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Effect of nano- and micro-roughness on adhesion of bioinspired micropatterned surfaces

Natalia Cañas [a], Marleen Kamperman [b,*], Benjamin Völker [c], Elmar Kroner [a], Robert M. McMeeking [a,c,d,e], Eduard Arzt [a]

[a] INM – Leibniz Institute for New Materials, Functional Surfaces Group and Saarland University, Campus D2 2, 66123 Saarbrücken, Germany
[b] Wageningen University, Physical Chemistry and Colloid Science, Dreijenplein 6, 6703 HB Wageningen, The Netherlands
[c] Department of Mechanical Engineering, University of California, Santa Barbara, CA 93106, USA
[d] Materials Department, University of California, Santa Barbara, CA 93106, USA
[e] School of Engineering, University of Aberdeen, King's College, Aberdeen AB24 3UE, UK

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ABSTRACT

In this work, the adhesion of biomimetic polydimethylsiloxane (PDMS) pillar arrays with mushroom-shaped tips was studied on nano- and micro-rough surfaces and compared to unpatterned controls. The adhesion strength on nano-rough surfaces invariably decreased with increasing roughness, but pillar arrays retained higher adhesion strengths than unpatterned controls in all cases. The results were analyzed with a model that focuses on the effect on adhesion of depressions in a rough surface. The model fits the data very well, suggesting that the pull-off strength for patterned PDMS is controlled by the deepest dimple-like feature on the rough surface. The lower pull-off strength for unpatterned PDMS may be explained by the initiation of the pull-off process at the edge of the probe, where significant stress concentrates. With micro-rough surfaces, pillar arrays showed maximum adhesion with a certain intermediate roughness, while unpatterned controls did not show any measurable adhesion. This effect can be explained by the inability of micropatterned surfaces to conform to very fine and very large surface asperities.

1. Introduction

Many insect and lizard species possess adhesive organs on their feet that allow them to adhere to a wide variety of surfaces. The key strategy to control adhesion in these natural systems is the incorporation of fibrillar structures [1–6]. In the particular case of the gecko foot, each fibril or seta is ~100 μm long, has a diameter of a few microns and branches into an array of hundreds of spatula structures. These structures terminate in a triangular plate tip with dimensions of ~0.2 μm in length and a thickness of 10 nm [1]. The gecko uses non-covalent surface forces to achieve adhesion, which relies primarily on van der Waals forces [7].

Because the strength of van der Waals forces strongly decreases with increasing distance between the surfaces, an important aspect in adhesion is the true area of contact. Although surface area is increased by the surface roughness, more elastic strain energy is needed for the adhesion structure to conform to the rough surfaces and make contact. Macroscopic solids normally do not adhere on rough surfaces; a root-mean-square (RMS) roughness of ~1 μm is sufficient to result in negligible adhesion between rubber and a hard flat surface [8]. For purely elastic materials, only very compliant materials (Young's modulus E ~100 kPa) can adhere well on hard rough surfaces, because the elastic energy stored during deformation of the compliant material is low compared to the energy gained by forming a contact [8,9].

Geckos show high adhesion to rough surfaces in spite of the stiff structural material (β-keratin: E ~1 GPa) [10–12]. In this case adhesion is possible, because the hierarchical build-up of the fibrillar structure results in a low effective modulus and allows conformation to rough surfaces by fiber bending and buckling [5,8,13–15]. Despite the ability of geckos to conform to rough surfaces, observations of living geckos show that adhesion strongly decreases for certain roughness values [10–12]. This may explain why geckos seem to have an over-redundant attachment system [16].

Significant decreases in adhesion were also found in the few studies published on biomimetic adhesives using technologically relevant rough surfaces [17–19] or model surfaces with well-defined roughness [19,20]. In all cases, the adhesion decreased with increasing roughness [19,20] and hierarchical structures outperformed single-level structures, but only on rough surfaces [18,20].

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[*] Corresponding author. Tel.: +31 (0)317 482358; fax. +31 (0)317 483777.
E-mail address: marleen.kamperman@wur.nl (M. Kamperman).

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