FABRICATION OF BIOMIMETIC WET ADHESIVE PADS WITH SURFACE MICROSTRUCTURES BY COMBINING ELECTROFORMING WITH SOFT LITHOGRAPHY

Kun Wang*, Bin He, Ming-he Li**, Yun Ji****

**College of Mechanical Engineering, Tongji University,*
rd. Siping 1239, Shanghai, 200092 PR China, kunwang@tongji.edu.cn
***College of Electric and Information Engineering, Tongji University,*
rd. Siping 1239, Shanghai, 200092 PR China, hebin@tongji.edu.cn

Biomimetic adhesive pads, which include seta adhesive pads and wet adhesive pads, are compelling to be applied for a climbing robot. A novel approach for fabricating biomimetic wet adhesive pads with surface microstructures by combining electroforming process with soft lithography is proposed in this paper. According to the principle of wet adhesive of insects' pads, the mechanism of wet adhesion is analyzed. Polydimethylsiloxane wet adhesive pads with surface microstructures with the width of 100 μm and height of 25 μm have been obtained experimentally. A series of testing experiments have been carried out to prove that microstructures on the surface of pads fabricated by the proposed technique can effectively improve the wet adhesive ability.

УДК 62-5

INTRODUCTION

Adhesive ability is one of the most important issues for a climbing robot. There are four usual types of adhesion mechanisms used in a climbing robot: vacuum, magnetic, viscous, and electric (static electricity). However, their disadvantages limit the area of applications. Vacuum adhesion is unobtainable in the vacuum environment, viscous adhesive will fail to stick to a surface after several tries, magnetic adhesive can only be used to metals, the range of power of static electricity in adhesion is limited.

Biomimetic adhesive pads that are inspired by repesentatives of reptiles and insects, such as geckos, crickets, ants and beetles, have strong and stable climbing ability, regardless of the roughness of the contact surface. Biomimetic adhesive pads, which include seta adhesive pads and wet adhesive pads, are compelling to be applied for a climbing robot.

There is certain progress in the investigations of the mechanism of the insect adhesion. Kellar Autumn and his partners [1] found out that the surface of foot pads of many seta adhesive repesentatives of reptiles and insects, such as geckos, flies and beetles, is covered with micro scale or nano scale setae, and seta adhesive power mainly comes from the van-der-Waals force. The adhesion mechanism of wet adhesive insects, such as ants, stick insects, crickets, is also investigated [2–4]. Wet adhesive insects' foot pads covered with the planar microstructure are soft and can copy the shape of the wall surface under preload conditions [2–3].

At the same time, the fabrication technology of biomimetic adhesive pads has been carried out based on carbon nanotube growth and mechanical micromachining [5]. Chemical vapour deposition was successfully used to obtain the high density carbon nanotube arrays with the width of 50~500 μm so as to fabricate biomimetic seta adhesive pads [5–6]. Still, most of biomimetic pads that were produced by materials with high elastic modulus (such as carbon nanotubes) generally require a large pressure (or preload) to achieve an effective contact, so this technology of fabricating biomimetic seta adhesive pads cannot be applied for fabrication of biomimetic wet adhesive pads. Moreover, in certain cases, slanting moulds were machined by mechanical micro cutting, and millimetre scale slanting polyurethane seta arrays with the adhesive intensity of 0.24N/cm^2 were fabricated by micro moulding [7–8]. However, materials distortion in mechanical micro cutting limits the application of this technology in fabricating microstructures. Besides, biomimetic wet adhesive pads without microsturctures have been investigated by traditional mechanical technique [11].

The present paper is focused on developing a novel approach for fabricating biomimetic wet adhesive pads with surface microstructures by combining two technologies of micro fabrication, in which Cu molds are machined by electroforming, and polydimethylsiloxane (PDMS) biomimetic pads are obtained repeatedly by the soft lithography replication in Cu molds. The biomimetic wet adhesive pads obtained by the proposed technology were experimentally demonstrated to improve the wet adhesive force in comparison with the adhesive ability of pads without surface microstructures.

