

Investigation of Fracture Toughness and Displacement Fields of Copper/Polymer Interface Using Image Correlation Technique

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Abstract

Delamination between the copper leadframe and the epoxy molding compound of microelectronic devices is a common failure concern. Interfacial adhesion characterizes the resistance of an interface to initiation and growth of interfacial delamination. In general, interface strength is an important factor for the successful fulfillment of package requirements such as structural integrity in micro- and nanoelectronic applications.

In conventional delamination testing methods, the critical force which leads to crack initiation or propagation together with the actual crack length are needed. Displacement fields can be used for the exact measurement of crack tip at the moment of crack onset or as it advances. A testing method which has been set up for a high resolution analysis of delamination process is further developed to investigate the displacement fields at the crack tip of polymer/metal interface. Bilayer metal/polymer specimens were employed to measure the adhesion strength in terms of interfacial fracture toughness using Four-Point Bending (4PB) and End Notched Flexure (ENF) delamination tests. During the bending tests, high resolution images of the crack tip area were taken at different loading stages. These images were analyzed later using the microDAC technique (*i.e.*, micro deformation analysis by image correlation). The microDAC approach is based on the application of digital cross correlation on grey scale submatrices of the analyzed images. The result is a full-field displacement description of the analyzed surface. This allows for the in-situ measurement of the crack length during the delamination test. In addition, the effects of mode angle and elevated temperatures on the interfacial fracture toughness were investigated in this work.

Key words

Fracture toughness, interface, delamination, image correlation.

1. Introduction

Bimaterial interfaces are encountered in many engineering applications, such as fiber-reinforced composites, thermal barrier coatings and microelectronics devices. The latter is a multilayered structure which typically undergoes complex failure modes, in particular interfacial delamination. Plastic Encapsulated Microcircuits (PEMs) use organic packaging material such as Epoxy Molding Compounds (EMCs) for environmental protection. PEMs are prone to failure mechanisms caused by moisture contamination and corrosion occurring during long-term storage and high temperature cycles. These failure problems are worsened even more by fractures caused by steep temperature gradients during solder reflow process for the assembly of these devices on the printed circuit board. The situation

becomes even more problematic when environmental considerations force the use of higher temperature lead free solders. To characterize the onset and growth of the interface delamination, the use of fracture mechanics has become common over the past years [1-3]. In a brittle, homogeneous, isotropic material, the crack propagates along the mode I path, that is, $K_{II} = 0$ at the tip of the crack as the crack advances. Contrary to homogenous isotropic materials, the so-called mode mixity is a critical parameter for interfacial fractures. The mode mixity is given by the relative proportions of tractions ahead of the crack tip in mode II and mode I fracture. A crack at an interface is subjected to mixed mode conditions and propagates in mixed mode while the preferred fracture path is in the

interface. Typically, the total fracture toughness depends on the mode mixity and it increases as the contribution of the mode II fracture increases. Failure is expected when, for a given mode mixity, the calculated strain energy release rate, G , exceeds the (critical) interlaminar fracture toughness G_C .

In this study, we will first review the theory of interfacial fracture mechanics. Then experimental results regarding the fracture toughness measurements will be presented. Digital image correlation is used for calculation of the in-situ crack length. Finally, the influence of mode angle and test temperature on fracture toughness will also be investigated.

2. Theory of Interface Fracture

The governing analytical solution for a plane interface crack between two elastic isotropic materials was obtained by Williams [4] who performed an asymptotic analysis of the elastic field at the tip of an open crack and found that the stress field possesses an oscillatory character of the type $r^{-1/2+i\varepsilon}$, where r is the radial distance from the crack tip, $i = \sqrt{-1}$ and ε is the bimaterial constant defined as

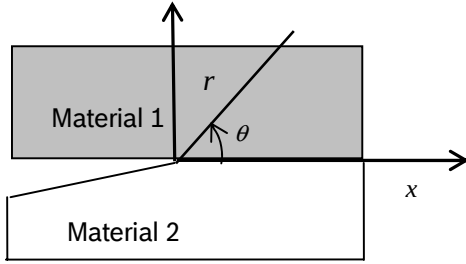


Fig. 1 Bi-material interface.

