THE ELASTO-PLASTIC THIN FILM/SUBSTRATE VIA BUCKLE-DRIVEN DELAMINATION AND CRACK GROWTH

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Summary: Thin films have a wide range of applications in microelectronics and magnetic recording industries where properties are needed to insure performance and reliability. In general, these applications are tied directly to interface structure and composition, i.e. the films must remain adhered to be of use. While many of these tests are semi-quantitatively measurements and are useful for functional or comparative purposes, there are some applicable to be direct quantitative assessment and indentation technique is a representative one of them for its simplicity, reproducibility and the ease of interpretation of the results. It is very interesting for this problem by using a combined approach between the elastic-plastic fracture mechanics and interfacial mechanics of buckling driven delamination. For brittle, weakly bonded films, indentation can be used to delaminate the films from the substrates, thus measuring the thin film interfacial strength. During this process. This indentation technique is mainly based on the pioneer works of Marshall & Evans[1] and Evans & Hutchinson[2] which gave the theoretical analysis for the conical indentation-induced thin film delamination.

Consider an indentation-induced interface crack in a residually stressed film. The film has a thickness t on a semi-infinite substrate, loaded by a hard angular indenter which leaves a permanent impression, and the residual stress is assumed to be σ_R. The strain energy release rate is obtained as follows by considering a few hypothetical operations with a combination of Linear Elastic Fracture Mechanics (LEFM) and simplified post-buckling theory [1,2]

$$G = t(1-\nu)\left\{(1-\alpha)\sigma_R^{\,2} + \sigma_0^{\,2}\left[(1+\nu)/2 - (1-\alpha)(1-\sigma_c/\sigma_0)^2\right]\right\}/E \qquad (1)$$

where $\alpha = 1$ for $\sigma_0 + \sigma_R < \sigma_c$ (no buckling) or $\alpha = \left(1 + 1.207(1+\nu)\right)^{-1}$ for $\sigma_0 + \sigma_R > \sigma_c$ (buckling),.The subscripts o, *R*, c denote characteristic stress, residual stress and critical buckling stress respectively. After measuring the strain energy release rate G or J integral, the interfacial adhesion between the thin film and substrate can be calculated, which needs the knowledge of the fracture of interface and the phase angle to interpret the results correctly. However it must be noted that the applicability of indentation technique to measure thin film adhesion has been limited because several complex fracture processes are involved and the results are not yet well understood, for example the equation (1) is only valid for initial stage of post-buckling, especially for the single buckling case, and Euler plate buckling assumption is taken without considering the plasticity of thin films. Most of the discussion in the references are based on the assumption of elastic deformation. But because of the large deformation during the post-buckling stage, it may be very helpful if we take the plasticity of the film into consideration to investigate its influence, especially for the film with low value of yield stress σ_y. The schematic of the model is similar as [2], but the thin film is modified as an elasto-plastic material which obeys the power hardening law.

In many indentation tests, if the indenter is driven deep enough, so that the crack reaches its critical buckling length, the film often double buckles during indentation with the plastic indentation volume V_0. But as what is mentioned above, the full analysis of double-buckling has not yet been done, which is essential for the indentation technique. Experiment of Kriese et al.[3] found that during indentation the interfacial fracture toughness was reproducibility high for shallow indents, $8-10\ \mathrm{J/m^2}$, but dropped to a fairly steady $0.7-1.2\ \mathrm{J/m^2}$ for deeper indents. It is hard to explain these experimental data via conventional analysis. As we know, the plasticity of materials will greatly affect the buckling process; can it be a reason for this phenomenon?

In this paper, we will also emphasize on some aspects of thin film bucking and their influences to the indentation test. An investigation on the post-buckling of thin film is carried out by FEM calculation. Some of the important factors, which are often omitted before, such as the double-buckling phenomenon and material plasticity, are discussed. The results show that for the case of $\sigma < 3\sigma_c$, the asymptotical solution is satisfactory with a relative error less than 10% for the elastic film/substrate system. For the double-buckling cases, the critical stress and initial slope parameter are obtained, and the comparison of the energy release rate with the single-buckling case shows that the different is obvious and need to be treated properly. Then we calculate the case of $\sigma_y / E = 2\times 10^{-3}$, i.e. $\sigma_c / \sigma_y \approx 1.7$. The post-buckling responses for different values of hardening exponent n are plotted under deformation plasticity. the non-dimensional critical stress decreases significantly when considering the film plasticity. For the perfect plastic case, the J integral or energy release rate decreases to one half of the linear elastic one when $\sigma \approx \sigma_c$, to 20% when $\sigma \approx 2\sigma_c$.

The plasticity has significant influence on the post-buckling responses and should be considered in interpreting the indentation test results. The greater the value of ratio of critical buckling stress to yielding stress σ_c / σ_y, the more contributions of the plasticity. The quantitative influences of plasticity on the energy release rate are shown by figures. the influence of the film plasticity will be a dominant factor for shallow indent, so it must be included to interpreter the results correctly. This might be one of the reasons for the discrepancy between shallow and deeper indent.

The results are shown that the plasticity is a significant factor for those films with low yield stress and must be taken in account in adhesion measurement. The abnormal experimental results of Kriese [3] can be explained by this calculation.

References

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