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Key parameters of biomimetic patterned surface for wet adhesion

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A B S T R A C T

Inspired by the polygonal arrays on the toe pads of tree frogs and newts, micro hexagonal pillars were fabricated on a cast polyurethane elastomer (CPUE) surface so that a network of interconnected channels was formed. To investigate the effect of channel sizes, adhesion experiments were carried out with a flat polymethyl methacrylate (PMMA) probe and the patterned surface of CPUE samples under wet conditions. It was found that single factors alone, such as channel width (W), length (L), and height (H) have a slight effect on wet adhesion force. Comparatively, the values of width-to-length (W/L), height-to-length (H/L), and height-to-width (H/W) determine the wet adhesion force significantly. Actually, the wet adhesion force is reduced with increasing W/L values. Furthermore, optimal ranges of H/L and H/W values clearly enhance the wet adhesion force, even considering the reduction with the increasing W/L values.

1. Introduction

The strong adhesion capability that some animals display has been an important area of research over the past decades. With such remarkable ability, some crawling animals can climb, attach to various surfaces, and hang upside down. A large number of studies have shown that this adhesion ability is closely related to the micro-patterns on their toe-pads.

Gecko is a typical animal that has been found to utilize van der Waals forces for dry adhesion [1,2]. These interaction forces are achieved by the direct contact of a hierarchical organization, which consists of millions of branched setae, each of them ending with thousands of spatula tips [3]. In addition to dry adhesion, wet adhesion is also an interesting ability for that amphibious animals exhibit. For example, tree frogs and newts can quickly climb and attach on wet, slippery rocks or leaves of plants. Observed by the naked eyes, their pads are flat and smooth. However, under a scanning electron microscope (SEM), they are patterned with hexagonal arrays of epithelial cells separated by mucus-filled channels [4–6]. Unlike dry adhesion, a thin fluid layer always lies between the substrate and toe pads in wet adhesion, and the adhesion force is mainly attributed to the combined effect of capillary and Steffen adhesion [5,7].

It has been proposed that the excess fluid has to be squeezed out of the contact zone quickly, facilitated by the micro-structure of the tree frogs' toe pads, to prevent hydrodynamic lubrication and achieve tight adhesion [7,8]. Drotlef et al. made different structured polydimethylsiloxane (PDMS) surfaces and proved that the wet adhesion force is dependent on the presence of the microstructure and its geometrical characteristics [9]. A network of interconnected channels, with a specific channel depth, width, and post diameter, results in significant reduction in hydrodynamic repulsion, compared to smooth surfaces [10]. Iturri et al. showed that elongated PDMS hexagonal patterns with an optimum pillar height increase friction forces, considering the deformability and edge density of pillars [11]. Huang et al. found that a pillar-patterned surface with high area density can maintain high friction at high sliding speed, which is different from micro-dimple patterned surfaces [12,13]. According to these studies, the dimensional design of hexagonal pillars and interconnected channels is closely related to the friction force. Unfortunately, few studies have been conducted until now to explore whether the wet adhesion of bio-microstructured surfaces is related to the sizes of pillars or channels. In addition, the most commonly used elastic material in biomimetic adhesion tests is PDMS, which has approximately a 110 ° static contact angle of its surface, and it is a well-known hydrophobic surface, contrary to the hydrophilic surface of the pads of the aforementioned animals. Therefore, it is apparent that a comprehensive and systematic study of micro hexagonal pillars' geometry sizes is essential to find out their influence mechanisms of wet adhesion, and it would be significant for the biomimetic microstructure design for the machines such as active capsule endoscopy.

In this study, because the pad surface of frogs and newts is hydrophilic, a new hydrophilic elastic material, cast polyurethane elastomer (CPUE), was used. Furthermore, taking into account the geometrical sizes of the microstructures, hexagonal pillars with interconnected

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channels of different parameters were designed, and face-to-face adhesion experiments were conducted in the presence of water.

2. Experimental section

2.1. CPUE - elastic material with hydrophilic surface

The Hei-Cast 8400 CPUE, purchased from HEI CAST (Tokyo, Japan), was selected to prepare the patterned samples. The cured CPUE surface is hydrophilic, with 70 ° static contact angle approximately; thus, compared to a PDMS surface, it is closer to the wettability of biological pads.

Hei-Cast 8400 is a typical casting material, which includes the component A (polymer polyol), B (polyisocyanate) and D (heterocyclic diol, as chain extender). The low viscosity of the A, B, and D mixture promises a fine flowing property and exact shape replication. Once the mixture is cured, the sample is highly elastic and hard to tear. By controlling the content of D, the Shore hardness can be adjusted from 10 HA to 90 HA and the Elastic modulus can vary in the range of 0.36 MPa to 5.09 MPa.