MECHANISM OF WET ADHESION

It was found out that the pads of insects (such as ants and stick insect) can generate adhesive force, which is several times their own weight [9–10]. Fig. 1,*a* is the amplificatory photo of a wet adhesive pad of the stick insect [2]. It was also revealed that when this kind of insects are climbing up the wall, their smooth pads would secrete to form a layer of a thin liquid film between the pad and the contact surface (the thickness of the film is smaller than several microns), as shown in figs. 1,*b*,*c* [2]. Their pads, compared with the insects' seta adhesive pads, are covered with well-regulated geometrical planar microstructures on the surface of wet adhesive insects' pads, as shown in fig. 1,*d* [10].

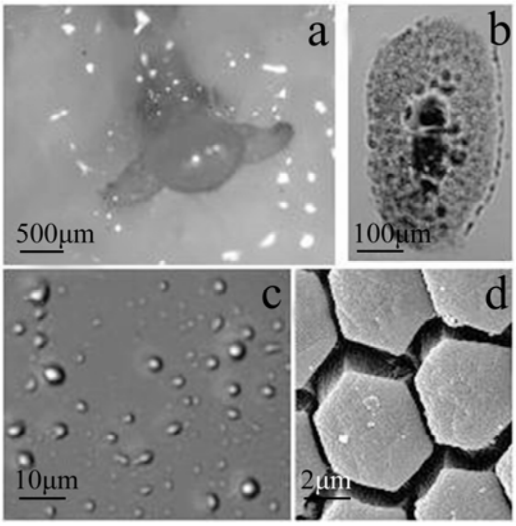

Fig. 1. Photo of pad and secretion of stick insect. (a) appearance of pad, (b) footprint of pad, (c) secretion, (d) microstructures of pad

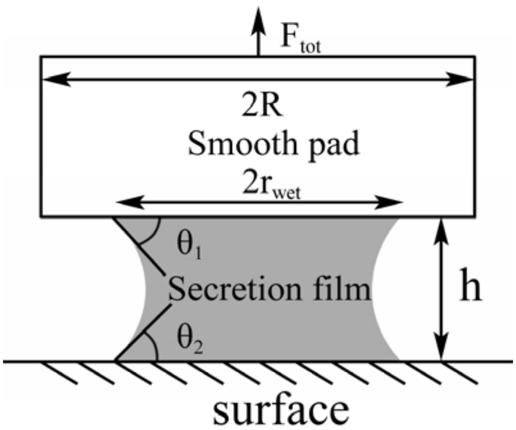

Fig. 2. Liquid bridge model of wet adhesive

Fig. 2 illustrates the model of wet adhesion, in which a liquid film (insects' secretion) is formed between the wet adhesive pad and the contact surface [2]. In fig. 2, R is the radius of the surface microstructure of the pad, r_{wet} is the radius of the liquid film, h is the height of the liquid film, θ_1 and θ_2 are contact angles. The liquid volume is constant, so when the pad is pulled or squeezed, the liquid bridge will shrink or expand. The wet adhesive force F_{tot} mainly comes from the surface tension F_{st}, capillary force F_c and glutinosity force F_g [2, 4]. When a wet adhesive pad is located on a surface, the glutinosity force is close to zero, and the wet adhesive force (located on the surface) $F_{tot(locating)}$ is:

$$F_{tot\ (locating)} = F_{st} + F_c = -\pi r_{wet}^2 \Delta p + 2\pi r_{wet} \gamma \cos\theta_1. \quad (1)$$

