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Detachment of an adhered micropillar from a dissimilar substrate

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ABSTRACT

The mechanics of detachment is analysed for 2D flat-bottomed planar pillars and 3D cylindrical pillars from a dissimilar elastic substrate. Application of an axial stress to the free end of the pillar results in a singularity in stress at the corner with the substrate. An eigenvalue analysis reveals that the stress field near the corner is dominated by two singular eigenfields having eigenvalues (λ_1, λ_2) with corresponding intensities (H_1, H_2). The asymptotic stress field σ_{ij} is of the form $\sigma_{ij} = H_1 r^{\lambda_1 - 1} f_{ij}(\lambda_1, \theta) + H_2 r^{\lambda_2 - 1} f_{ij}(\lambda_2, \theta)$, where f_{ij} describe the angular dependence θ of σ_{ij}, and r is the radial distance from the corner. The stress intensities (H_1, H_2) are calculated numerically, using a domain integral approach, as a function of the elastic mismatch between the pillar and substrate. The singular zone extends across approximately 10% of the pillar diameter (in 3D) or pillar width (in 2D).

Interfacial failure is predicted for an assumed crack emanating from the corner of pillar and substrate. For the case of an interfacial crack that resides within the domain of corner singularity, a boundary layer analysis is performed to calculate the dependence of the interfacial stress intensity factor K upon (H_1, H_2). When the crack extends beyond the domain of corner singularity, it is necessary to consider the full geometry in order to obtain K. A case study explores the sensitivity of the pull-off stress to the flaw size and to the degree of material mismatch. The study has implications for the optimum design of adhesive surface micropatterns, for bonding to either stiffer or more compliant substrates.

1. Introduction

The recent design and fabrication of bio-inspired adhesive surfaces follows a new paradigm for reversible adhesion (e.g. Jeong et al., 2009; Gorb et al., 2007; Greiner et al., 2007; Kamperman et al., 2010). Observation of the adhesion organs exhibited by some creatures of the animal kingdom, for example the beetle and gecko, has shown hair-like compliant structures at the tip of their limbs that enable them to climb on vertical walls and hang from ceilings. Adhesion is primarily due to van der Waals forces (Autumn et al., 2002) with a humidity-dependent contribution from capillary forces (Huber et al., 2005). This has led to the concept of 'contact splitting' (Arzt et al., 2003), according to which adhesion is enhanced by the presence of small, discrete and compliant ('fibrillar') contact elements.

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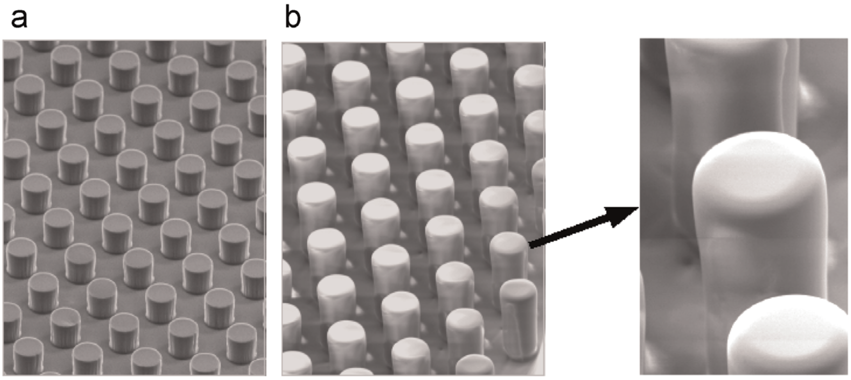

Fig. 1. Arrays of flat-bottomed micropillars with (a) sharp and (b) rounded edges. Pillars have a radius of 10 μm and were fabricated out of polydimethylsiloxane (PDMS). Such 'artificial gecko structures' were found to have adhesion properties superior to unpatterned materials. Scanning electron micrographs adapted from del Campo et al. (2007) and Kaiser et al. (unpublished 2014).

