MECHANICS OF THIN FILM STRUCTURES

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Abstract Cracking of thin films on substrates due to indentation is discussed. Previous results have been reviewed leading to a relationship between crack pattern and material parameters of the film. Interface fracture under steady-state conditions between thin films and substrates at corners is discussed. Crack front shapes are shown and it is shown that this mode of delamination is more critical than the plane strain edge crack. Possible explanations for the so-called telephone cord mode of buckling driven delamination are given.

Keywords: Interface fracture, delamination, thin films, telephone cord delamination

1. Cracking of Films During Indentation

Figure 1 shows crack patterns during indentation of a hard TiAlN coating with a thickness of $2.3\,\mu$m applied to tool steel in order to increase the wear resistance. Radial cracks with certain spacing propagate to a given length. In Jensen [1] an analysis was carried out in order to reveal the information which can be extracted from these experimental observations.

Below the analysis of [1] will briefly be reviewed and especially the steady-state propagation of cracks through the film under homogeneous stress states will be focussed on. The analysis allows for a calculation of the energy release rate along the front which only requires solutions for states far behind the front. Far behind the propagating crack front a one-dimensional analysis is sufficient to characterize the state. The steady state propagation of buckling driven delamination discussed in Section 4 may be analyzed by a similar approach.

The propagation of a system of equally spaced cracks at homogeneous stress states was analyzed in Thouless [2]. The steady-state energy re-

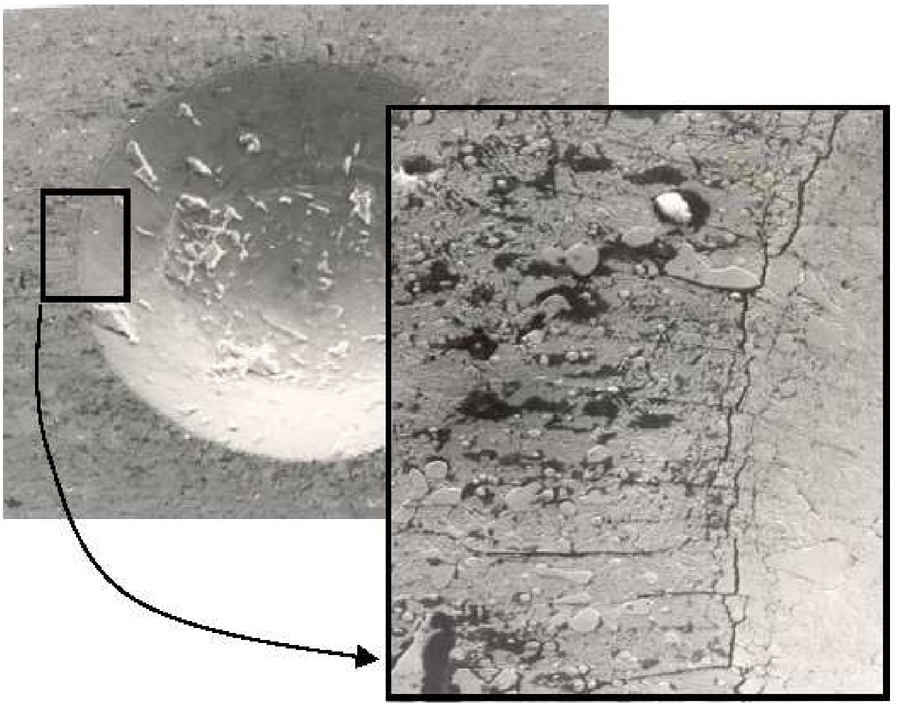

Figure 1. Crack pattern during indentation of TiAlN on steel.

lease rate, G_{ss}, at the fronts are calculated by

$$G_{ss} = \frac{1}{h}\int_0^h G(a)\mathrm{d}a \tag{1}$$

where h is the film thickness and G is the energy release rate for plane strain edge cracks propagating from the surface to the interface. A plot of G_{ss} as a function of the crack spacing is shown in Fig. 2. Next, a cross–plot of stresses in the film obtained in Drory and Hutchinson [3] with the results in Fig. 2 gives a relationship between crack length a, radius of the indent R, the plane strain Young's modulus of the film $\bar{E}$ and the fracture toughness of the film G_c. This relationship is plotted in Fig. 3.