Where γ is the coefficient of the surface tension of secretion, and Δp is the pressure between the inside and outside of the secretion, which can be calculated by:

$$\Delta p = \gamma(\cos\theta_1 + \cos\theta_2) / h. \quad (2)$$

When the wet adhesive pads move on the wall, the processes of adsorbing the wall surface, and peeling are rapidly carried out through the alternate glutinosity force F_g, which is:

$$F_{g} = \pm \frac{dh}{dt} \frac{3\pi\eta r_{wet}^4}{2h^3} \tag{3}$$

where η is the coefficient of glutinosity, then the wet adhesive force (move on the surface) $F_{tot(move)}$ is:

$$F_{tot\,(move)} = F_{st} + F_c + F_{g} = -\pi r_{wet}^2 \Delta p + 2\pi r_{wet} \gamma \cos\theta_1 \pm \frac{dh}{dt} \frac{3\pi\eta r_{wet}^4}{2h^3}. \tag{4}$$

Eq. 1 and Eq. 4 show that the normal wet adhesive force increases with the increase in the contact area. Furthermore, from Eq. 4, it is clea that the wet adhesive force also depends on the change rate of the thickness of the secretion film when the pad moves on the wall.

FABRICATION OF WET ADHESIVE PADS

In this study, electroforming with a SU-8 photoresist mold combined with soft lithography using PDMS were investigated with the view to fabricate biomimetic wet adhesive pads with surface microstructures. The proposed approach consists of three fabrication steps: (1) fabrication of SU-8 photoresist mold; (2) electroforming process; (3) soft lithography replication using PDMS. Fig. 3 shows the simplified procedures.

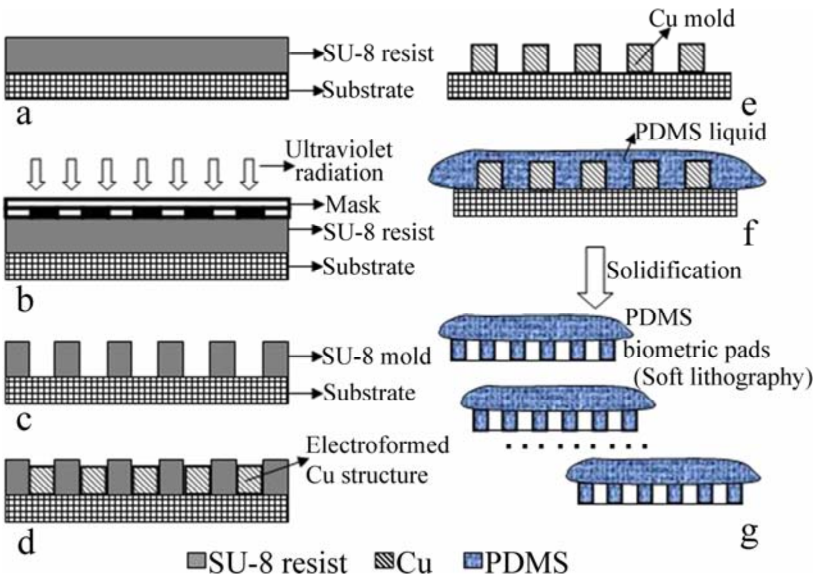

Fig. 3. Procedures of fabricating biomimetic wet adhesive pads. (a) SU-8 photoresist casting; (b) UV exposure; (c) bake and development; (d) electroforming; (e) SU-8 mold removal; (f) PDMS casting; (g) soft lithography repeatedly

In the first process, the photoresist is spin coated on the conductive substrate and is exposed to an ultraviolet radiation to form a patterned resist structure, which is used as an electroforming mold. SU-8 50 photoresist was chosen for the process, and the 100µm-thick SU-8 film was used as a coating on a stainless steel substrate, as shown in fig. 3,*a*. The temperature of the substrate with the SU-8 photoresist rose up to 65^0C, and was kept as such for 30 min, then the temperature was raised to 95^0C, with a 10^0C/min ramping rate, and this the temperature was kept for 30 min. After that, the substrate was cooled down to room temperature.

A chromium mask with amicro scale pattern, inspired by wet adhesive insects' pads, was fabricated by commercial plate-making machining. The pattern on the mask was square, with the side length of 100 µm and thickness of 1 µm. Then a traditional mask aligner was exposed to ultraviolet radiation, which is shown in fig. 3,*b*. After the post-exposure bake process, the substrate with a photoresist was developed using pure propylene glycol methyl ether acetate (PGMEA) for 1 hour, then rinsed with isopropyl alcohol, as shown in fig. 3,*c*. In this way the SU-8 photoresist mold was obtained for the following electroforming process.

