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Dry Adhesion of Artificial Gecko Setae Fabricated via Direct Laser Lithography

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Abstract. Biomimetics has introduced a new paradigm: by constructing structures with engineered materials and geometries, innovative devices may be fabricated. According to this paradigm, both shape and material properties are equally important to determine functional performance. This idea has been applied also in the field of the microfabrication of smart surfaces, exploiting properties already worked out by nature, like in the case of self-cleaning, drag reduction, structural coloration, and dry adhesion. Regarding dry adhesive properties, geckos represent a good example from which we take inspiration, since they have the extraordinary ability to climb almost every type of surface, even smooth ones, thanks to the hierarchical conformation of the fibrillary setae in their toe pads. Due to this design, they can increase the area of contact with a surface and thus the amount of attractive van der Waals forces. While reproducing with artificial materials the same functional morphology of gecko's pads is typically not achievable with traditional microfabrication techniques, recently Direct Laser Litography offered new opportunities to fabrication of complex three-dimensional structures in the microscale with nanometric resolution. Using direct laser lithography, we have fabricated artificial gecko setae, reproducing with unprecedented faithfulness the natural morphology in the same dimensional scale. Adhesion force of artificial setae toward different surfaces have been tested in dry condition by means of a dedicated setup and compared with natural ones.

Keywords: Biomimetics · Direct laser lithography · Gecko · Dry adhesion

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1 Introduction

Biomimetic principles have attracted great interest in the field of microfabrication techniques, since they represent the cutting edge in the production of smart functional surfaces [1]. In particular, several studies have tried to reproduce the dry adhesion capability of gecko foot [2–5]. Geckos are able to climb up surfaces with various roughness, even smooth, supporting their weight thanks to the hierarchical conformal morphology of the pads at the micro- and nano-scale that provides a huge number of short range interactions mainly governed by van der Waals forces [6]. As an example, *Gekko gecko* can produce 10 N of adhesive force since each of the 5000 setae mm^{-2} ensures an average adhesion force of about 20 μN, but this value can even be tenfold higher depending on the preload [7].

Artificial surfaces inspired by the gecko foot could have several technological applications in the realization of films with high and reversible adhesiveness to different substrates. A surface inspired by the gecko foot would have an asymmetric behavior: it provides strong adhesion and requires low force for the detachment.

It has been possible to mimic the Gecko effect by reproducing with traditional microfabrication techniques the adhesive terminal units of the gecko pads. However, the faithful reproduction of three-dimensional hierarchical morphology, and comparable adhesion force, is still far to be achieved. Direct laser lithography recently demonstrated its potentiality for the fabrication of biomimetic surfaces patterned with three-dimensional features in the micro- and nano-scale [8, 9]. Here this microfabrication technique has been used for the replication of complex artificial hairs inspired by the gecko's pads setae. A dedicated setup based on a single-axis force sensor, capable of measuring down to the nN scale, has been implemented for the measurement of the adhesion force of the structures on a flat silicon surface.

2 Microfabrication of Artificial Setae

The gecko foot skin is composed by a multilevel structure of lamellae, setae, branches and spatulae composed of β-keratin. The length of the setae is in the range of 30–130 μm and the diameter is 5–10 μm while the spatulae, the end portions ramified from the branches, have tips 0.5 μm long, 0.2–0.3 μm wide and 0.01 μm thick. Such type of structure is complex since the long stalk has a high aspect ratio and the tips are composed by nanoscale contact units. Direct laser lithography allows to overcome the challenge of replicating such complex design respect to other fabrication techniques.

Two different models have been prepared for the fabrication of artificial gecko setae. The first model tries to reproduce the rough morphology of the gecko setae and it has been used for the calibration of all the parameters of the 3D laser lithography, such as, for example, the laser power and the writing speed. The second model has been realized for the definition of a more realistic morphology that can reproduce the effective shape of the natural one with a higher level of details. The structures realized according to this type of model have been used for the adhesion test.

For the calibration of parameters of the 3D laser lithography a CAD model of the setae has been realized with Solid Works. The setae represent the basic element of the gecko toe hierarchical structures (Fig. 1a). The CAD model of the stalk has been sliced with Nanoslicer (Nanoscribe GmbH), obtaining the coordinates of the points of the sections parallel to the substrate. An external shell has been added to the stalk to cover the internal construction and enhance the structural stability.