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

where

$$\alpha = \left[\frac{\bar{E}_1 - \bar{E}_2}{\bar{E}_1 + \bar{E}_2} \right] \text{ and } \beta = \frac{\mu_1(\nu_2 - 1) - \mu_2(\nu_1 - 1)}{\mu_1(\nu_2 + 1) + \mu_2(\nu_1 + 1)}.$$

α and β are the so-called Dundurs parameters [5] and $j=1,2$ represents material 1 and 2, respectively (Fig. 1). Furthermore, $\nu_j = (3-4\nu_j)$ and $\bar{E}_j = E_j/(1-\nu_j^2)$ for plane strain, and $\nu_j = (3-\nu_j)/(1+\nu_j)$ and $\bar{E}_j = E_j$ for plane stress where E_j is the elastic modulus, ν_j is Poisson's ratio, and $\mu_j = E_j/2(1+\nu_j)$ is the shear modulus for material j .

Using the convention for an interface crack defined in Fig. 1, the complex stress intensity factor, K , is given by [6],

$$K = K_I + iK_{II} = |K| e^{i\Psi^*}, \quad (2)$$

where K is the complex stress intensity factor, which has the unit of $\text{Nm}^{-2}\sqrt{\text{mm}}^{-i\varepsilon}$ and Ψ^* is the mode mixity (phase angle). Just ahead of the crack tip ($\theta = 0^\circ$) the

stresses are dominated by a singular stress field of the form [7]:

$$\sigma_{yy} + i\sigma_{xy} = \frac{1}{\sqrt{2\pi}} K r^{i\varepsilon-1/2}, \quad (3)$$

where σ_{yy} is the tensile and σ_{xy} is the shear stress components. The oscillatory solution implies a coupled fracture mode which results in that K_I and K_{II} cannot be interpreted as mode I and mode II stress intensity factors. By using the concept of a reference length, an alternative definition of Stress Intensity Factors (SIFs) was suggested [7, 8]

$$\sigma_{yy} + i\sigma_{xy} = \frac{K_I + iK_{II}}{\sqrt{2\pi l}} \left(\frac{r}{l} \right)^{i\varepsilon}, \quad (4)$$

where K_I and K_{II} are complex SIFs of classical type based on a reference length l , where l is an arbitrary distance ahead of the crack tip, where the stresses are measured. The mode mixity then for an interface crack is expressed as:

$$\psi = \tan^{-1} \left(\frac{\sigma_{xy}}{\sigma_{yy}} \right)_{r=l}. \quad (5)$$

The mode mixity defined above is a local mode mixity and the stresses and SIFs are local quantities evaluated at a point defined by reference length ahead of the crack tip. The total strain energy release rate for an interface crack G is not oscillatory and can be expressed as [9]:

$$G = \frac{1-\beta^2}{E^*} |K|^2, \quad (6)$$

where $|K|^2 = (K_I^2 + K_{II}^2) = (K_I^2 + K_{II}^2)$ and $\frac{1}{E^*} = \frac{1}{2} \left(\frac{1}{E_1} + \frac{1}{E_2} \right)$

3. Delamination Experiments

3.1 Sample Preparation

Copper substrates were machined into $50 \times 10 \times 0.4 \text{ mm}^3$ strips. After cleaning with acetone, the substrates were placed in the cavity of a molding machine. Pellets of a commercial EMC were introduced into the cavity of a pre-heated mold at about 175°C and kept under a pressure of 60 MPa for 120 seconds; the molding compound was dispensed automatically on the copper surface at 175°C . After molding, the samples were placed in an environmental chamber for post-mold curing at 175°C for six hours to complete the polymerization process of the epoxy molding compound. Fig. 2 shows the dimensions of the bimaterial beam.

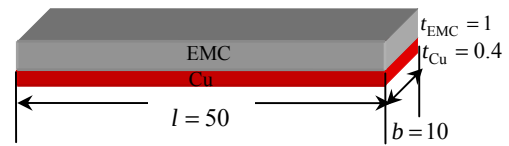


Fig. 2 Bimaterial beam sample (all dimensions in mm).

t_{EMC} and t_{Cu} are the thicknesses of EMC and Cu, respectively.

3.2 Four-Point Bending Tests

The Four-Point Bending (4PB) delamination test was initially proposed by Charalambides *et al.* [10] for the determination of the fracture resistance of bimaterial interfaces and is now a commonly used method to measure interfacial adhesion of thin film structures such as semiconductor devices [11-14].

