Strength anisotropy of heterogeneous adhesives: Optimizing the pinning site geometry

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Summary: Recently, it was shown that introducing heterogeneities of interfacial fracture energy on thin film adhesives could result in strength anisotropy. We propose here to design and optimize the geometry of the pinning sites responsible for this effect in order to achieve strong macroscopic effects. The results presented here illustrate how microscale fracture properties of brittle systems can be manipulated and designed in order to achieve new and improved macroscopic failure properties.

Heterogeneities of adhesion energy can produce anisotropy in the effective resistance of brittle solids [1]. As illustrated in Fig. 1 in the context of thin film adhesion, brittle failure results from the propagation of a crack front, the geometry of which is strongly influenced by the local landscape of fracture energy. Since the local driving force for the propagation of this front depends on the front geometry itself, the ability of the front to go through the pinning sites depends on their shape (e.g. a moon-shape in Fig. 1). As so, the effective resistance of the system – the maximum force required to make the front propagate from one side of the system to the other – depends on the direction of propagation if the shape of the pinning site is not symmetrical with respect to the axis parallel to the front.

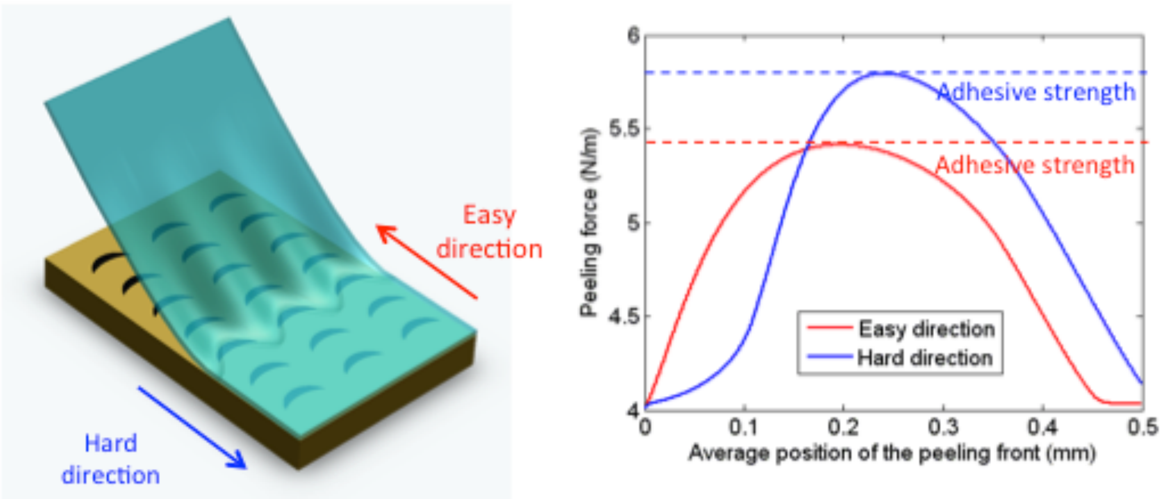

Fig. 1: Basic mechanism producing strength anisotropy: the pinning site geometry and their contrast govern the geometrical perturbations of the front that in turn determine the local driving force for crack propagation. As so, the ability to cross the defects depends on the direction of propagation for asymmetric pinning sites, resulting in an anisotropy of the effective resistance of the heterogeneous system.

However, taking advantage of this effect to design systems with strong anisotropy is not straightforward. On a general manner, geometrical perturbations of the front result into small perturbations of the local driving force with respect to the corresponding driving force for the homogeneous system with straight front. As a result, anisotropy induced by anisotropic pinning site is on a general manner rather small. In this study, we show that this effect can be largely increased and optimized by (i) identifying the quantities that govern the level of strength anisotropy (ii) using an adapted numerical method that allows for the rapid determination of the anisotropy of the system in order to proceed to the optimization of the relevant parameters.

To illustrate our approach, we will limit here to arc patterns, as shown on Fig. 2(a). More general optimization schemes based on a genetic algorithm will be presented during the conference. The optimization parameters for the arc geometry are presented on the figure 2. In the limit of large vertical spacing $L_x \gg \lambda_b$ (λ_b is the bending length of the homogeneous adhesive and depends on its mechanical properties and thickness), one can show that three parameters only are relevant: the width d of the arc, the lateral spacing s between arc and the contrast $C = \frac{G_c^{arc} - G_{c0}}{G_{c0}}$ of fracture energy where G_{c0} is the fracture energy of the substrate and G_c^{arc} is the fracture energy of the pinning pattern. To quantify the anisotropy of a given configuration, we quantify the level of anisotropy using $\frac{F_p^{hard} - F_p^{easy}}{F_p^{hard} + F_p^{easy}}$.

