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Surface properties of bionic micro-pillar arrays with various shapes of tips

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ABSTRACT

Gecko-inspired micro-pillar arrays with various tip structures including spatular, spherical and concave tips were fabricated by a facile soft-molding method. The tip structures of micro-pillar arrays strongly depend on different curing processes in soft-molding using the same template. The adhesion and the wetting properties of these micro-pillar arrays are investigated by means of triboindenter and optical contact angle measurement. The results suggest that the surface properties are determined by different tip structures of micro-pillars. The spatular tip and concave tip are helpful for the adhesion enhancement and the shape of tip can control the contact angles and stabilities of water droplets on the micro-pillar arrays. In addition, the procedures demonstrate that the present route to fabricate gecko-inspired micro-pillar arrays with various tip structures is reliable and convenient. We believe that this research may pave the road to further understanding the gecko-inspired attachment systems and designing new artificial structures for dry adhesives.

1. Introduction

The remarkable ability of geckos and some insects to climb any surfaces has intrigued researchers for many centuries and inspired an active research direction over the last decade. Microscopic research has shown that there are arrays of millions of fine microscale setae, branching into hundreds of nanoscale spatula-shaped structures on geckos' toes, which can form a large adhesive force through millions of intimate contact points with climbing surfaces [1,2]. This adhesion, called dry adhesion, is argued to arise from molecular surface forces such as van der Waals forces. In addition to this adhesion ability, self-cleaning and hydrophobic properties are also the unique characteristics of geckos which are attributed to the special structures on geckos' toes [3,4].

Since the discovery of dry adhesion, many researchers [5–9] have attempted to develop artificial structures by mimicking gecko foot hairs in order to obtain this dry adhesion which can be applied to precision industry, biomedical patch and climbing robot. Micro/nanomolding [10–12], electron-beam lithography [13] and carbon nanotubes [14,15] were exploited to form gecko-inspired fibrillar structures with different geometries and dimensions, but the tips of these fibers are mostly flat. In contrast, different tip geometries of hairs in biological systems have been observed, for example, spherical, conical, filamentlike, bandlike, suckerlike, flat, and toroidal shapes [16]. Furthermore, theoretical and experimental researches have shown that the shape of the tip is a crucial factor for adhesion or wetting property, so some smart designs were made to fabricate adhesive fibers with different tip structures in recent years. For example, del Campo obtained polydimethylsiloxane (PDMS) fibers with spatula-like tips by combining soft-molding and inking process [17]. Sitti reported a method to fabricate arrays of mushroom shaped microfibers by filling prefabricated masters containing corresponding holes [18,19]. Suh and coworkers have prepared micro-pillar arrays with various tip shapes [20,21]. Although they have been successful in fabrication of artificial bio-inspired hairs with different tip structures, the methods generally involve the use of complex etching techniques, complicated inking and printing steps or pressing process, which limits further investigations in this area. Thus, further research is needed to both extend fabrication methods and illuminate the interplay of tip structures and characteristics of bionic hair arrays.

In this work, gecko-inspired polyurethane (PU) micro-pillar arrays with spatular, spherical and concave tips were successfully prepared by a facile soft-molding method. Different curing routes of soft-molding resulted in different tip structures. The adhesion and the wetting properties of the micro-pillar arrays with different tip geometries were investigated by the triboindenter and optical contact angle measurement. The micro-pillar array with spatular tip shows adhesion enhancement with increasing preload and the

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shape of tip can control the contact angles and stabilities of water droplets on the micro-pillar arrays. The results demonstrate that the adhesion and the wetting properties of the bionic micro-pillar arrays can be regulated by tip geometries, and the shape of the tips play a key role in determining surface properties.

2. Materials and methods

2.1. Materials

A photolithographic mask labeled as Mask-1 with chrome hexagonal patterned circular dots (~3 μm in diameter, ~3 μm in spacing) and another photolithographic mask labeled as Mask-2 with chrome hexagonal patterned orbicular dots (~3 μm in external diameter, ~2 μm in internal diameter, ~3 μm in spacing) used in this work were manufactured from the 13th research institute of electronics technology group corporation (Shijiazhuang, China). Commercialized silicon wafers (3 in.) were purchased from Shanghai Jinhe electronic material company (China). PDMS (Sylgard 184) was purchased from Dow Corning (USA), and PU precursor with water as solvent (PU-3530) was supplied by Anhui University (Hefei, China).

2.2. Fabrication of PDMS template with cylindrical micro-hole arrays

Firstly, silicon template with micro-pillar arrays was fabricated by means of photolithography using Mask-1 and ICP deep reactive ion etching reported in the previous work [22]. Secondly, the uncured PDMS was poured over the silicon template and solidified in a vacuum oven at 70 °C for 4 h. Then the cured PDMS template with micro-hole arrays was obtained by peeling them off from the silicon template mechanically. The detailed fabrication process is depicted in Fig. 1. The parameter of template determining the shapes of gecko-inspired micropillar arrays can be controlled by the mask in photolithography and ICP etching time.

