



Discrete contact mechanics of a fibrillar surface with backing layer interactions

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ABSTRACT

The contact mechanics of a fibrillar micro-fabricated surface structure made of poly(dimethyl siloxane) (PDMS) is studied. The attachment and detachment of individual fibrils to and from a spherical indenter upon approach and retraction are detected as jumps in force and stiffness. A quantitative model describes the stiffness values by taking into account the deformation of the fibrils and the backing layer. The results emphasize the importance of long-range interactions in the contact mechanics of elastic materials and confirm some of the important concepts underlying the development of fibrillar adhesive materials.

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1. Introduction

Fibrillar microstructures of elastic materials interacting with substrates by short-range molecular forces, such as van der Waals attraction, have recently attracted attention as dry adhesives (Arzt et al., 2003; Boesel et al., in press; Del Campo and Arzt, 2008; Del Campo et al., 2007; Gorb et al., 2007; Greiner et al., 2007; Huber et al., 2005; Kim and Sitti, 2006; Lee et al., 2007; Peressadko and Gorb, 2004). Their development is motivated by the study of adhesion in biological systems exemplified by the feet of some insects and geckos (Arzt et al., 2003; Autumn, 2006; 2007; Autumn, et al., 2000; Huber et al., 2005; Sun et al., 2005). Such fibrillar architectures exhibit high adhesive strengths for a variety of reasons that have been summarized by Majumder et al. (2010) and subsequently by Kamperman et al. (2010). Such reasons include a higher peeling resistance, better conformation to rough surfaces, strengthening due to contact splitting (Arzt et al., 2003), the achievement of maximum van der Waals adhesive strength for a given area in contact (Gao and Yao, 2004), and better defect tolerance (Hui et al., 2004; McMeeking et al., 2008; Spuskanyuk et al., 2008).

Many of the systems that have been developed so far are produced by an integrated moulding process involving an elastomer, so that the fibrils are backed by a layer of the same elastic material. Efforts have been made to understand the pull-off mechanics of such systems. Long et al. (2008) used an elastic foundation to model the deformation of the fibril array while the deformation of the finite backing layer was modelled using linear elasticity theory. They found out that the normalized pull-off force is inversely proportional to both the thickness of the backing layer and the radius. Long and Hui

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(2009) used a similar approach with fibrils modelled as an elastic layer, and predicted the pull-off force for a prismatic circular indenter. They deduced that the pull-off force for a compliant backing layer should be less than that for a stiff one. Furthermore, Kim et al. (2007) modelled their fibrillar system as a foundation consisting of elastic springs between the rigid indenter and a backing layer. They focused mainly on the situation where a large number of fibrils are in contact. They found that very thin backing layers promote equal load sharing, maximizing adhesion. In the other extreme, very thick backings can lead to reduced adhesion, because of edge stress concentration similar to a rigid punch in adhesive contact with a half space. Noderer et al. (2007) observed an enhanced work of adhesion during the detachment of a glass indenter from an array of film-terminated fibrils, and deduced that the enhancement arose due to detachment trapping within the fibrillar system. In addition, they developed a successful model for the compliance of the film-terminated fibrillar array, deduced from the integrated effect of a large number of discrete fibrils.

In this study, following Noderer et al. (2007), we quantify the combined elastic response of fibrils and backing layer, and show that the measured stiffness of the system is strongly influenced by elastic deformations of the backing layer, even for the small strain deformations applied. Such long-range deformation of the substrate is an essential ingredient in recent models of the mechanical response of elastic systems (Persson, 2001). We focus mainly on the approach of a stiff sphere into contact with a fibrillar system, addressing this phenomenon with both experiments and a model. The high sensitivity of a nanoindenter allows us to register the sequence of attachment of individual fibrils. Investigating attachment, rather than detachment, allows us to avoid the non-linear effects of large strain and viscoelastic response, which often hamper the quantitative analysis of adhesion experiments involving elastomers. In our model we describe the combined deformation of fibrils and backing layer in a linear elastic analysis at small strains, as pioneered by Noderer et al. (2007). The combination of experiment and model allows us to understand the measured stiffness as a function of the number of fibrils in contact and to determine the elastic modulus of our material by in-situ measurements on individual fibrils on the backing layer. Finally we briefly discuss the compliance identified in experiments during retraction of the indenter, and extend our model for a single fibril in contact to include finite strains, observed during retraction.

2. Materials and methods

The PDMS samples, pillars integrated with the backing layer, were prepared using a soft-moulding process. A 10:1 ratio of Sylgard 184 prepolymer and cross-linker was mixed, degassed, and poured on a silanized SU-8 pattern containing cylindrical holes in a hexagonal packing arrangement. The mould was previously covered by a fluorinated polymer layer to favor the separation of the polymeric material. After curing at 60 °C and 600 mbar, during 24 h, the material was carefully demoulded, to obtain a structured PDMS surface on top of the backing layer. The tested area consisted of an arrangement of 7 fibrils of radius $a=5\text{ }\mu\text{m}$ each and of height $H=18.7\text{ }\mu\text{m}$, measured by means of a white light interferometer (Zygo New View 5010). They are arranged in a hexagonal pattern; separated by a distance $s_{ij}=20\text{ }\mu\text{m}$ between the centre of neighbouring fibrils with nos. i and j (see Fig. 1 for a schematic top view). The backing layer is $2.5 \pm 0.3\text{ mm}$ thick.

Nanoindentation tests were carried out using a TI 900 instrument with a Performech controller (Hysitron TriboIndenter, Hysitron Inc., Minneapolis, MN, USA). A spherical sapphire indenter (radius $R \approx 348\text{ }\mu\text{m}$) was used. The radius of the sphere was calibrated through a series of indents into polycarbonate (PC) with a maximum penetration depth of 140 nm. The radius was confirmed by means of imaging with an optical microscope, and also by scanning a cube-corner indenter tip under imaging mode with the above mentioned instrument (TI 900). Fig. 2 is a schematic of the cross-section of the centre fibril and two of its closest neighbours. Note the large radius of curvature of the indenter tip compared to the diameter of the fibrils. The contact between each fibril and the indenter can be described as a local “flat punch” contact.

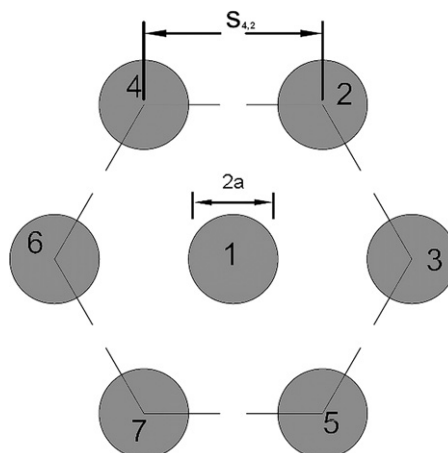


Fig. 1. Schematic top view of the hexagonal fibril arrangement. The fibrils have a radius of $a=5\text{ }\mu\text{m}$ and a centre-to-centre distance between neighbours of $s_{ij}=20\text{ }\mu\text{m}$.

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