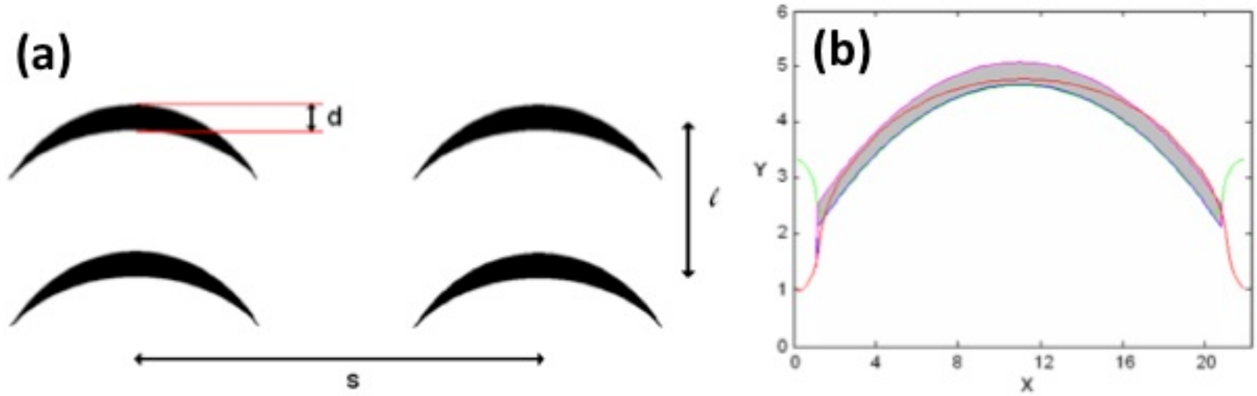

Fig. 2: (a) Geometry of the pattern used to design adhesives with strong directionality. (b) Optimal pattern geometry (d = 2, S = 5) with optimal contrast (C = 5) represented with the deformed front in the easy (green) and hard (red) directions (units are arbitrary).

This quantity is calculated numerically for a given set of parameters using a powerful algorithm developed in the context of elastic manifolds driven in random media [2,3]. In this algorithm, we do not compute the effective dynamics of the crack front as it propagates in the heterogeneous landscape of fracture energy, but instead, we converge directly to the critical configuration of the front corresponding to the maximum of the force using simple rules based on the Middleton's theorem that applies for elastic lines or interfaces propagating in heterogeneous media [4]. This algorithm is described in more details in Ref. [5].

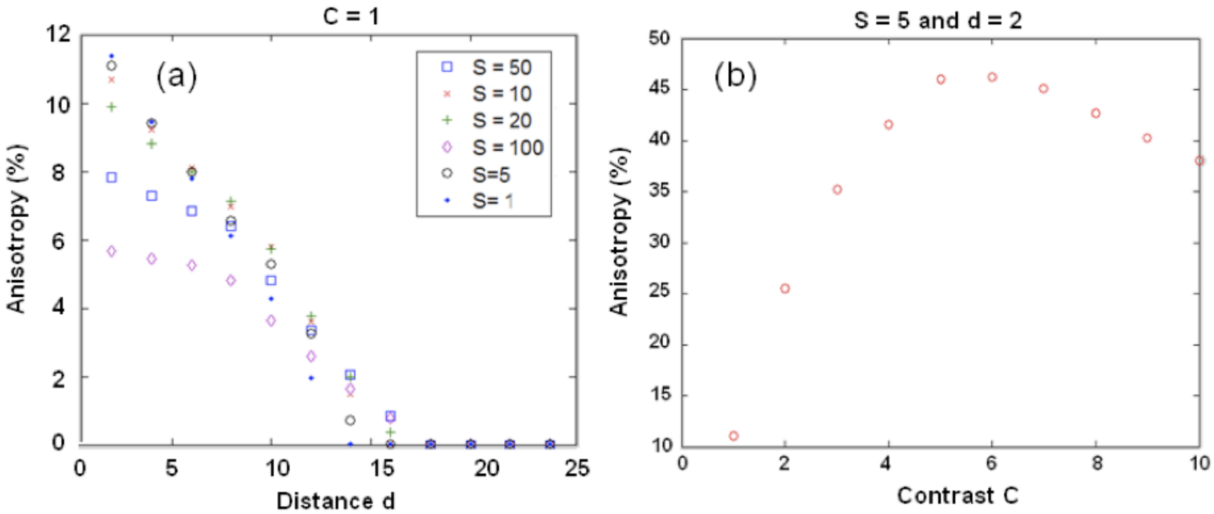

Fig. 3: Optimization of (a) the geometry of the pinning sites and (b) the contrast of local fracture energy in order to achieve strong anisotropy in resistance to peeling.

Figure 3 (a) shows the effect of the geometrical parameters of the pinning site on the strength anisotropy: the smaller the spacing s and the distance d between both arcs, the larger the anisotropy (here, for a contrast of fracture energy equal to unity). The effect of the contrast is studied in Fig. 3 (b), and we see here that strength anisotropy as large as 45% can be achieved by choosing a contrast close to 5. The solution of the optimization is provided on Fig. 2(a). Here, the system is about twice more resistance in one direction than in the opposite one. We will show that this performance can be overcome using optimization scheme based on genetic algorithm, without assuming arc pattern geometry, and will confront our predictions with experimental examples where adhesives can be patterned on a well controlled manner. Our results open the door to the design of new types of brittle composites for which microscale fracture properties are manipulated and designed in order to achieve new and improved macroscopic failure properties.

References

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