship between K_{III} and G_{III} described in (10) is still valid for closed crack tip, since the antiplane mode is not coupled to the in-plane modes.

Finite Element Implementation

Following De Roeck and Abdel Wahab [7], the crack closure integrals given in (6) and (7) can be calculated from finite element nodal solutions. For the quarter-point singular crack-tip finite element depicted in Fig. 1 (crack faces are on the negative- x, z plane, while the crack front is along z -axis), G_I is given by

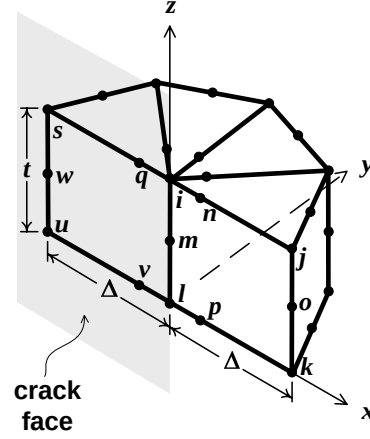


Fig. 1. Collapsed quarter-point crack-tip elements.

$$G_I = \frac{1}{2t\Delta} \left[F_y^i \left(C_1 \delta_y^q + C_2 \delta_y^w - 2C_2 \delta_y^s - \frac{C_2}{2} \delta_y^u \right) + F_y^l \left(C_2 \delta_y^w - \frac{C_2}{2} \delta_y^s - 2C_2 \delta_y^u + C_1 \delta_y^v \right) + F_y^m \left(\frac{C_1}{2} \delta_y^q + C_3 \delta_y^w + C_4 \delta_y^s + 2C_4 \delta_y^u + \frac{C_1}{2} \delta_y^v \right) + F_y^n \left(\delta_y^q + \frac{1}{2} \delta_y^s \right) + F_y^p \left(\frac{1}{2} \delta_y^u + \delta_y^v \right) \right], \quad (14)$$

where

$$\begin{aligned} C_1 &= 6\pi - 20, & C_2 &= \pi - 4, \\ C_3 &= \pi - 2, & C_4 &= -\frac{5}{4}\pi + 4, \end{aligned} \quad (15)$$

F is the nodal force, δ is the crack opening displacement, and the superscript denotes nodal location shown in Fig. 1. Similarly, G_{II} and G_{III} can be calculated by replacing (F_y, δ_y) in (14) with (F_x, δ_x) and (F_z, δ_z) , respectively. The finite element discretization for G_{I-II} is given by

$$\begin{aligned}
G_{I-II} = & \frac{1}{2t\Delta} \left[F_y^i \left(C_1 \delta_x^q + C_2 \delta_x^w - 2C_2 \delta_x^s \right. \right. \\
& \left. \left. - \frac{C_2}{2} \delta_x^u \right) \right. \\
& + F_y^l \left(C_2 \delta_x^w - \frac{C_2}{2} \delta_x^s - 2C_2 \delta_x^u + C_1 \delta_x^v \right) \\
& + F_y^m \left(\frac{C_1}{2} \delta_x^q + C_3 \delta_x^w + C_4 \delta_x^s + 2C_4 \delta_x^u \right. \\
& \left. + \frac{C_1}{2} \delta_x^v \right) \\
& + F_y^n \left(\delta_x^q + \frac{1}{2} \delta_x^s \right) + F_y^p \left(\frac{1}{2} \delta_x^u + \delta_x^v \right) \\
& + F_x^i \left(C_1 \delta_y^q + C_2 \delta_y^w - 2C_2 \delta_y^s - \frac{C_2}{2} \delta_y^u \right) \\
& + F_x^l \left(C_2 \delta_y^w - \frac{C_2}{2} \delta_y^s - 2C_2 \delta_y^u + C_1 \delta_y^v \right) \\
& + F_x^m \left(\frac{C_1}{2} \delta_y^q + C_3 \delta_y^w + C_4 \delta_y^s + 2C_4 \delta_y^u \right. \\
& \left. + \frac{C_1}{2} \delta_y^v \right) \\
& \left. + F_x^n \left(\delta_y^q + \frac{1}{2} \delta_y^s \right) + F_x^p \left(\frac{1}{2} \delta_y^u + \delta_y^v \right) \right].
\end{aligned} \quad (16)$$

For the case when large-scale contact occurs between crack faces around crack tip, the calculation for G_I using (14) results in zero because the nodal values for crack opening are zero. For the case of a closed crack-tip, the finite element discretizations for G_{II} and G_{III} are still applicable for obtaining II and III, respectively.