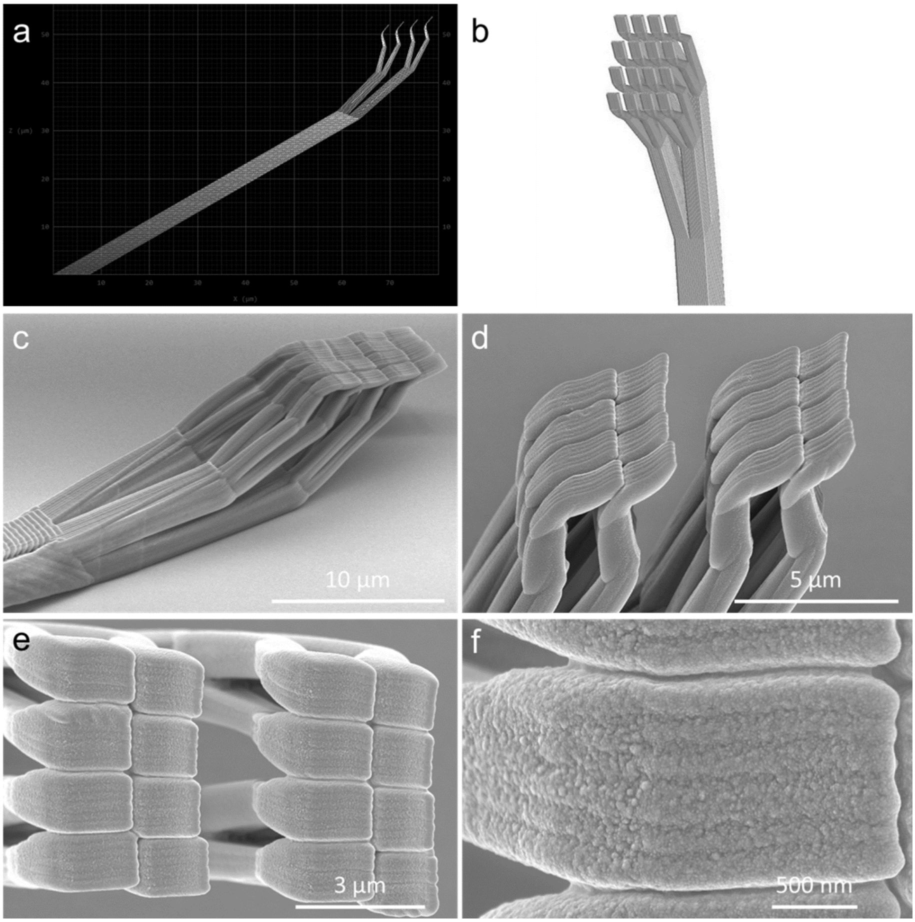

Fig. 1. First design of the setae for the calibration of the lithographic parameters: (a) Design in DeScribe; (b) Simulation of the tips in Matlab; (c-f) Results of the microfabrication.

The tips have been modelized as paths of coordinates in Matlab, and the photo polymerized structures have been simulated by sweeping an ellipsoid along the paths (Fig. 1b). The sorting strategy is based on a breadth-first algorithm, in which all adjacent edges at the same depth from the base are written before moving to the next level of edges that are further from the base. In this way the setae are better supported while being built. The programmed stalk has a nominal length of 68 µm and a square section with nominal sides of 3.4 μm; it forms an angle of 30° relative to the substrate. The branches grow of about 20 μm along the direction perpendicular to the substrate. There are 16 rectangular final tips with sides of 1 μm and 1.2 μm. The microfabrication produced outstanding results (Fig. 1c), even at the level of the tips (Fig. 1d–f).

The lithographic parameters have been defined selecting those providing the shortest fabrication time but with the best resolution of the features and used for the fabrication of the setae for the adhesion test. The second design consisted of a stalk with a nominal length of 60 μm and a square section with nominal sides of 2.8 μm; it forms an angle of 30° relative to the substrate. There are three levels of branches ending with 128 tips in total, each 300 nm in thickness and 1 μm in length (Fig. 2a, b).

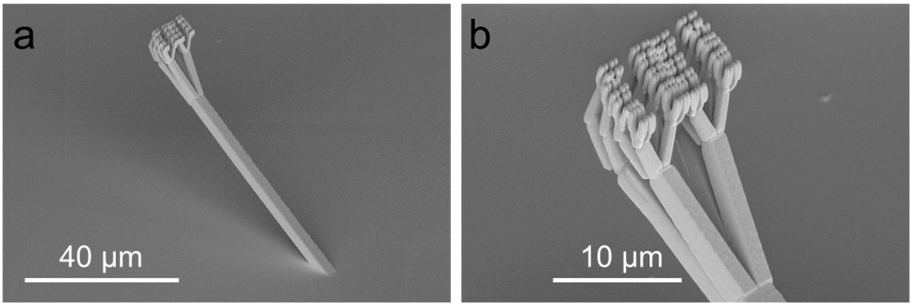

Fig. 2. Second design of the setae: (a) View of the seta; (b) Detail of the tips.

