DETERMINATION DE LA COURBE DE RESISTANCE INTERFACIALE PAR CORRELATION EXPERIMENTALE/NUMERIQUE

DETERMINATION OF INTERFACIAL TOUGHNESS CURVES USING EXPERIMENTS AND SIMULATIONS

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RESUME

Dans le cadre de la mécanique de la rupture, l'adhésion peut être considérée en terme d'une résistance interfaciale. L'énergie de rupture interfaciale dépend de l'angle de mode mixte (Liechti et al, 91), c'est-à-dire la proportion relative entre les forces de traction et de cisaillement à une distance donnée de la pointe de fissure (Shih, 91). Une telle approche a montré qu'elle pouvait efficacement prédire le comportement de structures en matériaux multi-couches ou de composants constitués de différents matériaux et qu'elle fournissait une méthode de simulation utile lors du développement de produits (Harries, 01).

Afin de déterminer la résistance interfaciale, de nombreuses géométries d'éprouvette existent, par exemple Asymmetric Double Cantilever Beam, Single Leg Bending (Sundararaman et al, 99), End Notched Flexure, Symmetric Center Cracked Beam (Charalambides et al, 89), ou Brazil Nut Sandwich (Wang et al, 99). De plus, quelques auteurs ont noté l'influence du traitement des surfaces aussi bien chimique que physique sur le délaminage (Amagai, 00) ou du processus de fabrication (Surcin et al, 03). Il en découle une variation de la résistance interfaciale. Ainsi, la grande palette de tests laisse le choix concernant les conditions de chargement et par là même permet d'obtenir une large gamme d'angle de mode mixte.

Dans cet article, nous présentons une méthode pour déterminer la courbe de résistance interfaciale fondée sur la corrélation entre mesures expérimentales et simulations numériques. Les expériences ont été menées sur des interfaces polymère / polymère similaires à celles rencontrées dans les applications d'enrobage électronique (protection de composants). Un code de calcul commercial a été utilisé en parallèle à un outil de maillage pour calculer l'angle de mode mixte et le taux de restitution d'énergie interfaciale qui lui est lié.

ABSTRACT

Within the fracture mechanics frameworks, adhesion can be considered in terms of an interfacial toughness. The interfacial fracture energy G_c depends on the mixed mode angle (Liechti et al, 91), i.e. the relative proportion of tensile and shear forces at a given distance ahead of the crack tip (Shih, 91). Such an approach has been shown to efficiently predict the behaviour of multi-layered structures or components containing different materials and to provide a usefull simulation technique for the development of industrial products (Harrie et al, 98).

In order to determine the interfacial toughness, lots of sample geometries exist, for example the Asymmetric Double Cantilever Beam, Single Leg Bending (Sundararaman et al, 99), End Notched Flexure, Symmetrical Center Cracked Beam (Charalambides et al, 89), or Brazil Nut Sandwich (Wang et al, 90). Besides, some authors quote the importance of manufacturing processes (Surcin, 03) or surface pre-treatment on the delamination due to chemical as well as physical interactions (Amagai, 00) and underline the influence on the interfacial toughness. The numerous test methods enable the choice of different loading conditions and at the same time allow to reach a wide range of mixed mode angles.

In this paper, we present a method to determine the interfacial toughness curves, based on the correlation between experimental techniques and numerical simulations. Experiments were conducted for typical polymer/polymer interfaces, similar to those encountered in electronic packaging applications, and a commercial finite element code was used in combination with a meshing tool to compute the mixed mode angle and the related energy release rate.

MOTS CLES : Interface, taux de restitution d’énergie, angle de mode mixte, méthode éléments finis

KEYWORDS : interface, energy release rate, mixed mode angle, finite element method

INTRODUCTION

A bimaterial interface joins two dissimilar materials that are typically fused or bonded together. Such interfaces are often sources of severe discontinuities in thermal and mechanical properties. The fracture mechanics has been chosen to study the assessment of multi-layered structures or components containing an assembly of multiple materials. The predominant failure mode in multi-layered structures wherein cracks are constrained to grow along the interfaces is termed “interfacial fracture”.