Fig. 3 shows a schematic picture of a four-point bending setup. The top layer of the EMC was carefully notched vertically with a diamond wafering blade. The notch depth was approximately 80% of the whole thickness of the EMC. The beams were placed in 4PB fixtures with adjustable inner and outer symmetrical loading pin positions. The initiation and propagation of cracks were observed by a high resolution camera which records up to 60 pictures per second.

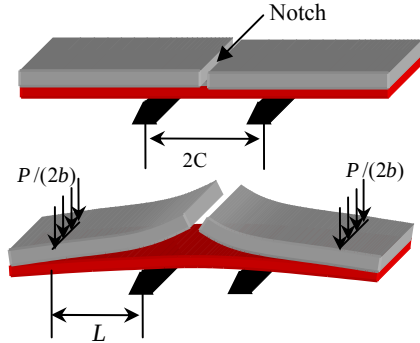


Fig. 3 Four-Point Bending (4PB) delamination test.

The strain energy release rate of 4PB delamination tests exhibits steady-state characteristics when the interfacial crack reaches a minimum length and does not exceed the distance between the inner supports (2C). The steady state value G , is the difference in the strain energy in the uncracked and cracked beam. Applying the beam theory and assuming linear elastic fracture mechanics, G can be calculated as [10]:

$$G = \frac{M^2(1-\nu_{\text{Cu}}^2)}{2E_{\text{Cu}}} \left(\frac{1}{I_{\text{Cu}}} - \frac{\lambda}{I_c} \right), \quad (7)$$

where $\lambda = \frac{E_{\text{Cu}}(1-\nu_{\text{EMC}}^2)}{E_{\text{EMC}}(1-\nu_{\text{Cu}}^2)}$ and $M = PL/2b$.

I_c and I_{Cu} denote quantities which are proportional to the moments of inertia of the composite beam and of the Cu, respectively, and they can be calculated from

$$I_c = \frac{t_{\text{EMC}}^3}{12} + \frac{\lambda t_{\text{Cu}}^3}{12} + \frac{\lambda t_{\text{EMC}} t_{\text{Cu}} (t_{\text{EMC}} + t_{\text{Cu}})^2}{4(t_{\text{EMC}} + \lambda t_{\text{Cu}})}, \quad (8)$$

$$I_{\text{Cu}} = \frac{t_{\text{Cu}}^3}{12}.$$

In the above equations, it is assumed that the initial cracks are symmetrical and both cracks propagate simultaneously at the same load. For the case of non-symmetrical crack propagation ref. [11] provided an alternative formula for the calculation of the energy release rate.

Eq. 7 provides the fracture toughness, provided that the load P is substituted by the critical load P_c . There are principally two methods for measuring the critical force using the 4PB setup. The 4PB delamination test can be applied in a single-step or a two-steps way. In the first method, the whole fracture test can be performed in one step without any previous precracking requirement. Fig. 4 depicts the force-displacement curve of such a test. The distance between lower and upper supports was fixed at 20 and 40 mm, respectively. Samples were loaded monotonically under displacement-controlled rate of 0.1 mm/min.

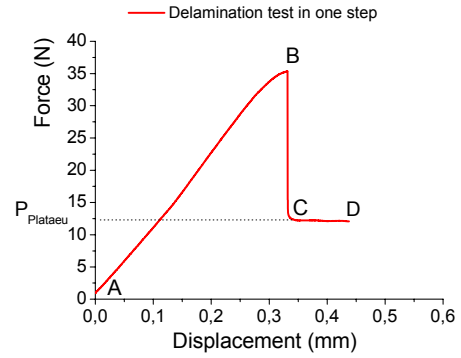


Fig. 4 Force-displacement curve of the 4PB test.