In the process of electroforming, the substrate with the SU-8 photeresist was electroformed, as shown in fig. 3,*d*. The electrodeposition of Cu was carried out in an acid sulfate copper solution. The substrate connected by a lead line was the cathode, and a stainless steel board with the thickness of 1mm after polishing was used as the anode. The cathode was positioned horizontally, 20 mm from the anode, facing each other. The electrolyte in the bath contained $CuSO_4 \cdot 5H_2O$ 250 g/l, H_2SO_4 60 g/l, NaCl 0.08 g/l. The NaCl, which was put in the electrolyte as an additive, could activate the surface of the anode in order to accelerate the dissolution of the anode. All solutions were prepared by distilled water. The operating temperature was 35–40^{0}C. Pulses supply with t_{on} of 50 μs, t_{off} of 50 μs, and frequency of 3333Hz were used in the process. The thickness of the deposition metal was kept at about 25 μm by controlling the current density and deposition time. After electroforming, the product with the SU-8 photoresist was immersed in an 80^{0}C NANO^{TW} Remover PG solution for 2 hours to separate the Cu mold, as shown in fig. 3,*e*. The Cu mold with the electroformed surface microstructures was evaluated by a scanning electron microscope (SEM), as shown in fig. 4. The width of the microstructure was 20 μm, and the parietal angle was close to 90^0.

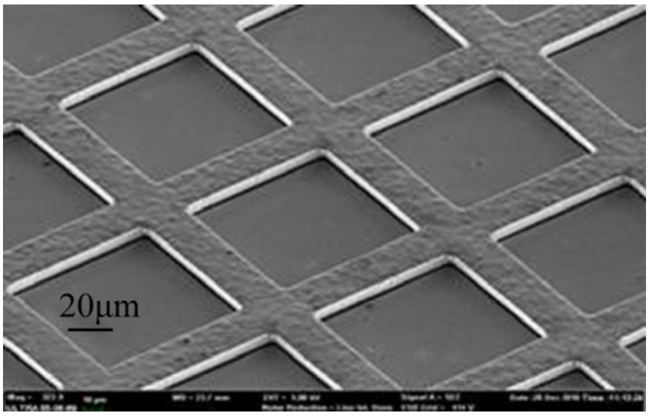

Fig. 4. Cu mold with surface microstructures by electroforming

In the process of soft lithography, PDMS used was a mixture of a PDMS precursor and a curing agent (Sylgard 184, DowCorning) with the volume ratio of 10:1. After sufficient stirring, the liquid mixture was put into a chamber with a reduced pressure for 10 min to remove air bubbles, and then it was directly poured onto the Cu mold electroformed. All this, as a whole, was treated at 65^{0}C for 2 hours in a furnace to achieve a PDMS prepolymer, as shown in fig. 3,*f*. The solidified PDMS microstructures were manually peel from the Cu mold. The soft lithography process can be easily repeated in the same Cu mold, as shown in fig. 3,*g*. Fig. 5 is a SEM photo of PDMS prepolymer with surface microstructures, which can be glued on the foot of a climbing robot as biomimetic wet adhesive pads.