In this study, the mass ratio of A, B, and D was set to 100:100:150 and the mixture was cured under 60 °C for 90 min. The Shore hardness of the samples is about 50 HA and the Elastic modulus is approximately 1.56 MPa.

2.2. Fabrication of textures by two-stage transfer process

Usually, the casting-material mixture can be directly poured on a surface of SU-8 2075 photoresist (a series of negative epoxy resists, provided by Microchem, USA) patterned by a UV-LIGA (ultraviolet light-lithographie, galvanoformung and abformung) process in order to transfer the textures to the samples. However, because of the high surface energy of the CPUE, the bonding strength between the CPUE samples and wafers is too large to keep the SU-8 patterned surface on the wafers without damage.

Thus, in this paper, a two-stage transfer process was adopted to make the CPUE samples. The specific process is shown in Fig. 1, which includes three steps:

(a) Preparation: Hexagonal pillars of SU-8 photoresist were primarily made on the glass wafers by UV-LIGA technology. The required conditions, such as spin speed and exposure energy, were optimized to manufacture the specific patterns.
(b) First-stage of the pattern transfer process to make PDMS negative mold: PDMS is selected as the negative mold material because of its lower surface energy, so that the negative mold can be stripped from the glass wafers easily without damaging the photoresist pattern.
(c) Second-stage of the pattern transfer to make CPUE samples: The mixture of CPUE was well stirred, casted to negative mode, degassed in vacuum condition and cured under 60 °C for 90 min to obtain the micro-patterned samples.

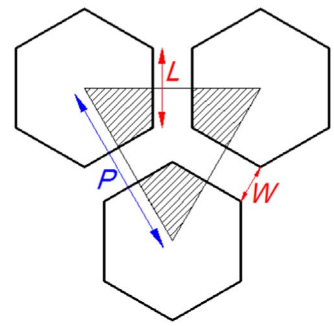

Fig. 2. Arrangement of hexagonal patterns. L is channel length, W is channel width and P is the center distance between two adjacent hexagons.

2.3. Pattern design of CPUE samples

The shape and distribution of the microstructures, shown in Fig. 2, were designed inspired by the textures of amphibian pads. Considering the real scale of the microstructures on amphibian toe-pads, SU-8 photoresist resolution, and manufacturing accuracy, different parameters of channel length, width, and height were chosen, as listed in Table 1.

The area density of hexagonal pillars can be defined as the ratio of hexagonal pillars area over the whole sample area. The area density of pillars (r_p) and the area density of channels (r_c) were calculated as follows, respectively:

$$r_p = 3L^2/P^2 \tag{1}$$

$$r_c = 1 - 3L^2/P^2 = 1 - 3/\left(\sqrt{3} + \frac{W}{L}\right)^2 \tag{2}$$

Fig. 3 shows three different patterned surfaces of the CPUE samples. The left image of each surface is the topography obtained by white light interferometer (Bruker, Germany), and the right image is the upper surface morphology observed by digital microscope (Keyence, Japan).

2.4. Adhesion measurements

Adhesion measurements were conducted with a self-made adhesion and friction tester [14], as shown in Fig. 4. The testing sample was brought into contact with the probe in a precise position by a piezo stage and two step motors. Wet adhesion tests were carried out with 2 μL of deionized water between the PMMA probe and CPUE samples. Both the probe and samples were of a cuboid shape with dimensions of 5 × 5 × 2 mm and 8 × 8 × 3 mm, respectively. Moreover, the 8 × 8 mm surface of the samples was in contact with the 5 × 5 mm surface of the probe, and thus, the contact area was 25 mm^2. There were 30 kinds of samples with different parameters, and each kind of sample had 8 specimens. In total, 240 specimens were tested in the adhesion measurements.

During the contact process, the contact condition was observed by

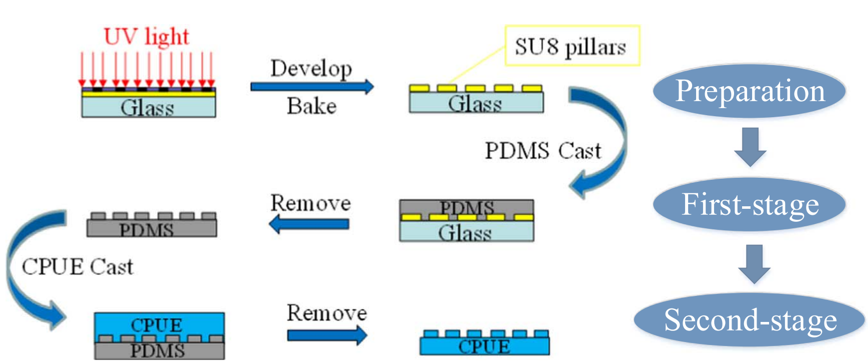

Fig. 1. Schematic diagram of two-stage transfer process.