Interfacial toughness determination using buckle propagation in films with controlled thickness gradients

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EXTENDED ABSTRACT

Thin film/substrate systems are ubiquitous in modern technologies such as microelectronics, protective coatings and functional surfaces [1]. Films elaborated by physical vapor deposition frequently develop high intrinsic compressive stresses, which can lead to interfacial delamination and buckling[2]. While such instabilities are usually detrimental to performance, they can also be exploited as powerful probes of interfacial mechanical properties. In particular, the quantification of interfacial toughness remains a critical issue for assessing the reliability and lifetime of coated systems.

In this work, we propose an original experimental–numerical strategy to quantify the interfacial toughness of thin film/substrate systems by controlling the propagation of straight-sided buckles in a well-defined thickness gradient. Nickel thin films were deposited on compliant polycarbonate substrates with a continuous thickness gradient along one direction. Under uniaxial compression of the substrate, straight-sided buckles nucleate in the thicker region of the film and propagate towards thinner areas, where the available elastic energy progressively decreases. As a result, buckle propagation systematically arrests at a critical local thickness, which can be accurately measured (see Fig. 1).

The experiments reveal that the buckle morphology evolves continuously along the gradient: both the buckle width and maximum deflection decrease as the film thickness is reduced. Increasing the applied compressive stress allows the buckle to propagate further into thinner regions, leading to a smaller critical arrest thickness. These observations provide a direct energetic signature of the competition between the elastic energy release rate and the interfacial fracture toughness, as described in mixed-mode approaches [3].

Finite element simulations were performed using a large-deformation framework combined with a cohesive zone model to describe interfacial fracture. The numerical model explicitly accounts for the thickness gradient and reproduces the experimental loading conditions. Simulations successfully capture buckle initiation, propagation and arrest, as well as the progressive tapering of the buckle near the arrest point. The mode mixity angle along the delamination front was systematically analyzed. The results show that fracture is predominantly mode I at the curved buckle front, while mode II becomes dominant along the straight sides, explaining why propagation mainly occurs at the front, in agreement with [4].

By comparing the experimentally measured critical arrest thicknesses with numerical predictions, the interfacial toughness can be quantitatively identified. This approach allows not only the determination of the mode-I interfacial toughness, but also the identification of the non-dimensional parameter governing the sensitivity of toughness to mode mixity in the Hutchinson–Suo phenomenological law. A unique combination of these parameters is found to consistently reproduce all experimental loading steps.

Overall, the present methodology provides a robust way to quantify interfacial toughness in thin film systems. The use of a controlled thickness gradient transforms buckle arrest into a reliable energetic criterion, opening new perspectives for adhesion measurements in a wide range of film/substrate combinations.

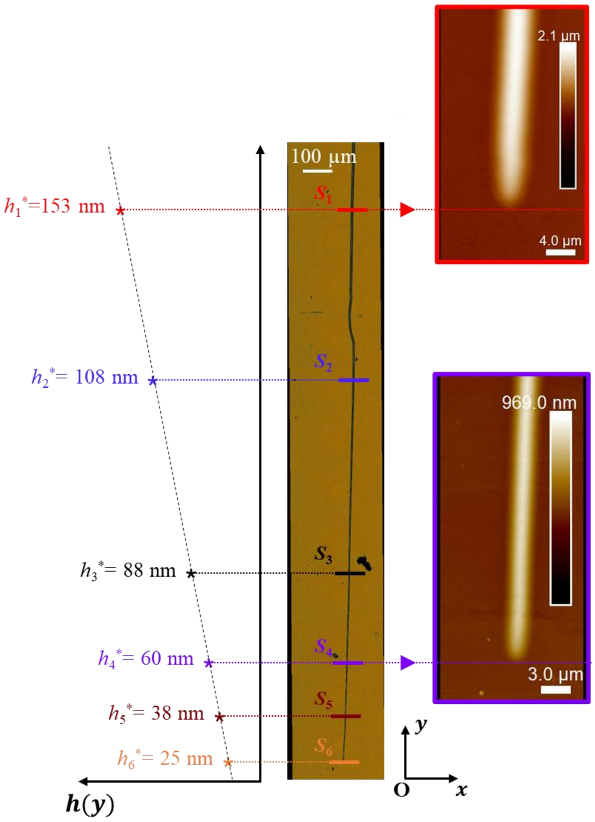

Figure 1*: Straight-sided buckle propagating in a nickel film deposited on a polycarbonate substrate along a controlled thickness gradient. The buckle initiates in the thicker region and progressively propagates towards thinner areas, where it arrests at a critical thickness h* depending on the applied compressive stress.*

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