The slope of the linear part of the curve shown in Fig. 4 (point A to B) corresponds to the stiffness of the whole beam. The force at point B represents the required force for fracture in the upper bulk EMC through the notch. This force is primarily a function of the shape and length of the notch and does not provide any information about the interface. When a vertical crack originating from the end of the notch formed, it moved very fast, reached the interface, and kinked into it (point C). Afterwards, the crack advanced along the interface (Point C to D). The constant force during crack propagation (P_{plateau}) represents the critical force required to propagate the crack. Its constant value suggests that the critical energy release rate does not depend on the crack length, when a 4PB delamination test is used. This is furthermore supported by applying the two-step delamination test. In this method, the precracking and the delamination tests were performed separately. First a symmetric precrack was forced to propagate from the notch along interface by means of a 4PB with the minimal inner span size of 10 mm. The sample was then loaded, and

during the loading, the force-displacement curve was monitored. As soon as a decrease in the stiffness was observed, the machine was stopped. The vertical crack kinked into the interface and formed a sharp precrack at interface. After initiation of the interfacial crack, it arrested after arriving at the inner load pins. Consequently for all samples a precrack length of about 10 mm was obtained. After precracking, the distance between the lower supports was increased to 20 mm and the specimens were placed into a 4PB delamination fixture again to conduct the fracture toughness measurements. Fig.5 illustrates a typical curve of the 4PB delamination tests for a sample with an initial symmetric precrack. The single-step delamination test of the same sample (dotted curve) is also depicted for comparison. The slope of the linear part of the curve represents the stiffness of the whole beam, which was lower for the sample with the pre-crack inside. When the sample with the precrack was loaded, the crack remained stationary up to a certain load. However, when the force reached a critical value, the crack started to advance and the reaction force reached a plateau which represented the critical force. This force was the driving force of a stationary crack to move. It was found, that the critical force found from the two-steps delamination test had the same magnitude as the critical force found from the single-step method. For some samples, there was a slight difference between these two values, which was within the scatter of data. From the results it can be postulated, that the interfacial fracture toughness found by 4PB delamination test is independent of crack length as reported *e.g.* in [11-14]. In addition, the driving force for propagating a stationary crack seems to have almost the same magnitude as the driving force for propagation a moving crack.

For the characterization of interfacial fracture toughness an Instron Microtester testing equipment was used. During all tests, delamination growth was observed using a high speed camera. The images were synchronized to load and displacement data after test. The images of a few tests were later correlated using the MicroDAC software [15, 16] in order to find the actual crack tip position [1].

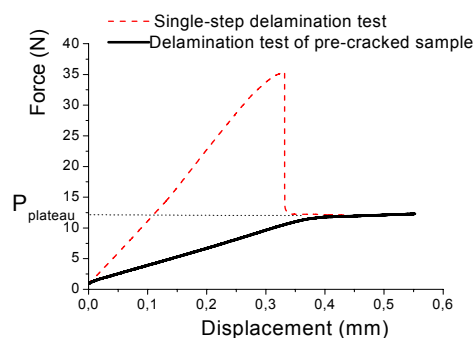


Fig.5 Comparison of the force-displacement curve of a uncracked with a pre-cracked sample.

In addition, some delamination tests were performed in the micro bending stage shown in Fig. 6a. This equipment fits into an SEM chamber for in-situ delamination testing under optical microscopes. Fig. 6b shows a bimaterial sample under 4PB delamination.

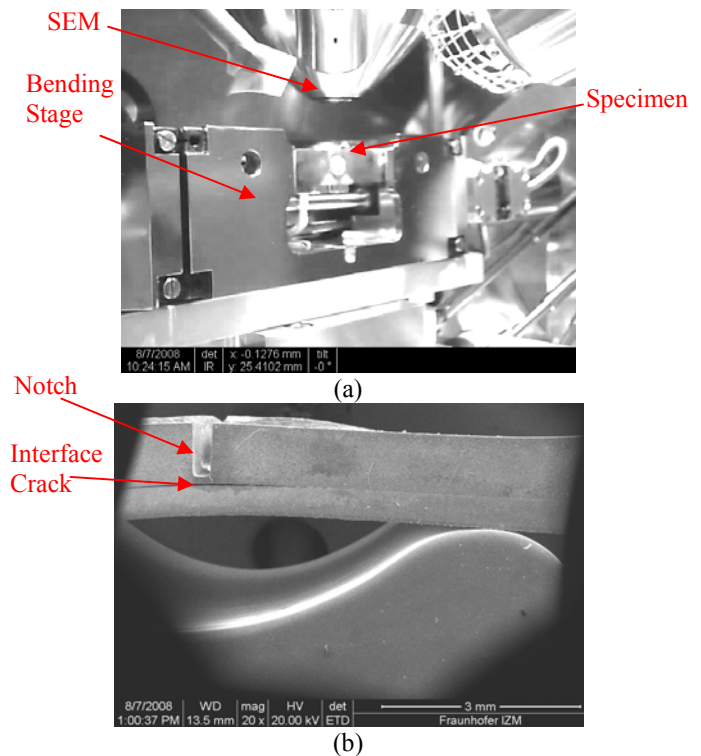
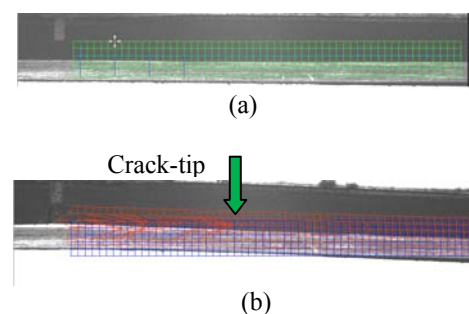


