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Influence of nonlinearities on the accuracy of the analytical solution for the shaft loaded blister test

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ABSTRACT

Finite element analysis (FEA) is employed to study the effects of nonlinearities on the accuracy of the analytical solution for the shaft loaded blister test. The FEA model was validated using constrained blister test measurements showing a good correlation between the experimental and the FEA data. The analytical solution is then compared with the energy release rate obtained from *J*-integral evaluation in the FEA. For small and large shaft displacements deviations larger than 20% are encountered which is explained with the violation of the membrane limit condition and the onset of plasticity for larger displacements, respectively. Simplifications of the analytical solution are discussed using a random sampling method and it is shown that the thickness ratio between film and substrate can be neglected for thin films on rigid substrates. Further, values for the angular quantity, ω, which is required to calculate the mode mix phase angle are tabulated for the case of thin, elastic films on stiff substrates using a crack surface opening displacement extrapolation method.

1. Introduction

Thin polymer coatings are widely used across many industries to protect underlying substrates from wear and tear. Strong adhesion to the substrate is often one of the main performance criteria and hence quantitative assessment of the interface bond strength is highly desired. A test considered particularly suitable for this task, is the blister test as it allows determination of the energy release rate with a relatively simple experimental setup.

The blister test was initially suggested by Dannenberg (1961) as a method to measure the adhesion of thin films to a rigid substrate. Two different loading configurations have been studied as a means to drive the circular crack along the film/substrate interface. The pressurised blister test makes use of a pressurised fluid to drive the crack, whilst the shaft loaded blister test (SLBT), first reported by Williams (1969), introduces the crack driving force via a central load acting on a spherically capped shaft (Fig. 1). Last-mentioned configuration is of particular interest due to the simpler experimental setup and has received a considerable amount of attention in the last 20 years.

Analytical solutions for the blister test typically consist of two integral parts. One is the description of the mechanical behaviour of the film in respect to its loading condition. The second part is the underlying fracture mechanics model. Despite the equal importance of these two parts most previous work has combined elaborate theory of plates and membranes, e.g. nonlinear Föppl membrane theory, with relatively simple classical fracture mechanics concepts. In these models, based on energy conservation, the energy release rate, G, is expressed as $G = \frac{d}{dA}(U_p - U_e)$, where U_e is the strain energy stored in the elastic medium, U_p is the potential energy and $\frac{d}{dA}$ is the change in area (Malyshev and Salganik, 1965). Examples of contributions using this principle are abundant and include Williams (1969), Bennett et al. (1974), Storåkers and Andersson (1988), most of the contributions from a group around Wan et al. (2002), Wan and Liao (1999), Wan (1999), Wan et al. (2003), Wan and Mai (1995) and more recently Jin and Wang (2008). In Jensen's work (Jensen, 1991) interface fracture mechanic concepts based on the work of Rice (1988), Cao and Evans (1989), Evans and Hutchinson (1989), Suo and Hutchinson (1989) and Jensen (1990) are for the first time applied to the blister test. This approach allows a more detailed investigation of the interface fracture problem by considering both the film layer (Material 1) and the substrate (Material 2), which also allows assertions about the mode mix. An additional advantage of this model is the independence from the theory describing the blister geometry/response, as the coupling of the two models is achieved via the load per unit length, P, and the bending moment per unit length, M (see Fig. 2 for schematic). In consequence, the fracture model can be used for a wide variety of fracture test configurations and not only for the blister test.

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