Accurate delamination predictions can be accomplished if a precise characterisation of resistance to crack growth along the various interfaces of interest is conducted. It is generally accepted (Harries et al, 98) that crack growth at a bimaterial interface occurs when the energy release rate (ERR) calculated at the crack tip is compared and found to exceed a critical ERR for a given mixed mode angle.

Interfacial fracture mechanics is by now well developed and a large number of samples are used in the literature to determine the interfacial fracture toughness. The results are interpreted in the framework of the linear elastic fracture mechanics (LEFM). Analytical Solutions to interfacial cracks can be found in works of Rice and Shih (Rice et al, 91). Closed form analyses were conducted over the range of tests and Williams (Williams, 88) determined analytical solutions for different double cantilever beam configurations. Data reduction methods were employed to determine the critical ERR from experimental results by (Sundararaman et al, 01) and (Auersperg et al,01). Numerical methods are also available and simulations were led to compare results delivered by the different methods. (Xiong et al, 00) calculated the ERR and the mixed mode angle by the Virtual Crack Closure Technic (VCCT) and compared it to the modified J-Integral computed by the Abaqus® Finite Element (FE) program. (Harries et al, 98) compared the forward finite difference method, the VCCT and the J-Integral method in the determination of ERR and mixed mode angle. They concluded that all three methods produce comparable estimates for the ERR.

For this work, a special device is developed in order to experimentally evaluate the interfacial fracture toughness of a polymer/polymer interface and to compare ERR values obtained by numerical and analytical analyses.

INTERFACIAL FRACTURE TOUGHNESS

Generalities.

In the framework of homogeneous materials, the Linear Elastic Fracture Mechanics solutions (LEFM) for the elastic near tip stress state are based on analytical solutions provided by Hutchinson and Rice. Solutions in elasticity for the bimaterial fracture have been adapted and provided by Williams and Erdogan. These solutions are under the form:

$$\sigma_{ij} = \frac{1}{\sqrt{2\pi}}\left(\mathrm{Re}\left(kr^{-\frac{1}{2}+i\varepsilon}\right)f_I(\theta) + \mathrm{Im}\left(kr^{-\frac{1}{2}+i\varepsilon}\right)f_{II}(\theta)\right) \qquad \text{Eq.1}$$

where k denotes the stress amplitude factor, $f_i(\theta)$ are angular functions (Fig. 1) and ε is a constant depending on the elastic properties of both materials.

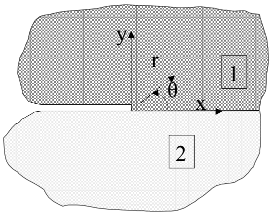

Figure 1 : Domaine en pointe de fissure interfaciale
Interfacial crack tip region

Dundurs (Dundurs, 69).defines ε as:

$$\varepsilon = \frac{1}{2\pi}\ln\left(\left(\frac{\kappa_1}{\mu_1}+\frac{1}{\mu_2}\right)/\left(\frac{\kappa_2}{\mu_2}+\frac{1}{\mu_1}\right)\right) \qquad \text{Eq.2}$$

where ν_i is Poisson's ratio, μ_i is the shear modulus of the material i, $\kappa_i=(3-\nu_i)/(1+\nu_i)$ for plane stress, and $\kappa_i=3-4\nu_i$ for plane strain.

The stress state described in (Eq. 1) is an oscillatory field due to the presence of the constant ε. Since units of k are [stress][length]$^{(1/2-i\varepsilon)}$, it is interesting to note that this k is not the exactly the stress intensity factor defined in the case of a crack in homogeneous materials but still delivers informations about the loads applied around the interfacial crack tip. Finally, the ERR is given by:

$$G = \left(\frac{1}{E_1'}+\frac{1}{E_2'}\right)\frac{1}{\cosh^2(\pi\varepsilon)}\frac{|k|^2}{2} \qquad \text{Eq.3}$$

where E'$_i$ denotes the Young's modulus in plane strain, respectively in plane strain. One may define the mixed mode angle ψ as the angle represented by:

$$\psi = \arctan\left(\frac{\mathrm{Im}(k)}{\mathrm{Re}(k)}\right) \qquad \text{Eq.4}$$

