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Brief communication

Influence of surface roughness on gecko adhesion

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Abstract

In this study we show the influence of surface roughness on gecko adhesion on both the nano- and macroscales. We present experimental data for the force necessary to pull off single spatulae from hard rough substrates and also detail observations on living geckos clinging to various surfaces. Both experiments consistently show that the effective adhesion shows a minimum for a root mean square roughness ranging from 100 to 300 nm.

Keywords: Gecko; Lizards; Adhesion; Roughness; AFM

1. Introduction

Observations and force measurements on plant surfaces with fine roughness have demonstrated a strong reduction in the attachment force exerted on insects [1–5]. Friction measurements on flies and beetles walking on surfaces with well-defined surface roughness [6,7] also show that the roughness plays an important role in adhesion of these animals. A minimum in frictional force was identified for a certain range of surface roughness, varying from 0.3 μm to 1 μm for the beetle *Gastrophysa viridula* [2] and for the fly *Musca domestica* [7]. These results suggest that a similar roughness effect on the adhesion might be observed for geckos, which also possess hairy attachment devices similar to those of flies and beetles [8].

It is well known that the strength of the short-range intermolecular forces strongly depends on the surface topography. Two competitive quantities have to be considered when studying adhesion of an elastic body to a rough substrate: (i) the attractive interaction due to the adhesion energy and (ii) the repulsive interaction as a result of the elastic strain energy during the contact formation. The influence of roughness on the adhesion between two elastic bodies has been in the focus of scientists for several decades [9–13] and has also been investigated in biological systems [1–5,14]. Recently Peressadko et al. [15] reported experiments with rubber balls against hard rough substrates. They showed that the effective pull-off force can be accurately calculated from the surface roughness power spectra obtained from the measured surface height profile.

This study provides new insight into the adhesion mechanism of the gecko from two different experiments. On the one hand, adhesion measurements of a single hair (seta) were performed at the nanoscale by means of atomic force microscopy (AFM) and, on the other hand, observations under laboratory conditions were made on a living Tokay gecko (*Gekko gecko*) clinging to substrates with different roughness. In this way, the critical surface roughness was identified and conclusions could be drawn on the interplay of the spatula dimensions with the surface roughness.

2. Experimental

All experiments were performed at ambient temperature and relative humidity (25 °C and 45%). The experimental

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force measurement setup as well as the specimen preparation technique was the same as described in Refs. [16,17]. A single seta was glued to the tip of a contact mode cantilever and subsequently manipulated by means of a focused ion beam microscope. In this way, we were able to reduce the number of spatulae per seta from several hundred to less than four. Subsequently, the cantilever was mounted in a commercially available atomic force microscope (JPK instruments NanoWizard®, Berlin, Germany) with which the adhesion measurements were carried out.

The surfaces were produced by vacuum evaporation of aluminum on a silicon wafer at different substrate temperatures. Polyvinylsiloxane replicas were prepared from the rough aluminum-covered surfaces. Samples for the AFM experiment were prepared from the polyvinylsiloxane templates using epoxy resin. The nine different surfaces were denoted by numbers (from 1 to 9) according to increasing root-mean-square (RMS) roughness. The substrates investigated were identical with those used in the work of Peressadko et al. [15], who provided full details of the surface preparation and analysis.

The attachment ability of a living Tokay gecko was tested on five different types of polishing papers with a nominal asperity size of 0.3 μm, 1 μm, 3 μm, 9 μm and 12 μm. The RMS values were measured using white light interferometer Zygo NewView 5000 (Zygo Corporation, Middlefield, CT): $RMS_{0.3} = 90.0$ nm ± 2.7; $RMS_1 = 238.4$ nm ± 6.0; $RMS_3 = 1156.7$ nm ± 133.1; $RMS_9 = 2453.7$ nm ± 87.2; $RMS_{12} = 3060.3$ nm ± 207.7. Clean smooth glass was used as a control surface. The bottom of an empty clean glass terrarium (40 cm × 20 cm × 20 cm) was completely covered with the polishing paper of a particular roughness. An animal was positioned at the bottom of the terrarium. After 2–3 min of adaptation time, the terrarium was slowly turned upside down and the behavior of the animal was videorecorded. From video sequences, the angle at which the animal began to slip off was estimated. The entire procedure was repeated three times for each surface for two individual animals.

