Etude expérimentale et numérique du piégeage d'un front de fissure par une interface hétérogène modèle

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Résumé :

Dans cette étude, la propagation d'un front de fissure le long d'une interface texturée a été étudiée expérimentalement et numériquement. Nous avons réalisé des expériences de clivage sur des empilements de couches minces texturé pour plusieurs types de texture. Tous les résultats montrent que notre dispositif expérimental permet d'analyser la modification du front par la structuration dans le cadre de la théorie du piégeage. Par ailleurs, les paysages d'adhésion ressentie par la fissure ont été déterminés par une approche élastique 3D au moyen de calculs par éléments finis. La comparaison entre les résultats des expériences, les valeurs numériques et les prédictions des modèles de ligne montre un accord quantitatif lorsque l'épaisseur des échantillons est prise en compte. Ces accords quantitatifs nous ont motivé à appliquer la même stratégie à des textures de plus en plus complexe.

Mots clefs : Interfacial brittle fracture, Toughening, Crack pinning, Finite element method, Perturbation approach

1 Introduction

Thin film multilayers deposited on glass are widely used for flat optical, photoelectric and electrochromic devices. In many applications, adhesion is a crucial issue. This is the case for instance when mechanical strength is required for further processing or for integration in complex systems. Thus, it becomes of great interest for those applications to increase the adhesion. Many mechanisms of toughening a brittle solid can be found in literature (local transformations, crack bridging, crack trapping, microcracking. . .); but few of them can be applied to thin film layer. One possible way to increase the adhesion of an interface between two brittle solids is to create a composite interface in order to modify the crack front morphology due to pinning on region of higher toughness. By a judicious choice of the heterogeneous interfacial toughness field, it becomes possible to have an adhesion which will be higher than the simple mean value of the local toughness. This toughness modification is the consequence of the existence of a pinning regime which is characterized by a local change of the toughness [1,2]. Crack pinning has been widely theoretically and experimentally [3,4,5] studied since more than two decades, but few, if any, of these experimental studies have been done in the past in a manner which allows evaluating the front morphology modification due to pinning by a single defect.

Here, we report on a study of crack propagation measured along a well-controlled patterned interface in a classical Double Cantilever Beam (DCB) geometry. Our aim here is to assess the use of analytical perturbation theories to model crack propagation in heterogeneous interfaces [1,6]. To evaluate the merits of these models, we need a reference solution which would provide an exact modeling of the data. In the case of the mildly distorted crack fronts proposed here, Finite Element (FE) simulations can be used to determine the local values of the ERR. In addition, with FE simulations, we can accurately take into account the exact geometry of the sample, including the shape of the crack front which is determined experimentally.

2 Experimental set-up

In this experimental study, we investigate the crack front pinning by macroscopic toughness defects. We have performed cleavage tests (see figure 1) on multi-layer coated samples with a heterogeneous field of toughness [4,5,7].

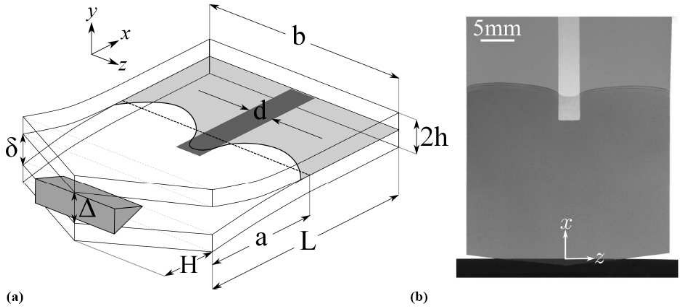

FIG. 1 – (a) Schematic of cleavage test on a double cantilever beam. The opening of the crack is imposed by the wedge in order to control the average length of the crack a. (b) Top view sample photography during the cleavage test. The deformation of the crack comes from the difference of adhesion energies between the silver interface and the defect strip.

The crack propagates at the weakest interface in a stack of thin films deposited on glass, allowing direct visualization of the crack front. This weakest interface is not homogeneous however: a defect strip with a different interfacial toughness lies at the center of the sample. This defect is introduced by using a mask during the magnetron deposition of the stack (see figure 2). Several values of toughness contrast have been investigated (see figure 3) and we have monitored the interaction of the interface crack with these defects. The interface cracks are either trapped or attracted by the defect depending on the sign of the toughness contrast between the defect strip and its homogeneous surrounding medium. This setup has several advantages: 1) the crack is loaded in pure tensile mode (mode I); 2) the crack propagation is purely interfacial (without deflexion out of the plane of the interface); 3) the toughness contrast can be tuned to keep the deformations of the crack front small.