The mixed mode angle ψ is an indicator of the relative proportion of mode I and mode II ahead of the crack tip. In the case of an interfacial crack, the factor k is not well defined as we approach the crack tip (when r tends to zero, the stress field contains an oscillatory part). Besides, one may choose between two different ways to define this mixed mode angle. One definition is based on the ligament stresses (stresses for θ=0) or on the stress intensities. For that (Shih, 91) proposes to fix a distance L_0 ahead of the crack tip where the stresses are taken and to define ψ as a function of the length L_0.

$$\psi_{L_0} = \arctan\frac{\sigma_{xy}(L_0,0)}{\sigma_{yy}(L_0,0)} = \arctan\frac{\mathrm{Re}\left(kL_0^{i\varepsilon}\right)}{\mathrm{Im}\left(kL_0^{i\varepsilon}\right)} \qquad \text{Eq.5}$$

Some authors, i.e. (Hutchinson,90) and (Harries et al, 01), distinguish the real part and the imaginary part of k and consider to simplify them as the two stress intensity factors K_I for mode I and and K_{II} for mode II respectively such that the mixed mode angle is written like for homogeneous materials as:

$$\psi = \arctan\left(K_{II}/K_I\right) \qquad \text{Eq.6}$$

Experimental devices.

Fig. 2 shows the schematic of the specimen employed in this study. It deals with an assembly of two beams. The thickness of the upper beam (thermoplastic) will be held constant and equal to 2mm. The interfacial crack length is denoted *a* and the lower thickness is variable and takes the values 2, 4 and 10mm. As shown in Fig. 3, the total length of the resin (lower beam) is 100mm and the width is 25mm.

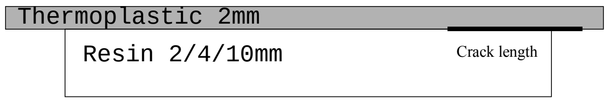

Figure 2 : Eprouvette bimateriaux
Bimaterial specimen

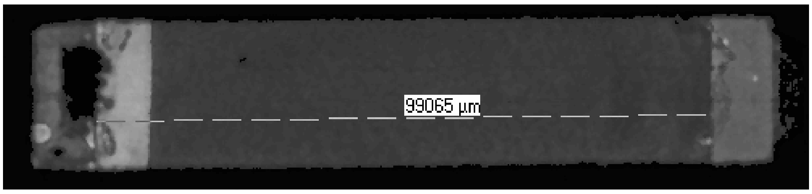

Figure 3 : Vue d'une éprouvette double poutre par microscope à ultrasons
Ultrasonic Microscope view of a Double Cantilever Beam specimen

The reason for the choice of such a specimen is that double cantilever beam-like specimens (DCB) allow a wide variation in loading conditions, realised either by a standard 3 point bending (3PB) device or by a special testing device which was developed in this work (Fig. 4). The particularity of this device is the variability of the physical orientation. It will help us to test the specimens in such different manners that with one type of geometry we can afford to reach a wide range of mixed mode angles and to be able to determine the interfacial toughness curve for a given couple of materials. The specimen is clamped on the pre-cracked side and a block is glued on the top of the specimen which enables the loading of the specimen.

Data processing.

An analytical method to interpret the experimental results comes from the Linear Elastic Fracture Mechanics. It allows to compute the critical energy release rate (ERR) by derivation of the specimen compliance. This may be reached by the classical beam theory (Williams, 88). Using the hypothesis that the global behaviour of the specimen is linear for each fixed crack length a, the ERR for a DCB test can be expressed as

$$G = \frac{P^2}{2B}\frac{dC}{da} \qquad C = \frac{\delta}{P} \qquad \text{Eq.7}$$

where P is the applied loading force, B is the width, a is the crack length and δ is the displacement in the case of the Asymmetric Double Cantilever Beam.

From the load-unload curves for different crack lengths, it is possible to determine the compliance corresponding to each crack length. The compliance $C=\delta/P$ corresponds to the slope of the curve $P=f(\delta)$. Each test is recorded thanks to a digital camera. It allows a post-processing of the images to detect as accurately as possible the crack tip on the sample surface and the length increment as the crack grows. From the measured data for C=f(a), a linear regression allows to estimate an analytical function for C. Kanninen (Kanninen, 73) proposed a 3rd order polynome for C(a). With this function, it becomes easy to derive the compliance and to make use of the Eq. 7. This method is widely used for specimens with a linear response which is the case for most configurations. Besides the Compliance Method, some studies deliver other forms of data processing to achieve the determination of the energy release rate like the Area Method of Data Reduction or developed closed-form analyses adapted to specific tests (Sundararaman et al, 01).