The setae were fabricated in IP-DiLL photoresist (Nanoscribe GmbH) by means of Nanoscribe (Nanoscribe GmbH). A square silicon sample of side of 1 mm was glued on a glass slide; the resist was poured on the silicon substrate and exposed to a laser beam (center wavelength 780 nm), using a writing speed of 100 μm s^{-1} with a power of 5.6 mW (Calman laser source). The sample was developed for 20 min in SU-8 Developer (MicroChem Corp) and rinsed in IPA and deionized water.

3 Adhesion Test of Artificial Setae

Frictional adhesion in gecko mostly relies on relatively weak van der Waals forces which become significant at very small setae-surface distances, that is in the range of an atomic gap distance of 0.3 nm. The normal force between the setae and a flat surface can be calculated as [10]:

$$F_{VDW} = -\frac{AL\sqrt{R}n_f n_s}{8\sqrt{2}D^{5/2}}$$

where n_f and n_s are the number of tips in the spatulae and the number of spatulae in the setae, respectively; A, the material-dependent Hamaker constant, is in the range of 10^{-20}–10^{-19} J, the typical values for condensed phases. According to this model, the adhesion force for this type of artificial setae range from 0.5 to 5 μN. The parallel friction forces, that were investigated in this work, are instead in the range of 20 μN [7].

The measurement of such small forces required a dedicated setup, prepared for the test of adhesion properties of the artificial gecko setae (Fig. 3a). The sample was mounted on the end effector of a nano-manipulator (Kleindiek Nanotechnik) which allows the movement with three degrees of freedom. The single-axis sensor (FemtoTools), able to detect perpendicular force in both directions in the range of ± 100 μN was positioned on a micro-manipulator used to move it in the correct configuration relative to the sample under an optical microscope (Hirox KH-7700). The cycles of movement of the nano-manipulator with the artificial setae against the force sensor was controlled by a dedicated software. Adhesion to the silicon smooth surface of force sensor was tested.

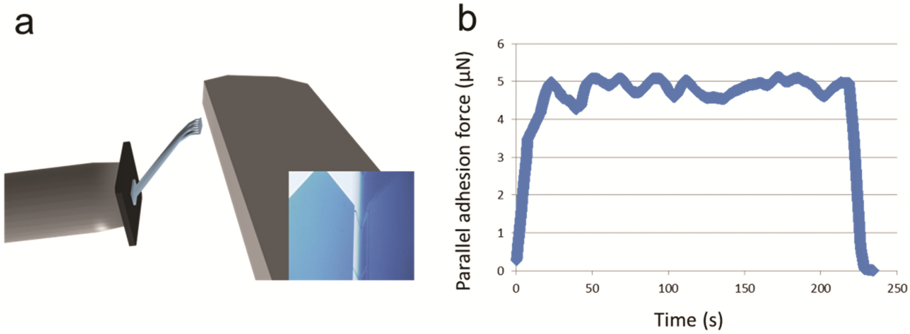

Fig. 3. Experimental results: (a) Experimental setup for the measurement of the adhesion of the setae; (b) Adhesion test result.

For the adhesion test a cyclic procedure was repeated. It consisted of a phase of approaching and perpendicular preloading, a phase of parallel displacement of about 5 μm, in order to ensure the proper conformation of the tips to the substrate, a sliding phase of the setae along the surface of the micro-force sensor during which the parallel adhesive force is measured, and finally a perpendicular detachment. Also a calibration procedure for the estimation of the perpendicular preload as a function of the bending of the setae was required. All the measurement of the adhesion force was carried out at a pushing speed of 35 nm s^{-1} that can be considered quasi-static.

In Fig. 3b the typical behavior of the parallel adhesive force as a function of time is reported. A linear relation between the adhesive force and the perpendicular preload was found. The range of interest of the preload is around 5 μN, since this is the typical value observed in gecko setae, which can provide an average force of 20 μN in this condition. Finally, in order to compare the performances of the artificial setae and the natural ones, it is necessary to normalize their contact area. The area covered by the artificial spatulae is about 50% of the area of the natural ones, so that the normalized adhesion force value is 10 μN. Compared with the performance of the natural gecko, the measured force is lower but in the same range, meaning that there could be the possibility to improve it by tuning the morphology of the setae, by modifying the angles of the branches, the dimensions and the numbers of the adhesive features.

4 Conclusions

Here it has been presented a procedure for the fabrication of gecko foot-like microstructures by means of direct laser lithography. These structures faithfully reproduced the features at the microscale of the animal model, representing a new goal in the microfabrication field respect to standard techniques. The adhesion test of the artificial setae provided encouraging results; in order to achieve higher forces and emulate the natural model the results obtained so far permit to envision as a promising strategy an interplay of morphology, dimensional scaling and materials. Thus artificial setae could be the starting point of a new generation of dry and reversible adhesives able to conform to almost every surface.

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