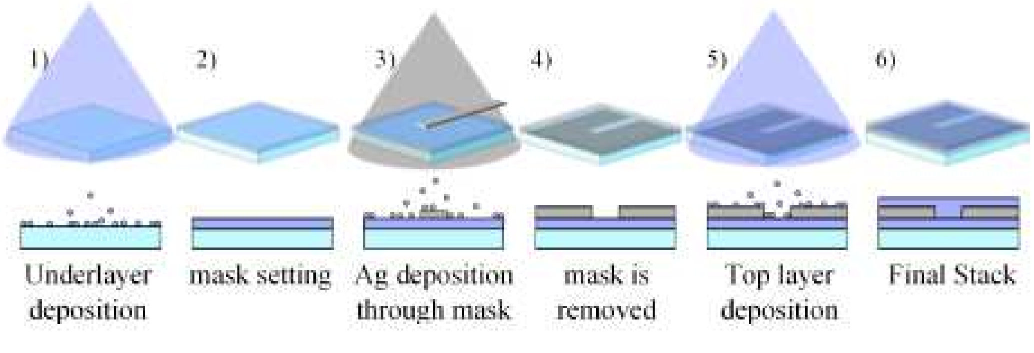

FIG. 2 – Principle of deposition of an heterogeneous thin film stack. The silver layer is deposited trough a mask avoiding it to be deposited at the masked zone.

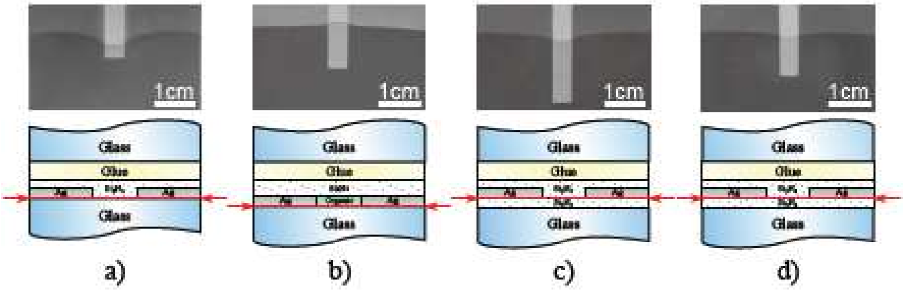

FIG. 3 – Top view of the samples during the cleavages test where the deformed crack front can be observed for the different interfaces and schematic representation of the weakest interface (red arrows).

3 Results and analysis: crack front morphology evolution

Fig. 1 gives the evolution of the crack front morphologies during cleavage tests [4,5]. This evolution can be divided in three successive stages (figure 3) :

– **Stage 1:** Propagation of the front without any modification of the morphology.
– **Stage 2:** Accommodation period. Due to high toughness zone, the front shape is locally modified.
– **Stage 3 :** Weak pinning regime. The front motion is a simple translation with a constant shape.

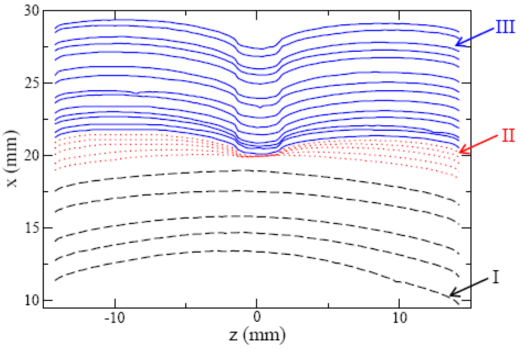

FIG. 3 – Evolution of the equilibrium shape of the measured crack front.

4 Estimation of the energy of adhesion

The energy of adhesion of samples is estimated by two different methods in order to be compared. The first one is a FE method which takes in account the full geometry of the samples, the opening and the shape a(z) of equilibrium cracks. This model provides us the reference results of adhesion. FE calculations are performed with the aim to analyze the validity of the analytical perturbation approaches proposed by Gao et al. [1] for infinite media and its derivation for thin plate proposed by Legrand et al. [6]. To directly model the whole experimental cleavage tests and obtain a reference solution of the global and local ERRs, we needed to take into account the whole geometry of the problem, including specimen geometry and the crack morphology. This is the major part of the present FE calculations.

The evolution of the ERR landscape G(z) when the crack propagates is reported in figure 4. The ERR contrast expected between the defect strip and its surrounding homogeneous medium is well reproduced by the ERR landscape. As reported in figure 3, three successive stages can be associated with this ERR landscape: homogeneous propagation (the front has a curved shape characteristic of finite width effect); interaction between the crack front and the central defect strip (the front is progressively deformed); stationary pinning (the deformation stays invariant in the direction of propagation).