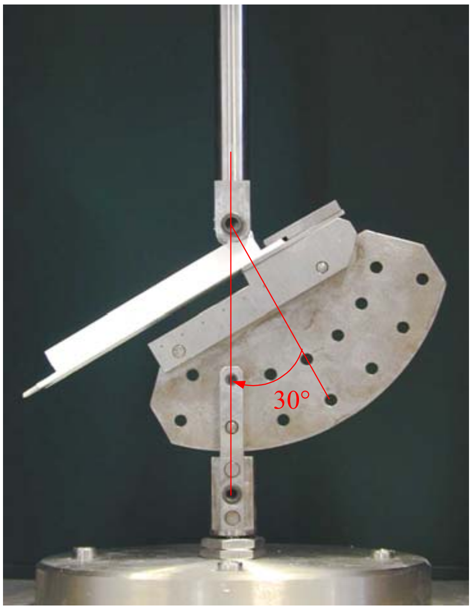

Figure 4 : Dispositif experimental pour les éprouvettes bimateriaux (configuration +30°)

Testing device for bimaterial specimens (configuration +30°)

Numerical solutions.

The uncracked model of the DCB specimen used in this study is parameterised such that resin thicknesses and crack lengths measured during the tests are easily implemented in the numerical analysis (Fig. 5), as well as the associated forces. A meshing tool is employed in parallel with a standard FE code, and the input files are slightly modified to give as an output not only the J integral but also the K-factors corresponding to the case of a crack lying between two different materials.

Results.

Experimental results obtained for different specimens tested with the special device under a configuration of +15° are depicted in Fig. 6. The interpolation fits very well the experimental data and allows us to determine the compliance function. Once the compliance as a function of crack length and the critical load for each crack length are known, it is possible to apply Eq. 8 and to compute the critical ERR for each crack length by means of the compliance method.

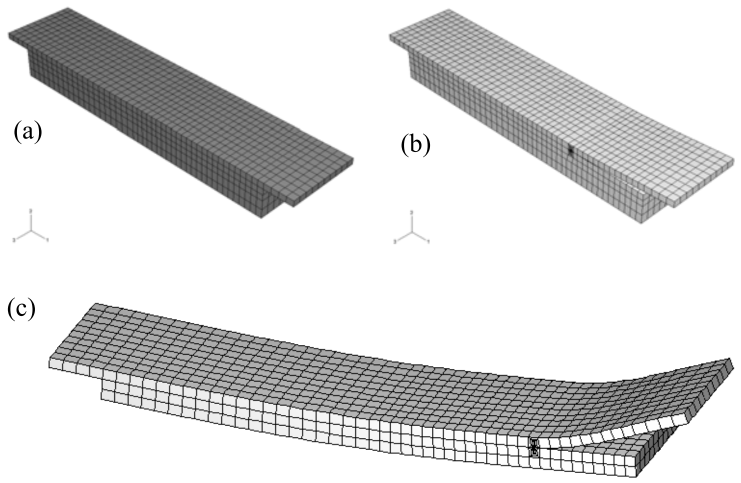

Figure 5 : Modèles numériques d'éprouvettes bimateriaux ; (a) épaisseur de résine de 10mm, non fissurée ; (b) avec une fissure de 31,44mm ; (c) épaisseur de résine de 4mm, fissure de 23,50mm

Numerical models of bimaterial specimems ; (a) resin thickness of 10mm, uncracked ; (b) with a crack of length 31,44mm ; (c) resin thickness of 4mm, crack length of 23,50mm

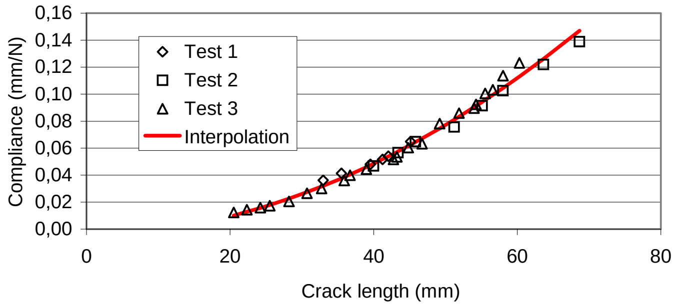

Figure 6 : Courbe de la compliance pour des éprouvettes avec une épaisseur de résine de 10mm sous une configuration de +15°