Fig.6. (a): A micro bending stage in a chamber of scanning electron microscopy (SEM), (b): SEM image of the delamination of a bi-material beam by 4PB test.

Fig. 7 illustrates the use of the grey scale correlation method which was applied for all time steps. In this technique the displacement of material portions underneath and above the material interface was measured [1]. The first picture was the reference image before applying the load. The second image was taken at a time when the crack advanced. The crack tip was a position where the vertical displacements of the points above and beneath the interface started to have different directions. The kink in Fig. 6b represents the crack tip.



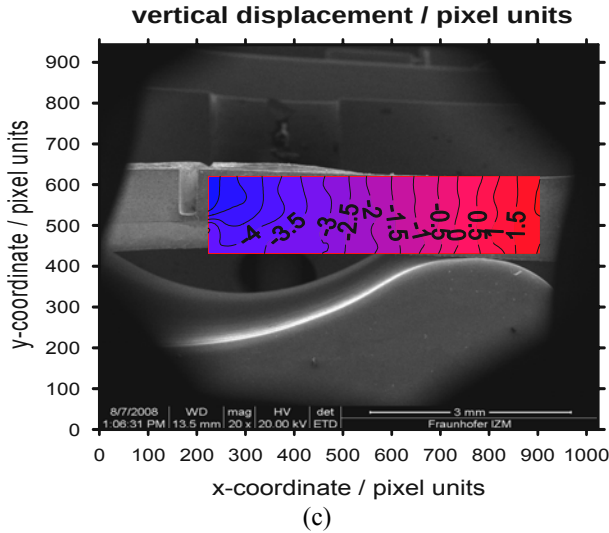


Fig. 7 In-situ measurement of the crack size using image correlation technique by comparing the displacement fields above and below the interface for the initial (Fig. 7a) and the current states (Fig. 7b) and mapping the displacement field on the whole sample (Fig. 7c).

3.3 ENF Tests

The End-Notched Flexure (ENF) test [17] has widely been used to characterize the mode II fracture toughness. However, due to mismatch between the mechanical properties of substrate and adhesive a pure mode II can not result when interface fracture is considered. A typical ENF testing setup for the bimaterial interface is essentially Three-Point Bending (3PB) with an initial crack length of a at one end of the beam as shown in Fig. 8. Since the upper layer undergoes a larger deflection, the sample was positioned with the copper side facing up. At first, a precrack was generated by coating the desired area of the leadframe with a special spray to prevent it from adhering to the EMC during the molding process. Later a razor blade was introduced at the end of the beam at the interface to facilitate precracking. After the delamination test, there was a visible trace on the region of the EMC which was precracked and the precrack length was measured by using a ruler. Furthermore, the precrack length was verified for a few samples by C-mode scanning acoustic microscopy.

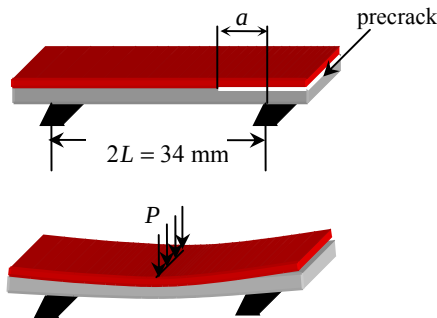


Fig. 8 ENF fracture setup.