Corner Delamination in Fan-Out Package

The corner delamination on the interface of Si die and redistribution polyimide layer in a fan-out package subjected to uniform thermal cooling from 125°C to -40°C is investigated by using the 3-D VCCT. Figure 2 shows the schematics of the package. As depicted in Fig. 2(a), the embedded corner interface crack is assumed to be of quarter circular shape with a radius of 0.365mm. In the finite element analysis a quarter package model as shown in Fig. 3 are considered with zero out-of-plane displacement boundary conditions on the symmetric

planes. Sizes of the crack tip elements shown in Fig. 3(c) are such that $\Delta = 0.005\text{mm}$. Material properties for the package are given in Table 1. It is assumed that the metal loading in the fan-out redistribution is 10%. The bimaterial constant for the Si-polyimide interface is given by $\varepsilon = -0.08814$.

Results of the finite element analysis indicate that the crack faces of the corner delamination are in full contact at -40°C. Consequently, K_I is zero along the quarter-circular crack front. The stress intensity factors K_{II} and K_{III} along the quarter-circular crack front are shown in Fig. 4. Note that the crack fronts along die edges are not considered, since the crack tips along die edges are surrounded by a 90° silicon wedge and a 270° underfill wedge, which leads to a stress singularity weaker than 1/2, and is beyond the scope of linear elastic fracture mechanics. From Fig. 4 it can be seen that the mode-II stress intensity factor remains relatively constant throughout the whole quarter-circular crack front. On the other hand, the mode-III stress intensity factor is most significant near the periphery of die ($s = 0$ or 1). This is reflected

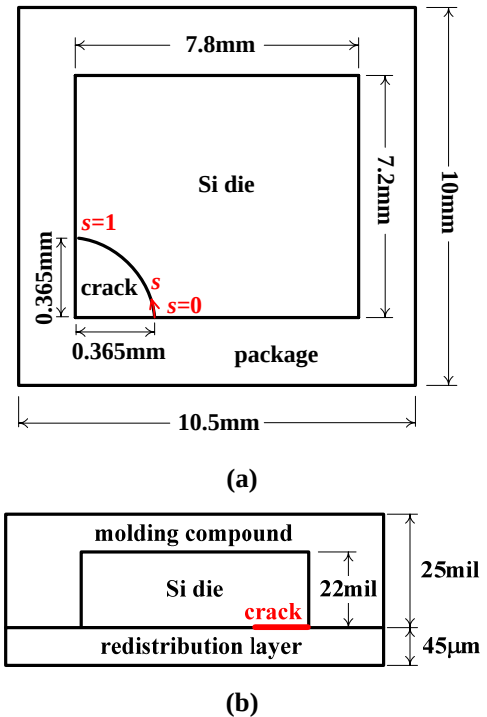


Fig. 2. Schematics of a fan-out package containing a quarter-circular interface corner crack between die and the redistribution polyimide layer, (a) top view, (b) cross-sectional view.

in the plot of strain energy release rate vs. crack front location, which is shown in Fig. 5. It may be seen from Fig. 5 that the strain energy release rate is higher near the periphery of die. This is indicating the likelihood of faster delamination growth around die periphery for the quarter-circular interface corner crack.

Effects of molding compound material and die thickness on the corner delamination driving force is shown in Fig. 6. It may be seen from Fig. 6 that the maximum strain energy release rate (occurring near the edges of die) for the package with MC2 compound is about 1/3 of that for package with MC1 compound. The lower G value for the package with MC1 may be attributed to the lower CTE of the MC1 molding compound. Therefore, the interfacial fracture reliability for package with MC2 compound is expected to be better than that with MC1 compound. Also it can be seen from Fig. 6 that, as die thickness increases, the strain energy release rates around the interior part of the crack front reduce. However, the difference in G values is less than 5% for die thicknesses varying between 10mil and 22mil. Therefore, the risks of delamination growth are relatively the same for fan-out packages with thick or thin dies.

For investigating the effect of crack shape on the delamination growth, finite element analyses are also performed for the case of a triangular corner delamination (Fig. 7) and for the case of a cusp-shaped corner delamination (Fig. 8). Again, in both cases the crack faces are in full contact at -40°C , and consequently, the mode-I stress intensity factor is zero. Distributions of K_{II} and K_{III} along the crack front for the triangular and cusp-shaped corner cracks are shown in Figs. 9 and 10, respectively. It may be seen from Figs. 9 and 10 that, for both triangular and cusp-shaped corner cracks, the magnitude of K_{II} is much higher than that of K_{III} throughout the whole crack front. This is different from the trend observed for the quarter-circular crack.