Compliance curve for a specimen with a resin layer of 10mm under a loading angle of +15°

Then, the specimen thickness, the crack length and the critical force are implemented into the FE model and the numerical J integral is computed (Fig. 7a). The mixed mode angle is extracted from K_1 and K_2, the numerical estimations of the stress intensity factors in the case of an interfacial crack (Fig. 7b).

The diagrams in Fig. 7 show that the experimental and numerical ERR is constant along the range of measured crack lengths, and the corresponding simulations show that the mixed mode angle is constant for the given configuration, namely here a specimen with a resin layer thickness of 10mm tested under a physical angle of +15°. Thanks to this configuration, one is able to say that, for this material combination, in order to let a crack propagate under a stress state corresponding to a mixed mode angle of 15°, the required energy release rate equals 8,3 J/m^2.

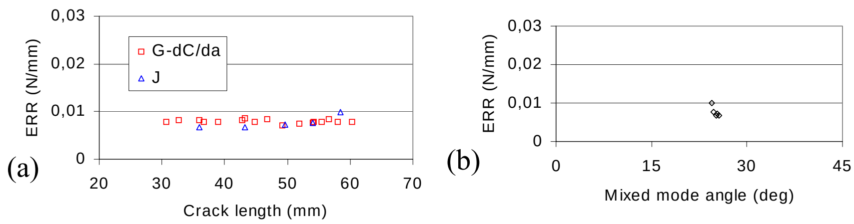

Figure 7 : TRE experimental et numérique en fonction de : (a) la longueur de fissure et (b) de l'angle de mode mixte

Experimental and numerical ERR depending on (a) the crack length and (b) the mixed mode angle

Following this scheme, a sensitivity analysis is led in order to study the influence of different factors on the interfacial frature toughness. Firstly, tests were performed on a three points bending (3PB) device. The thickness of the resin beam has been varied. The resulting mixed mode angles are plotted in Fig. 8. In the case of 3PB, increasing resin thickness leads to diminishing mixed mode angle, i.e. a decreasing contribution of mode II to the crack tip stress state.

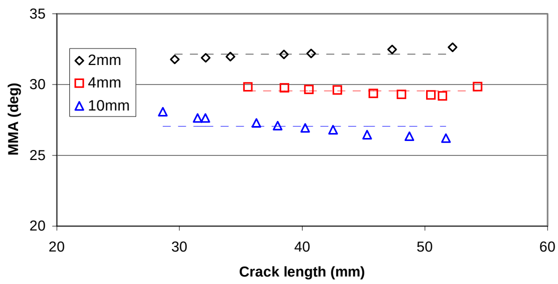

Figure 8 : Variation de l'angle de mode mixte avec l'épaisseur de résine en flexion 3 points

Variation of the mixed mode angle with the resin layer thickness under 3 points bending

Secondly, tests were performed with the device in Fig. 4. While keeping the physical loading angle constant to 0°, one lets the resin layer thickness vary. In this case, the mixed mode angle increases with the resin layer thickness as shown in Fig. 9.

At last, when the resin thickness is held constant and when the physical angle varies, the mixed mode angle depicted in the Fig. 10 tends to decrease while the angle increases.

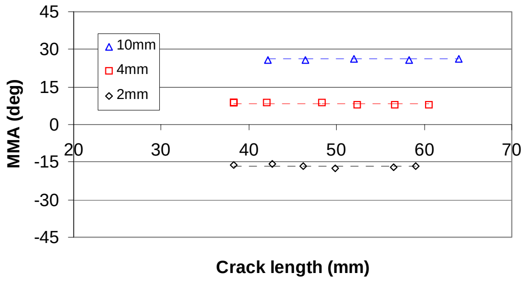

Figure 9 : Variation de l'angle de mode mixte avec l'épaisseur de résine sous un angle physique de 0° (d'après l'appareillage Fig. 4)
Variation of the mixed mode angle with the resin layer thickness under a physical angle of 0° (device according to Fig. 4)