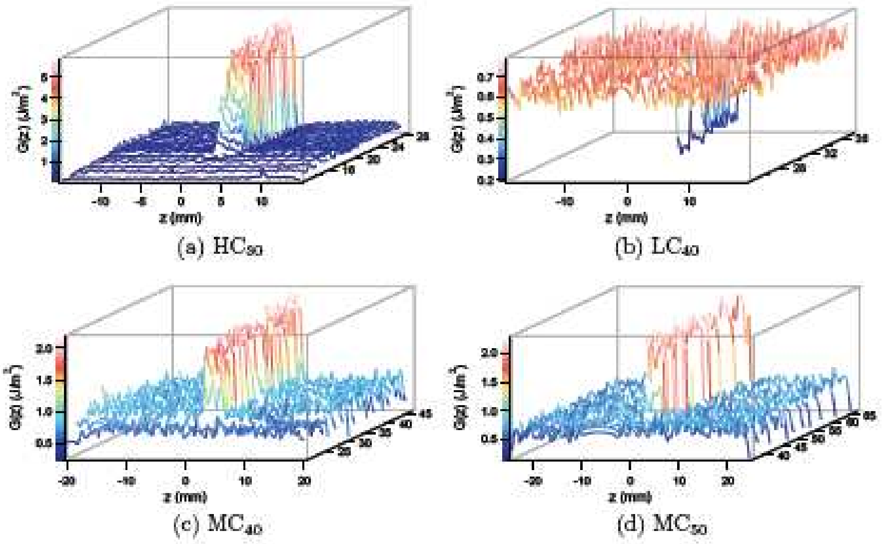

FIG. 4 – Evolution of the energy of adhesion landscape obtained by the finite elements measurement. The highest energy of adhesion of the sample is represented in pink and the lowest energy of adhesion is represented in blue.

The second method consists in the application of perturbative models for the local evaluation of adhesion. These models takes in account only the shape of the crack a(z). We investigate the semi-infinite solution proposed by Gao et al. [1] and its thin plate derivation proposed by Legrand et al. [6]. The morphologies of the fronts obtained by the best fit of the both elastic kernels are shown in the figure 5. Both approaches reproduce properly the crack shape, except at the crack edges due to the free surface condition.

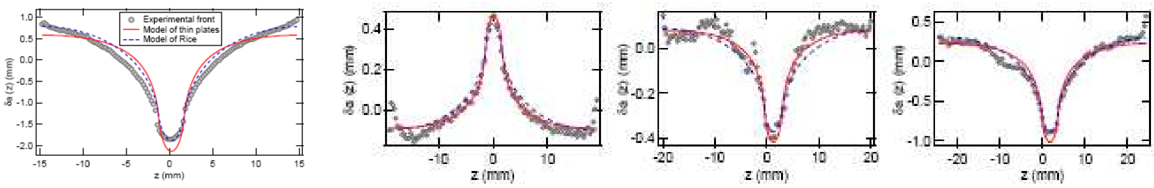

FIG. 5 – The adjusted fronts by the perturbative models are plotted in dashed blue line for the case of Rice model [1] and in red continuous line for the thin plates model [6].

5 Comparison between perturbation methods and FE results

Figure 6 shows a comparison between the normalized contrast of adhesion obtained by the FE method and by the perturbative models for all samples. The black continues lines represent a perfect accordance between the compared models. We can observed that the semi-infinite model underestimate systematically this value. The thin-plates models reproduce in a more accurate way the normalized contrast of adhesion with a relative underestimation of 16% compared with FE results.

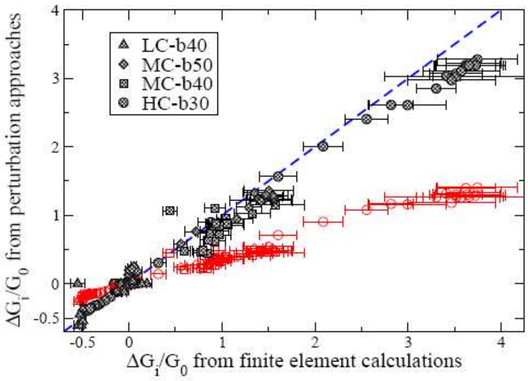

FIG. 6 – Comparison of normalized Energy Release Rate (ERR) contrasts calculated by the finite element method with those obtained from the semi-infinite (red open symbols) and the thin plate (black solid symbols) theoretical approaches.

6 Conclusion

We have shown how the results of cleavage test experiments can be thoroughly analyzed by FEM. The ERR has been computed for all the measured crack fronts and a consistent picture of the crack propagation in an heterogeneous interface has been reconstructed. Due to the increasing curvature of the crack front, the local energy release rate rises until it reaches the toughness of the pinning area which then starts to rupture. This relation between front curvature and local energy release rate is at the core of the perturbation method proposed by Rice. Fitting the front with a perturbation kernel is a much lighter way of analyzing the data. Here we have demonstrated that plate thickness is a first order parameter in modeling crack front morphology by perturbation methods. In our experimental configuration, the semi-infinite kernel [1] gives results which are only qualitatively correct, while the agreement is clearly improved when the finite plate thickness kernel is used [6].

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