The surfaces of artificial, bio-inspired adhesive surfaces typically have a micropattern comprising an array of short cylindrical pillars made from a soft material such as PDMS or other polymers. The diameter of individual pillars ranges from sub-micron to sub-millimeter dimensions, with length-to-diameter aspect ratios typically between 1 and 10. These pillars have been fabricated with a variety of tip shapes (flat-bottomed Greiner et al., 2007 or mushroom-shaped Gorb et al., 2007; Greiner et al., 2007; Murphy et al., 2009) and geometries (straight Greiner et al., 2007 or slanted Jeong et al., 2009). An example of an array of flat-bottomed micropillars is shown in Fig. 1. Such adhesive pillars have also been made from shape memory polymers (Reddy et al., 2007) and from flexible nickel paddles coated with polymeric nanorods (Northen et al., 2008). A switchable adhesion has been achieved in such systems by controlling temperature (Reddy et al., 2007), magnetic field (Northen et al., 2008) or compressive preload (Paretkar et al., 2013). Especially the latter system is now on the verge of practical application in industrial robotic systems.

For the optimisation of artificial fibrillar surfaces, a full understanding is required of the micromechanical detachment mechanisms and the influences of the geometrical and materials parameters involved. When collective mechanisms and backing layer effects are neglected, the problem can be reduced to the detachment of a single elastic pillar from an elastic substrate. Furthermore, mechanisms that involve the collective behaviour of many pillars, or that are motivated by the behaviour of the layer of material backing a pillar array, depend on the manner in which individual pillars detach from the elastic substrate. This involves a strong interplay between surface energy and elastic strain energy. The detailed push-on/pull-off behaviour is sensitive to the contact shape and to the elastic mismatch between pillar and substrate. Much progress has been made for a conforming contact, where the bottom of the pillar is spherical (or cylindrical) in shape. For example, the Johnson–Kendall–Roberts (JKR) theory (Johnson et al., 1971) considers the elastic-brittle limit such that the traction-separation law of the interface enters the analysis only via the work of separation G_c . In this limit, the process zone (over which the force-separation law is active) is much smaller than the contact size. The domain of validity of the elastic-brittle idealisation has been explored (Paretkar et al., 2013; Northen et al., 2008), and found to have widespread application. Much less is known about the detachment of a non-conforming pillar, such as a flat-bottomed cylinder from a flat substrate.

Arrays of cylindrical pillars have been fabricated from PDMS (e.g. del Campo et al., 2007). The tip of such pillars can be flat or rounded with a prescribed radius at the corner, see Fig. 1. Adhesion studies have been performed by del Campo et al. (2007), using these arrays, to measure the pull-off stress against a sapphire spherical substrate. They report that the pull-off strength for an array of pillars with rounded tip is only a fraction that of flat-tipped pillars. Note that the pull-off stress for the array of pillars is governed by the pull-off stress for an individual pillar and the rounded tip can be considered to be a crack-like flaw. Consequently, it is important to have an accurate estimate for the pull-off stress for an individual pillar as a function of the crack length, pillar geometry and elastic mismatch between the pillar and substrate. This is the subject of the paper.

The pillar substrate geometry analysed is shown in Fig. 2. For this geometry, detachment begins at the corner of the pillar and propagates inwards. The details are made complex by the presence of a corner singularity in the perfectly bonded state, with the level of singularity sensitive to the degree of elastic mismatch between pillar and substrate. Furthermore, the geometry shown in Fig. 2(a) is the fundamental shape for a fibril undecorated by a special tip shape such as a mushroom head or a flange, but perhaps having an edge radius of curvature arising as a natural outcome of fabrication (see Fig. 1(b)). Such an edge radius can be represented to first order as the crack depicted in Fig. 2(c) with the its length being equal to the edge radius. Detachment at the tip of the crack/edge radius, shown in Fig. 2(c), is controlled by stresses arising from the edge singularity in the problem of Fig. 2(a). Solution of the problem depicted in Fig. 12(a) is thus of primary importance in the characterisation and understanding of the detachment of micro-pillars from an elastic substrate dissimilar or similar to the material from which the pillar is made.

The purpose of the present paper is thus to present a comprehensive mechanics analysis for the detachment of a 2D flat-bottomed rectangular pillar of width D, and of a flat-bottomed pillar in the form of a 3D circular cylindrical pillar of diameter D, from a possibly dissimilar substrate, see Fig. 2(a). We take the 2D pillar to be sufficiently thick in the z-direction of Fig. 2