2.3. Fabrication of PDMS template with protuberances at bottoms of cylindrical micro-hole arrays

The process for the preparation of PDMS template with protuberances at bottoms of cylindrical micro-hole arrays is similar to that of PDMS template with cylindrical micro-hole arrays, except the use of different initial silicon template with tubal micro-pillar arrays obtained by photolithography and ICP etching process using Mask-2.

2.4. Fabrication of PU micro-pillar arrays with three different tip structures

A special curing process was carried out for the fabrication of PU micro-pillar arrays with spatular tips. At first, the PDMS template with cylindrical holes was heated to ~80 °C and then filled with PU precursor. Then, the template filled with PU precursor was placed in an oven to make the solvent volatilize completely at 30 °C for a period of 6 h. Last, by peeling away from the template, PU micro-pillar arrays with spatular tips were obtained. The similar procedure was used to fabricate other two PU micro-pillar arrays with spherical tips and concave tips structures. The PU micro-pillar arrays with spherical tips could be obtained by pouring PU precursor over the PDMS template with cylindrical holes and allowing them to cure at 30 °C for a period of 6 h in an oven. Once cured, the PU micro-pillar arrays with spherical tips were carefully peeled away from the template. The PU micro-pillar arrays with concave tips could be obtained by pouring PU precursor over the PDMS template with protuberances at the bottoms of cylindrical holes and allowing them to cure at 30 °C for a period of 6 h in an oven. Once cured, the PU micro-pillar arrays films with concave tips were carefully peeled away from the templates. These fabrication processes are depicted in Fig. 2.

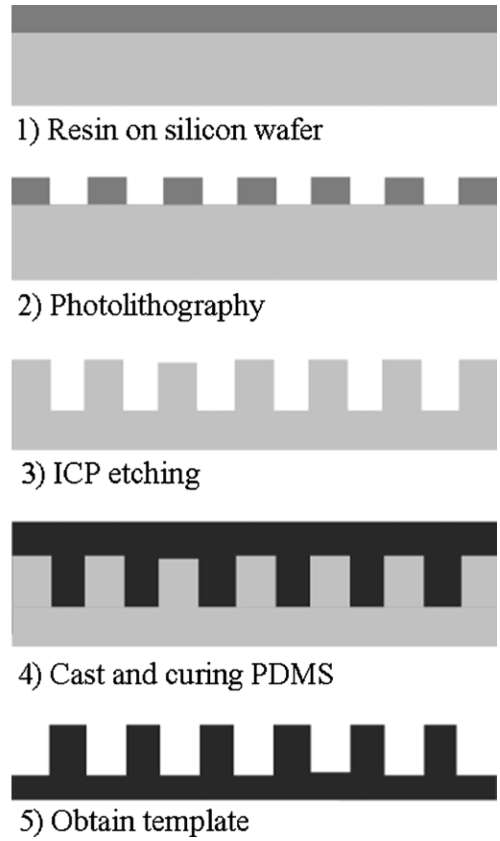

Fig. 1. Schematic illustration of the fabrication of PDMS template.

2.5. Characterization

Scanning electron microscopy (SEM) (Quanta-200, FEI, USA) was used to obtain SEM images of the as-prepared specimens. The adhesion behavior of PU micro-pillar arrays with different tip structures was measured by Triboindenter (Hysitron, Inc., Minneapolis, USA). The water contact angle was measured using an optical contact angle measurement (OCA20, Germany) at ambient temperature (22 °C) by placing a 10 μL deionized water droplet on the specimen.

3. Results and discussion

3.1. Characterization of the gecko-inspired micro-pillar arrays and the formation mechanism

Fig. 3(a) shows SEM image of the as-prepared PU micro-pillar arrays with spatular tips and the inset shows the magnified image. It can be seen from Fig. 3(a) that the pillar's stalk and tip is ~1.8 μm and ~2.9 μm in diameter and the pillar is ~3.8 μm in length. The diameter of cylindrical hole in PDMS template is ~3 μm, which is identical to the diameter of chrome circular dots in Mask-1. Moreover, the length of cylindrical hole is ~5 μm, which is determined by the time of ICP deep reactive ion etching. It is obvious that the dimension of as-prepared PU pillar is not identical to that of template hole, which demonstrates that the shrinkage of pillar's stalk has taken place in the curing step. At 80 °C during fabrication process, air in the holes of template became thin apparently so that PU precursor would fill the holes and then the precursor would