The higher crack driving force around die edges for all three types of interface corner cracks considered may also be observed from the strain energy release rate distribution, which is shown in Fig. 11. By assuming that the interface toughnesses under shearing and tearing modes are similar, the stronger crack driving force around die edges implies that the corner delamination is likely to grow faster around the edges of the crack front. Comparing to the value of G for cusp-shaped delamination, the values for both quarter-circular and triangular-shaped delaminations are higher around the edges of the crack front. Consequently, under thermomechanical

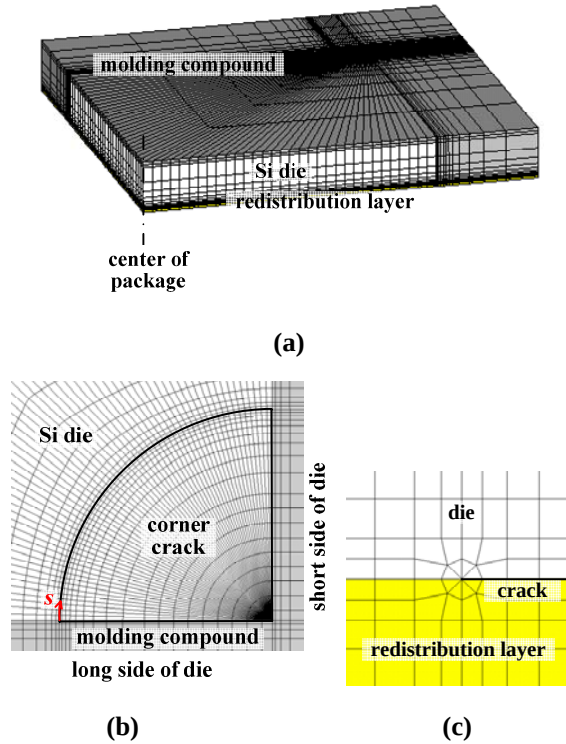


Fig. 3. Finite element model for the package containing an interface corner crack, (a) the quarter model (48988 elements with 210152 nodes), (b) mesh on the crack plane (viewing from the bottom of die), (c) mesh around the crack tip (cross-sectional view).

Table 1. Material properties for the fan-out package.

Material	E (GPa)	ν	CTE (ppm/ $^{\circ}\text{C}$)
Si	150	0.17	2.9
molding compound MC1	23(-60 $^{\circ}\text{C}$) 17(40 $^{\circ}\text{C}$) 12.8(146 $^{\circ}\text{C}$)	0.33	8(-30 $^{\circ}\text{C}$) 11(90 $^{\circ}\text{C}$) 17(135 $^{\circ}\text{C}$)
molding compound MC2	27.4(-50 $^{\circ}\text{C}$) 25.4(10 $^{\circ}\text{C}$) 23.3(120 $^{\circ}\text{C}$) 19.9(150 $^{\circ}\text{C}$)	0.33	5.5(-40 $^{\circ}\text{C}$) 7.2(135 $^{\circ}\text{C}$)
polyimide	3.3	0.3	55

loading both quarter-circular and triangular corner delaminations are likely to evolve into cusp-shaped delamination before it propagates further more. Note that, for all three types of interface corner crack front, the sign of K_{II} is negative. This implies that the

interface crack is likely to propagate either along the silicon die-polyimide interface or kink into the bulk of the silicon die, depending on which has the weaker resistance to fracture. Since at low temperature the adhesion for typical polyimide material to die is much weaker than the toughness of the silicon die, the interface delamination is more likely to stay and propagate along the interface.

Conclusions

In this study the corner delamination on the interface of silicon die and polyimide in a fan-out package under thermomechanical load is analyzed by using numerical finite element analysis. Fracture mechanics parameters, including the strain energy release rate and the stress intensity factors, are obtained along the curvilinear crack front by using the 3-D virtual crack closure technique. Effects of dimension and materials on the trend of fracture reliability are discussed. The fracture mechanics parameters may further be combined with experimental data on the fracture toughness to quantitatively predict delamination reliability for the fan-out package.

Acknowledgments

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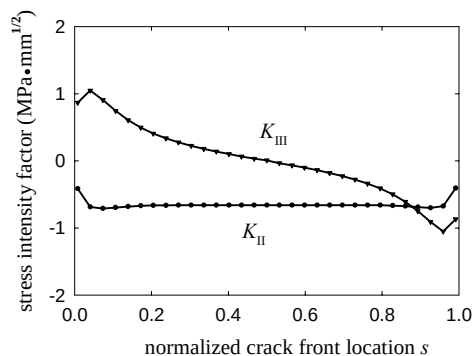


Fig. 4. Stress intensity factors for the quarter-circular interface crack under uniform cooling from 125°C to -40°C, molding compound: MC1, die thickness: 22mil.