According to beam theory, the energy release rate can be found by the following formula [17]:

$$G = \frac{3}{2} \frac{P^2 a^2}{b^2} \left[\frac{1}{t_{EMC}^3 E_{EMC} + t_{Cu}^3 E_{Cu}} - \frac{(t_{EMC} E_{EMC} + t_{Cu} E_{Cu})}{k} \right] \quad (9)$$

where,

$$k = 4t_{EMC}t_{Cu}E_{EMC}E_{Cu}(t_{EMC} + t_{Cu})^2 + (t_{EMC}^2 E_{EMC} - t_{Cu}^2 E_{Cu})^2.$$

A typical load-displacement curve of an ENF test is shown in Fig. 9. To perform each test, the specimen was placed on the lower supports; the upper support was moved down manually to reach above the specimen. Then the loading was done and the displacement was read upon reaching a preload of 1 N (Point A in Fig. 9).

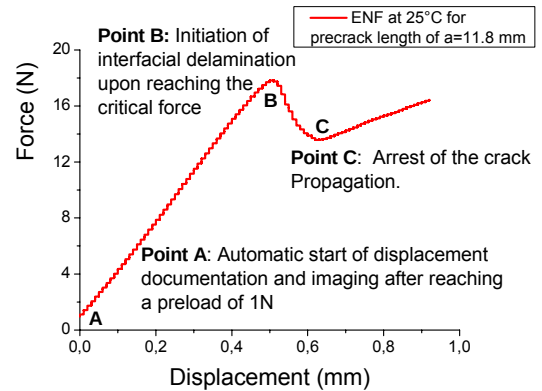


Fig. 9 A typical load-displacement curve of ENF test.

At the early stages of applying load, an initial linear relation between force and displacement can be observed. The slope of the curve at this stage represents the bending stiffness of the composite EMC/Cu structure. The peak of the load profile corresponds to the critical force and the initiation of the interfacial delamination. This force was used later as the critical force in the finite element analysis. After reaching the peak load (Point B in Fig. 9) the delamination propagates until it stops at a point (Point C) which is usually in the middle of the beam. During crack propagation (from Point B to Point C) the compliance of the beam increases, which means that the energy release rate of the 3PB test is dependent on the crack length. After the crack stops at point C, the load increases again linearly. After point C, the slope of the graph represents the stiffness of the EMC only. The fracture load at the onset of crack propagation at which the load suddenly drops (point B) was used for the measurement of the interfacial fracture toughness via finite element analysis. For each test

condition, between four to eight specimens were used, and each peak load with its corresponding precrack length was used for a separate finite element calculation.

In order to prevent large deformations, the span between two lower supports was fixed at 34 mm.

4. Results

Finite Element Analysis (FEA) was performed for each delamination test. Linear elastic fracture mechanics was assumed to hold true, because a linear relation between reaction force and applied displacement up to the delamination was always observed. The required material data was characterized and reported in reference [18]. No plastic deformation was observed in the copper leadframe which undergoes a larger deformation. The crack opening was visible when the 4PB test was applied. However, ENF leads to sliding the cracked surfaces on each other. This was modeled by frictionless contact elements along the delamination path.

The residual stresses during the manufacturing process of the samples were taken into account as follows: First, the chemical cure shrinkage during the molding process was introduced in the FEM model. Then the cooling process from mold temperature (175°C) to room temperature (25°C) was taken into account. Due to the difference in the coefficients of thermal expansion between EMC and Cu, large residual stresses are present at room temperature. The finite element results were later validated by comparing the out-of-plane displacement of the beam with the experimental warpage measurement by Shadow Moiré Interferometry. Finally, introducing a precrack, which leads to some stress relaxations in the sample, was modeled by decoupling the selected nodes at the interface.

For the calculation of the energy release rate G , the Virtual Crack Closure Technique (VCCT) [20] based on the results of the finite element analysis was applied. The method yields the total energy release rate in the direction in which the crack is extended virtually. Equal element sizes were used around the crack-tip and a macro was written for the FEM tool ANSYS, which finds the force at the crack tip as well as the nodal displacements at the crack surface and calculates the mode I (G_I) and mode II (G_{II}) energy release rates. A convergence analysis was performed and an element size of 1 μm was found to be appropriate for the convergence of total energy release rate ($G = G_I + G_{II}$). However, due to the oscillatory nature of the stress and displacement fields, the components of the strain energy release rate for an interface crack are oscillatory. Consequently, G_I and G_{II} become dependent on the assumed crack-extension size. The method proposed in ref. [21] for the mode separation by *normalizing length* equal to the substrate thickness was used.