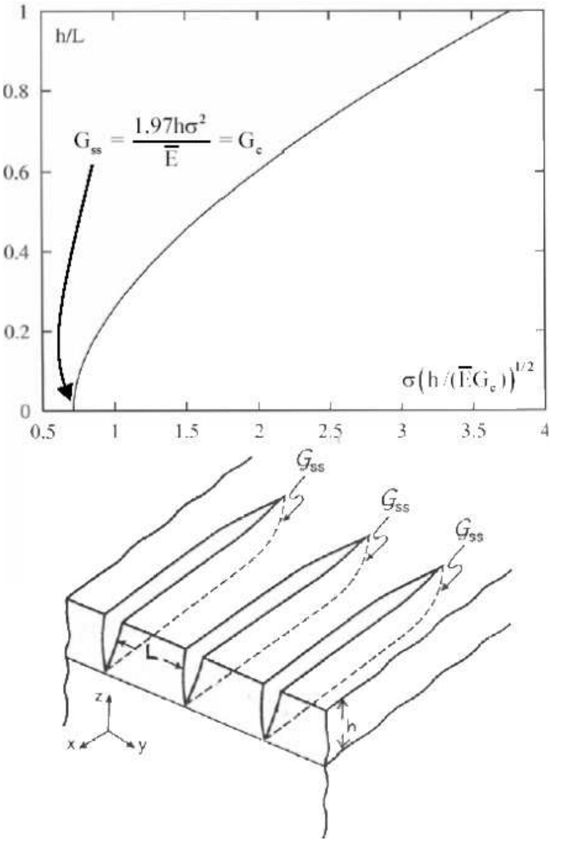

Figure 2. Steady-state energy release rate for a system of equally spaced cracks.

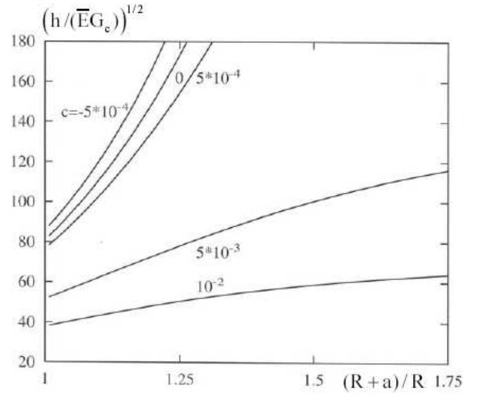

Figure 3. Crack length for a given film thickness h and residual stress σ_0. Here $c = \sigma_0(1 - \nu^2)/E$.

2. Interface Fracture

The relations between the mode I/II and the mode III energy release rates and the normal membrane force, N, the effective moment, M, and shear membrane force, T, in the thin film along the interface crack front are given by (Jensen et al. [4])

$$G = G_{I/II} + G_{III}, \quad G_{I/II} = \frac{1-\nu^2}{2Eh^3}\left(12M^2 + h^2N^2\right), \qquad G_{III} = \frac{1+\nu}{Eh}T^2. \tag{2}$$

The relationship between the energy release rate and the stress intensity factors K_I, K_{II} and K_{III} is given by

$$G = \frac{1}{\cosh^2(\pi\varepsilon)}\frac{1}{2}\left(\frac{1}{\bar{E}} + \frac{1}{\bar{E}_s}\right)\left(K_I^2 + K_{II}^2\right) + \frac{1}{2}\left(\frac{1+\nu}{E} + \frac{1+\nu_s}{E_s}\right)K_{III}^2. \tag{3}$$

An interface fracture criterion formulated in [4] for non-oscillating singular crack tip fields is applied here in the form

$$G_I + \lambda_2 G_{II} + \lambda_3 G_{III} = G_{1c}. \tag{4}$$

where λ_2 and λ_3 are parameters between 0 and 1 adjusting the relative contributions of mode II and III to the fracture criterion, and G_{1c} is the mode I interface fracture toughness.

3. Delamination at Corners

Delamination in thin film systems at corners as sketched in Fig. 4 was analyzed in Jensen [5] and Pane and Jensen [6]. The motivation for the study is observations in e.g. flip-chips subject to thermal cycling where spontaneous delamination usually is initiated at corners. It is for this reason of interest that we study the critical stress required to propagate a crack at a corner compared to the stress required to propagate a plane strain edge crack.

The residual stresses are assumed tensile so that Eq. (4) reduces to

$$\sigma_{nn}^2 + \frac{2\lambda}{1-\nu}\sigma_{nt}^2 = \sigma_c^2 = \frac{2EG_c^*}{(1-\nu^2)h} \tag{5}$$

where σ_{nn} and σ_{nt} is the effective normal and shear stress in the film at the crack front, and where

$$\lambda = \frac{\lambda_3}{1 + (\lambda_2 - 1)\sin^2\psi}, \quad G_c^* = \frac{G_{1c}}{1 + (\lambda_2 - 1)\sin^2\psi}. \tag{6}$$

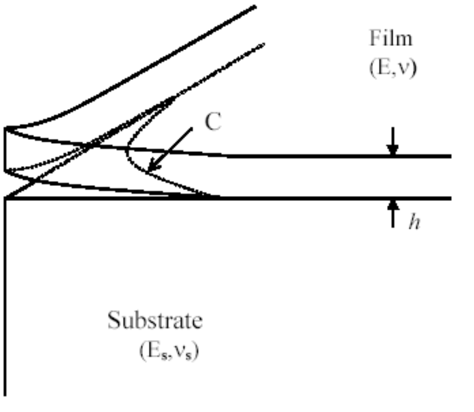

Figure 4. Delamination at a corner.

The properties of the substrate affect the fracture criterion through the phase angle of loading, ψ.

The finite element method is used for calculating σ_{nn} and σ_{nt}. The shape of the crack front is determined by an iterative procedure so that Eq. (5) is satisfied locally along the crack front.