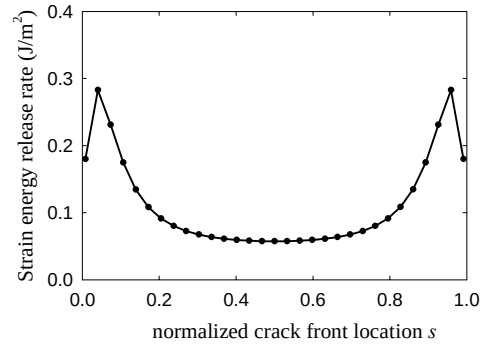


Fig. 5. Strain energy release rate for the quarter-circular interface crack under uniform cooling from 125°C to -40°C, molding compound: MC1, die thickness: 22mil.

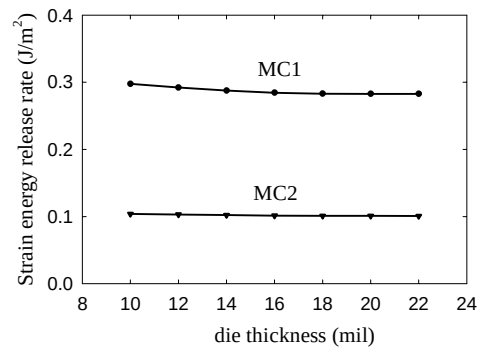


Fig. 6. Effect of molding compound material on the maximum strain energy release rate for the quarter-circular interface crack.

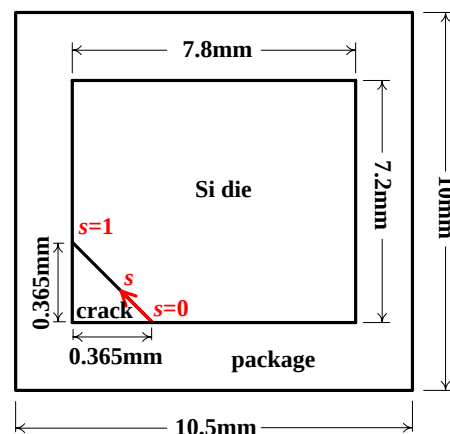


Fig. 7. Schematic of a die-polyimide interface triangular corner crack in a fan-out package.

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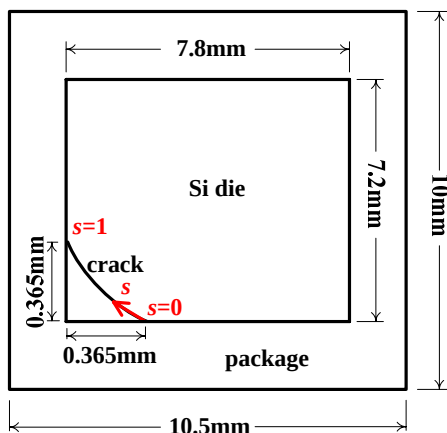


Fig. 8. Schematic of a die-polyimide interface cusp-shaped (with a radius of curvature of 0.65mm) corner crack in a fan-out package.

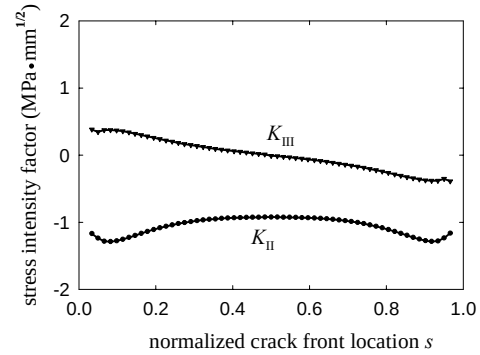


Fig. 9. Stress intensity factors for the triangular interface crack under uniform cooling from 125°C to -40°C.

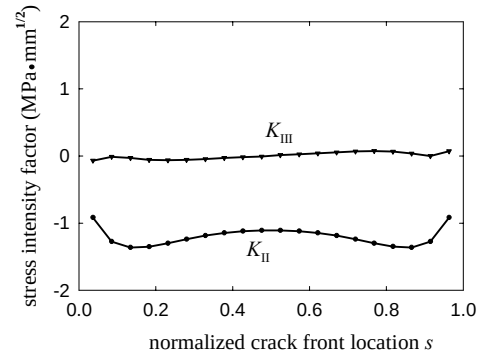


Fig. 10. Stress intensity factors for the cusp-shaped interface crack under uniform cooling from 125°C to -40°C.

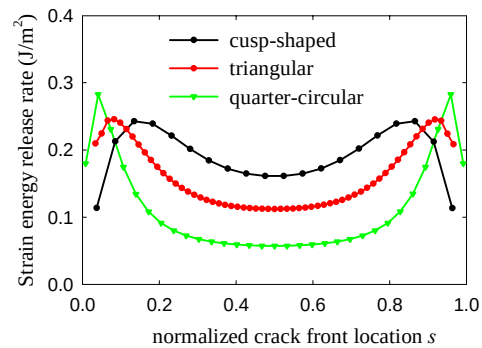


Fig. 11. Strain energy release rate for the interface crack under uniform cooling from 125°C to -40°C.