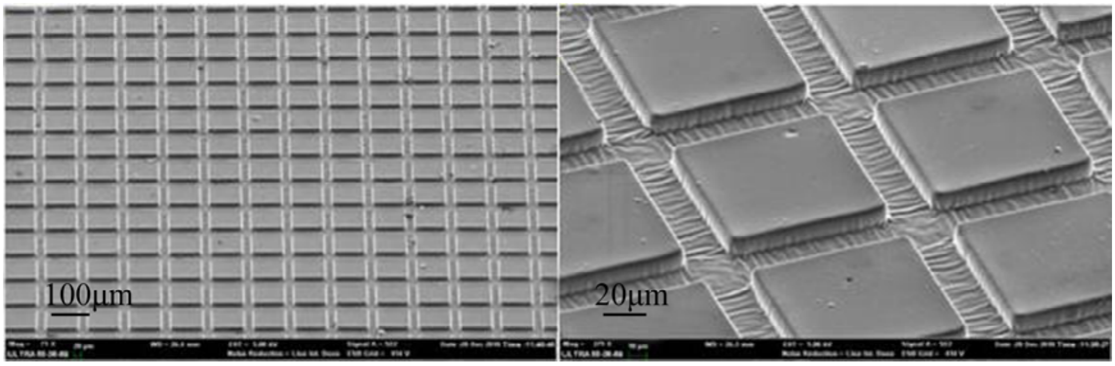

Fig. 5. PDMS biomimetic wet adhesive pad with surface microstructures. (a) microstructures array; (b) amplificatory photo of the microstructures

TESTING OF WET ADHESIVE FORCE

The wet adhesive force of biomimetic pads with/without surface microstructures are test- contradistinctive with various preloads and velocities of peel. The testing system was a set up based on a two-dimensional micro-force sensor with the resolution of 0.001N, as shown in fig. 6. The system also contained a motion stage with a servo motor, a data acquisition module, biomimetic wet adhesive pads, an out-of-flatness surface and the data processing software.

Before the force testing process, blob water was daubed on the surface and then wiped out after 2 min in order to form a liquid film with the thickness of 10 μm. The wet adhesive pad was approaching the surface vertically, at the speed of 10 mm/s, until the given preload between the pad and the surface was obtained. Then the direction of the motion was reversed, and the pad was moving away from the surface at various velocities, while a micro-force sensor was collecting signals during the entire process. The wet adhesive force of the pad could be track-recorded with the testing software. The experiments of the wet adhesive force with the peel velocity of 0.6 mm/s were carried out at various preloads, as shown in fig. 7. The results of the experiments with the peel velocity of 0.3 mm/s, carried out under the same conditions, at various preloads, are shown in fig. 8.