Delamination at corners is possible at lower stress levels than σ_c and examples of delamination shapes are shown in Fig. 5.

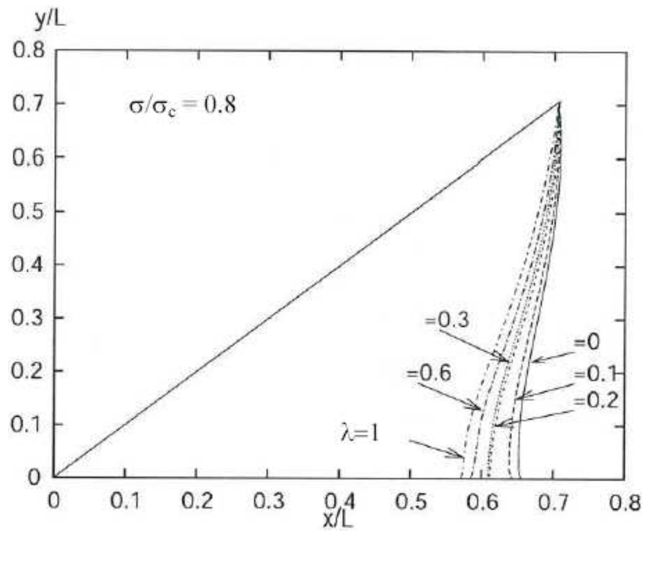

Figure 5. Predicted crack front shapes.

4. Morphology of Buckling Driven Delamination

Examples of buckling driven delaminations are shown in Fig. 6 (taken from Moon et al. [7]). Especially the telephone cord mode of delamination in Fig. 6(c) has received much attention since it is the most commonly observed mode of delamination.

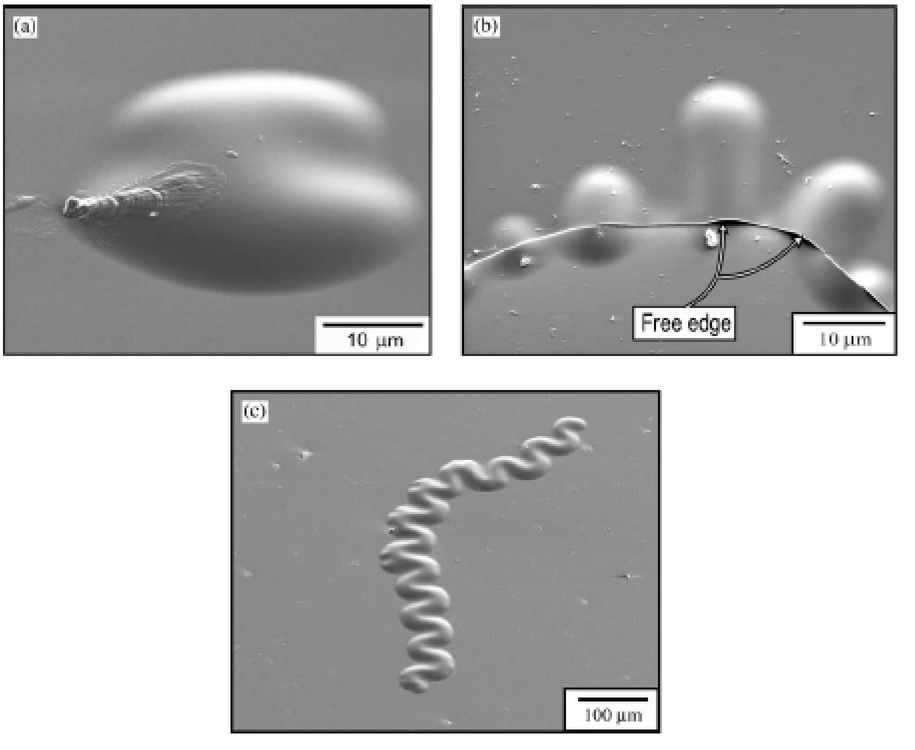

Figure 6. Shapes of bucking driven delamination, (a) circular, (b) straight sided, (c) telephone cord delamination.

The straight-sided mode of buckling driven delamination was analyzed in Hutchinson and Suo [8] along similar lines as the steady-state propagation of film cracks in Section 1. The accuracy of that approach was discussed in Jensen and Sheinman [9].

The mechanism for the telephone cord delamination suggested in Jensen and Sheinman [10] and supported by the experimental results in [7] is that steady state buckling driven delaminations which propagate along a curved path rather than a straight path release most energy at high stress levels. The cross over point for the two mechanisms of delamination growth lies roughly at $\sigma/\sigma_c = 4$. It was also found in [7] that the straight sided and telephone cord delaminations only exist in a narrow range of mechanical parameters for the thin film system, which separates two regions where either no delamination or complete delamination of the film occurs. The two main parameters for determining whether complete or no delamination occurs is the ratio between the mode I and mode II interface fracture toughness and the total energy per unit area in the film normalised by the mode II fracture toughness.

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