Fig. 10 shows the interfacial fracture toughness of the EMC/Cu interface vs. two mode angles. From the 4PB

delamination test at room temperature a mean fracture toughness of 16.8 J/m² was gained. The fracture toughness found in the ENF test was higher (39.2 J/m²), because the total fracture toughness depends on the mode mixity and it increases as the contribution of the mode II fracture increases.

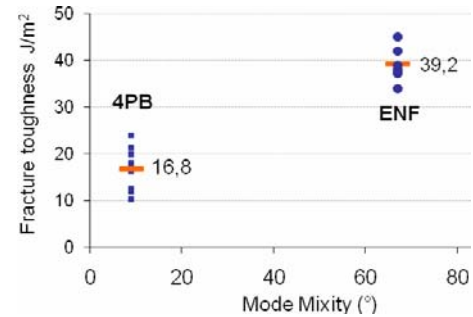


Fig. 10. Fracture toughness as a function of mode mixity.

The influence of temperature on interfacial fracture toughness when considering viscoelasticity was also investigated [18]. Only the ENF test was used. The geometry of the samples was similar to the one depicted in Fig. 2. However, the thickness of EMC (t_{EMC}) was designed to be 0.6 mm in order to investigate the fracture toughness at another mode angle. Fig. 11 shows the influence of temperature on interfacial fracture toughness. The fracture toughness at room temperature was found to be 58.7 J/m². The higher amount of fracture toughness in comparison to the one in Fig. 10 can be attributed to the higher mode angle. In addition, the interfacial fracture toughness decreased significantly, when the temperature was increased above the glass transition temperature, which was measured to be at 120°C. The effect of loading rate was also significant at higher temperatures. The complex response of interface to temperature and rate is due to a combination of three effects, a decrease in modulus, an increase in strain to failure, and a decrease in material strength. Moreover, the effects of load rate and viscoelasticity [18] and moisture [22, 23] on the fracture toughness were studied, which showed significant influence of these parameters on the structural integrity of interfaces.

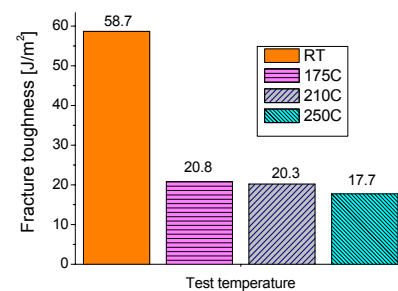


Fig. 11 Effect of temperature on the interfacial fracture toughness of EMC/Cu interface.

5. Conclusion

Adhesion and adhesion degradation in electronic devices are key reliability concerns in semiconductor industry. For the measurement of interfacial fracture toughness, the following important points should be considered:

First, the sample history such as cure shrinkage of polymers during manufacturing, stress relaxation because of viscoelasticity, and swelling/shrinkage during moisture absorption/desorption should be considered for measurement of the intrinsic interfacial fracture toughness. Significant influence of the residual stresses on the measured energy release rate was observed, which suggests that using the analytical solutions for the calculation of energy release rate can cause errors. Compressive stresses in general impede the crack propagation while tensile stresses facilitate it. Residual stresses contribute to the stored energy in the specimen. Therefore, geometric parameters such as adhesive thickness can have direct effect on the outcome of the test, unless the residual stresses are considered in a finite element analysis.

Second, the mode angle plays a significant role in the magnitude of interfacial fracture toughness. In general, the strength of the interface increases when the contribution of mode II fractures increases. The key to successful characterization of interfacial adhesion is the exact measurement of fracture related parameters such as the crack length. Digital image correlation is a helpful tool for obtaining the required information about the interface during the delamination test. For example, an in-situ measurement of crack length becomes possible. Using the optical devices may even be helpful for the direct measurement of Crack Tip Opening Displacement (CTOD), which may have a non-oscillatory nature compared to the stresses at the crack tip.

Finally, the simulation tools should be applied in order to gain the intrinsic fracture toughness at interface. For the joints of polymer/metal interface, linear elastic fracture mechanics may be still acceptable, if the load-displacement curve of the delamination test up to delamination is linear and the delamination tests are conducted within time periods that are short when compared to the time needed for stress relaxation of the polymer.

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