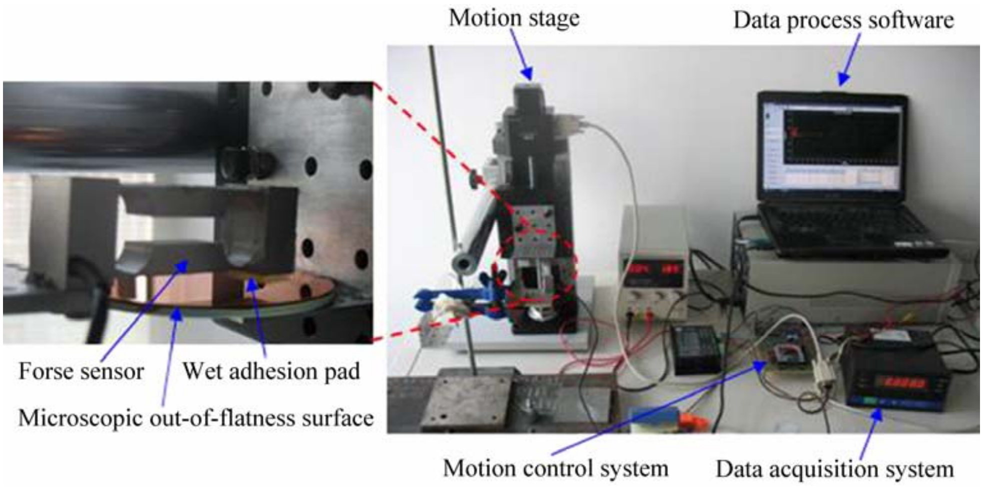

Fig. 6. Photo of testing system of wet adhesive force

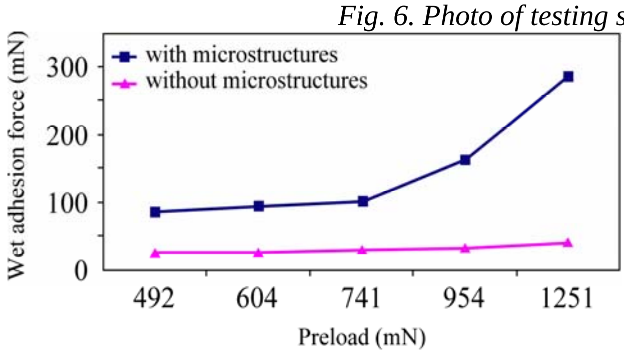

Fig. 7. Effect on wet adhesive force with pads' surface microstructures in peel velocity of 0.6 mm/s

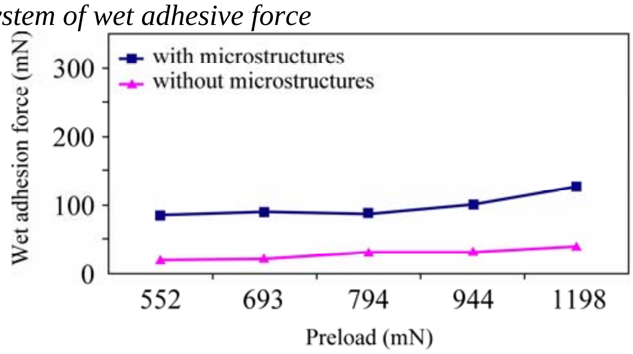

Fig. 8. Effect on wet adhesive force with pads' surface microstructures in peel velocity of 0.3 mm/s

From Eq. 1 and Eq. 4 it is clea that the wet adhesive force increases with the increase in the contact area. In general, the array of surface microstructures on wet adhesive pads can significantly inlarge the contact area, if compared with pads without microstructures. So, in theory, surface microstructures on biomimetic wet adhesive pads can improve the wet adhesive force.

The experimental results in fig. 7 and fig. 8 show that the adhesive power of the pads with microstructures fabricated by the proposed technique is effectively enhanced in comparison with that of pads without microstructures, i.e. there is the improvement of wet adhesive ability. The model analysis of the wet adhesive force is in good agreement with experimental results. In addition, it was also experimentally observed that the wet adhesive force increased with the increase in preload.

CONCLUSION

A novel approach for fabricating biomimetic wet adhesive pads with surface microstructures is proposed in this paper. According to the principle of wet adhesive of insects' pads, the wet adhesion mechanism has been analyzed. The process of fabricating biomimetic wet adhesive pads has been developed by combining the electroforming with soft lithography replication. PDMS pads with surface microstructures with the width of 100 μm and height of 25 μm have been obtained experimentally. A series of testing experiments have been carried out to prove that microstructures on the surface of pads fabricated by the proposed technique can effectively improve the wet adhesive ability.

ACKNOWLEDGMENTS

The work was financially supported by the Natural Science Foundation of China (51105279, 61040056), Shanghai Key Project of Foundation funding (09JC1414600), Huo Yingdong Foundation for basic research (121064), the National Basic Research Program of China (973 Program: 2011CB013800), and the “Chen Guang” project supported by Shanghai Municipal Education Commission and Shanghai Education Development Foundation (10CG20).

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Received 24.10.11
Accepted 25.11.11

Реферат

Биомиметические адгезизионные прокладки, включающие волосяные и жидкие адгезионные прокладки, представляют интерес для применения в самоподъёмных роботах. В данной работе предлагается новая методика получения биомиметических адгезионных прокладок со смазочным слоем и поверхностной микроструктурой, получаемой посредством электроформинга в сочетании с мягкой литографией. В соответствии с принципом адгезии на основе увлажнения лапок насекомых исследовался механизм такой адгезии. Экспериментально были получены биомиметические адгезизионные прокладки с поверхностной микроструктурой шириной 100 микрометров и толщиной 25 микрометров, на основе полидиметилсилоксана. Был проведен ряд экспериментов, подтверждающих, что микроструктура поверхностного слоя, полученного по предлагаемой методике, значительно улучшается.