3. Results

3.1. AFM tests

Fig. 1 shows the surface topography of three substrates imaged by AFM in contact mode. For the sake of comparison, the scan size (10 μm × 10 μm) and height range (dark: 0 nm and bright: 580 nm) were kept constant. Spatular adhesion forces for two different specimens at ambient conditions on nine different surfaces having RMS roughness values ranging from ~20 nm up to ~1.1 μm are presented in Fig. 2. The pull-off forces show a distinctive minimum between 100 nm and 300 nm RMS roughness. Each data point is a mean value of 10 measurements at one randomly chosen site on the corresponding surface. This procedure resulted in a total number of 150 measurements for the two different specimens. The cantilever represented by the black squares in Fig. 2 broke down after testing surface number 6 (RMS roughness of ~200 nm). Therefore a second specimen (open circles) was measured on all nine surfaces.

3.2. The attachment ability of living geckos to different substrates

On the polishing paper with a nominal asperity size of 0.3 μm (RMS = 90 nm), geckos were not able to stay on the substrate and started to slide on the slope of 135.0° (standard deviation = 11.4°, $n = 6$). On a rougher substrate with the asperity size of 1 μm (RMS = 238 nm), animals were able to cling to the ceiling for a while, but their toes slowly slid off the substrate and the contact had to be continuously renewed. On the remaining tested substrates,

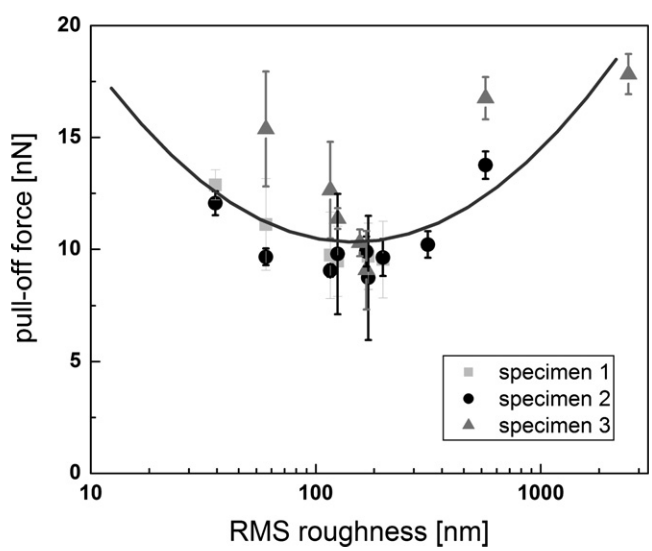

Fig. 2. Pull-off forces of two different spatula specimens as a function of the surface RMS roughness. The substrates were epoxy resin replicas of aluminum films. The error bars result from 10 measurements at one randomly chosen location on the corresponding substrate. The continuous line has been drawn as a guide to the eye.

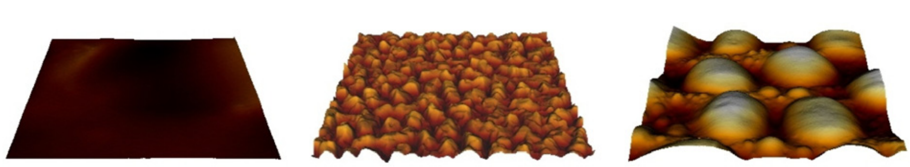

Fig. 1. The 3-D height profile (10 μm × 10 μm, z-range: 0–580 nm (dark–bright)) of surfaces 1, 5 and 9 as measured by AFM in contact mode. The surface roughness increases from the left to the right.