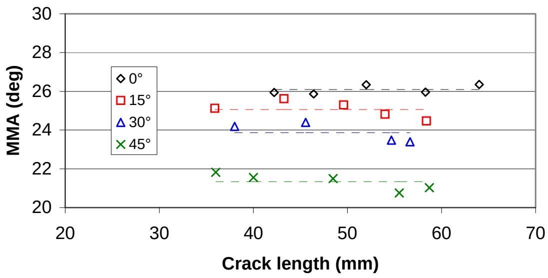

Figure 10 : Variation de l'angle de mode mixte avec l'angle physique de sollicitation, épaisseur de résine constante à 10mm (d'après l'appareillage Fig. 4)
Variation of the mixed mode angle whit the physical angle, the resin thickness being constant and equal to 10mm (device according to Fig. 4)

CONCLUSION

A method has been developed in this work to determine the critical energy release rate of a polymer/polymer interface typically encountered in electronic packaging. For this purpose, an experimental device has been especially developed for this study, and results were compared to numerical simulations. The experimental results gathered with this device fit pretty well the numerical simulations, which validates the developed testing procedure. This method can be applied to the determination of the interfacial toughness curve of material assemblies and integrated in the methods already in use in the development of industrial components.

BIBLIOGRAPHIE

Amagai M., 2000. "The effect of polyimide surface chemistry and morphology on critical stress intensity factor ", *Microelectronics Reliability*, v 40, pp 2077-2086.

Auersperg J., Kieselstein E., Schubert A., Michel B., 2001. "Interfacial fracture toughness tests suited for reliability enhancements of advanced plastic packages", *1st International IEEE Conference on Polymers and Adhesives in Microelectronics and Photonics*, pp 155-159.,

Charalambides P.G., Lund J., Evans A.G., McMeeking R.M., 1989. "A test specimen for determining the fracture resistance of bimaterial interfaces", *Journal of applied mechanics*, v 56, pp 77-82.

Dundurs J., 1969. "Edge-bonded dissimilar orthogonal elastic wedges under normal and shear loading", *Transaction of the ASME*, pp 650-652.

Harries R.J., Sitaraman S.K., 2001. "Numerical modeling of interfacial delamination propagation in a novel peripheral array package", *IEEE Transactions on Components and Packaging Technologies*, v 24, no 2, pp 265-270.

Hutchinson J.W., 1990. "Mixed mode fracture mechanics of interfaces", *Acta Scripta Metallurgica, Proceeding series*, v 4, pp 295-306.

Kanninen M.F., 1973. "An augmented double cantilever beam model for studying crack propagation and arrest", *Int. Journal of Fracture*, v 9, pp 83-92.

Liechti K.L., Chai Y.S., "Biaxial loading experiments for determining interfacial fracture toughness", *Transactions of the ASME*, **58**, 680-687, 1991

Sundararaman V., Sitaraman S.K., 1999. "Determination of fracture toughness for metal/polymer interfaces", *Journal of electronic packaging*, v 121, pp 275-281.

Sundararaman V., Sitaraman S., 2001. "Interfacial fracture toughness for delamination growth prediction in a novel peripheral array package", *IEEE Transactions on Components and Packaging Technologies*, v 24, no2, pp 265-270.

Surcin L., Lachaud F., Piquet R., Nemes O., 2003. "Procédés de mise en oeuvre et délaminage des stratifiés en carbone/époxyde", *Transaction des JNC13*, pp 161-170.

Shih C.F., 1991. "Cracks on bimaterial interfaces: elasticity and plasticity aspects", *Materials Science and Engineering*, v 143, pp 77-90.

Wang J.S., Suo Z.,1990. "Experimental determination of interfacial toughness curves using Brazil-Nut-Sandwiches", *Acta metall. Mater.*, v 38, pp 1279-1290.

Williams J.G., 1988. "On the calculation of energy release rates for cracked laminates", *Int. Journal of Fracture*, v 36, pp 101-119.

Xiong Z., Tay A.A.O., 2000. "Modeling of viscoelastic effects on interfacial delamination in IC packages", *IEEE Electronic Components and Technology Conference*, pp 1326-1331.