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The influence of substrate roughness, patterning, curvature, and compliance in peeling problems

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Abstract

Biological adhesion, in particular the mechanisms by which animals and plants 'stick' to surfaces, has been widely studied in recent years, and some of the structural principles have been successfully applied to bioinspired adhesives. However, modelling of adhesion such as in single or multiple peeling theories, have in most cases been limited to ideal cases, and due consideration of the role of substrate geometry and mechanical properties has been limited. In this paper, we propose a numerical model to evaluate these effects, including substrate roughness, patterning, curvature, and deformability. The approach is validated by comparing its predictions with classical thin film peeling theoretical model results, and then is used to predict the effects of substrate properties. These results can provide deeper insight into the experimentally obtained results, and the developed model is a useful tool to design and optimize artificial adhesives with tailor-made characteristics.

1. Introduction

In recent years, there has been growing interest in the study of biological systems displaying architectures that are optimized for specific functions such as structural resilience, protection, locomotion, self-cleaning, or self-repair [1–3]. The observation and mimicry of natural systems has therefore led to the emergence of novel smart strategies to improve artificial system functionalities [4]. This applies to the field of biological adhesion, which also studies the way in which animals like beetles, spiders, or geckos achieve optimized adhesion control by arrays of tape-like micro- or nano-contacts organized in a hierarchical manner, especially in heavier animals [5]. It has been demonstrated that these contact units can be modelled as delaminating (or 'peeling') thin films, rather than punch-like units [6], and that structures such as gecko, spider, or insect pads can be described using models based on this description of the contacts [7, 8]. One of the key features of analytical tape peeling models, such as the Rivlin model [9] or the Kendall model [10], is that the peeling force, i.e. the force necessary to initiate detachment of the adhesive structure, strongly depends on the angle between the applied force and the substrate, i.e. the 'peeling angle'. In addition to the observed contact geometries, one of the main arguments for treating animal attachment as ensembles of delaminating tapes is that the angle dependence on the detachment force has been experimentally observed in all species displaying 'hairy' contacts, both at micro and macro scales [6]. In addition to the geometry of the tape unit and the peeling angle, the adhesive energy at the interface between the contact units and the substrate contributes to determining the peeling force. This adhesive energy is mainly due to van der Waals interactions [11] and to capillarity [12], but in the cited contact models, all substrate and interface properties are condensed into a single adhesive energy term. For a given loading scenario and tape geometrical/mechanical properties, the adhesive energy varies as a function of the material and the surface profile of the substrate [13, 14]. In turn, the peeling force derived in analytical peeling models is related to the variation of the difference between adhesive energy and total potential energy, which describes the micro scale physics of interface failure.

With current progress in mimicking natural adhesives, the understanding of peeling mechanisms and the derivation of adhesion optimization criteria