Tunable adhesion of a bio-inspired micro-pillar arrayed surface actuated by a magnetic field

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Abstract

Bio-inspired functional surfaces attract many research interests due to the promising applications. In this paper, tunable adhesion of a bio-inspired micro-pillar arrayed surface actuated by a magnetic field is investigated theoretically in order to disclose the mechanical mechanism of changeable adhesion and the influencing factors. Each PDMS micro-pillar reinforced by uniformly distributed magnetic-particles is assumed to be a cantilever beam. The beam's large elastic deformation is obtained under an externally magnetic field. Specially, the rotation angle of the pillar's end is predicted, which shows an essential effect on the changeable adhesion of the micro-pillar arrayed surface. The larger the strength of the applied magnetic field, the larger the rotation angle of the pillar's end will be, yielding a decreasing adhesion force of the micro-pillar arrayed surface. The difference of adhesion force tuned by the applied magnetic field can be a few orders of magnitude, which leads to controllable adhesion

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of such a micro-pillar arrayed surface. Influences of each pillar's cross section shape, size, intervals between neighboring pillars and the distribution pattern on the adhesion force are further analyzed. The theoretical predictions are qualitatively well consistent with the experimental measurements. The present theoretical results should be helpful not only for the understanding of mechanical mechanism of tunable adhesion of micro-pillar arrayed surface under a magnetic field, but also for further precise and optimal design of such an adhesion-controllable bio-inspired surface in future practical applications.

Keywords: Micro-pillar arrayed surface; magnetic field; tunable adhesion; mechanical mechanism; large elastic deformation.

1. Introduction

Many animals and insects possess strong and reversible adhesion on many surfaces, which has been attracting scientific research interests in order to disclose the mysterious mechanical mechanisms and fabricate bio-mimetically novel materials and devices [1-5]. Gecko, as a typical example, is capable of climbing on a vertical wall and even on a ceiling [6, 7]. The mechanism underlying such a reversible adhesion behavior is mainly attributed to the elaborate hierarchical adhesion system [4, 5]. It has been experimentally proved that the basic principle adopted by gecko is the van der Waals interaction [6, 7], while the capillary force [8, 9] and the electrostatic force [10] may also play significant roles.

In order to disclose the inherent mechanism of gecko adhesion and the influencing factors, many works have been carried out experimentally and theoretically [11-21]. The adhesive contact mechanics is often used to study the macro-adhesion mechanism of gecko. The oblique array and the hierarchical properties of gecko adhesion system were modeled as an anisotropic material [11], a graded material [12] and a hierarchical material [13-15]. It was found that the reversible adhesion could be achieved by changing the loading direction, which has been successfully proved by a bio-inspired experiment [16]. The graded and the hierarchical features are helpful for the strong adhesion [12-14]. In order to study the micro-adhesion mechanism, Gao et al. [13] modeled a gecko seta as a cylinder fiber, and found that saturation of the interfacial adhesion strength could be achieved as the radius of fiber is smaller than a

critical size. Arzt et al. [4] found that splitting of a single contact into multiple smaller

contacts can result in adhesion enhancement. Considering the real profile of gecko

spatula, which is similar to a nano-thin film, the classical Kendall's peeling model [17]

and the frictional adhesion model [18, 19] are often used to study the peeling behavior

of a gecko spatula. It is found that the adhesion force is significantly influenced by the

peeling angle, with which reversible adhesion between strong attachment and easy

detachment can be achieved [18-20]. It has been widely accepted that gecko's

reversible adhesion is realized mainly by the peeling behavior of its spatula pad [14,

21].

Inspired by geckos' adhesion system and adhesion mechanism, bio-inspired

surfaces with micro- or nano-pillars have been successfully synthesized in order to

study gecko adhesion in much more complex conditions, such as coupled temperature

and humidity environment [22], underwater [23], and contaminated surface [24], by

precisely adjusting the aspect ratio, tilting angle, contact shape and distribution

patterns [25-28]. The adhesion strength of these bio-inspired synthetic surfaces could

match and even pass the adhesive ability of geckos. However, how to realize

reversible or tunable adhesion and how to fabricate spatula-like contact tip still need

further investigations.

Fortunately, recent experiments found that micro-pillar arrayed surfaces could

change the real contact area yielding tunable adhesion strength [28-30]. Two types of

approaches are usually adopted to tune the surface contact area. The first way is

through elastic large deformation of wedge-shape arrayed surfaces [31-33]. Through a

loading–dragging–pulling (LDP) process, polymeric micro-wedges can be easily bent

by the friction force, inducing a dramatically increasing contact area. Such a friction

induced adhesion can be potentially used in micro-gravitational outer space for

grasping and manipulating uncooperative objects [33]. Detachment can also be

conveniently achieved by releasing the applied load to achieve the un-deformed state.

Another way to change the contact area is via an external field. Drotlef et al. [34] have

successfully prepared magnetic-particle contained PDMS micro-pillar arrayed

surfaces, which would undergo significant bending deformation in response to an

applied magnetic field. Thus, tunable adhesion could be realized by a varying

magnetic field. Gillies et al. [35] studied the controllable particle adhesion with a

magnetically actuated synthetic gecko adhesive, and also found that the adjustable

adhesion could be achieved by the bending deformation of gecko-inspired

micro-ridges under a magnetic field. The two methods to achieve tunable adhesion are

well proposed [31-35]. However, in real applications, both precise design and

accurate control are further required. How to achieve the industrialization in the future

needs systematically theoretical analysis since some main factors cannot be

systematically analyzed in the experiment due to the difficulty of sample preparation.

What factors would influence the tunable adhesion still needs systematically

theoretical analysis.

The present paper is mainly based on the well-done experiment by Drotlef et al.

[34], in which micro-pillar arrayed surfaces with each micro-pillar filled with magnetic particles were fabricated. When an external magnetic field was applied, the micro-pillars on the surface would deform due to the magnetic force. Then, a spherical indenter was used to measure the adhesion force at each deformed configuration [34]. Only the van der Waals force between the spherical indenter and the deformed micro-pillar arrayed surface was mainly measured, similar to the geckos' adhesion mechanism. The van der Waals force between a single micro-pillar and the indenter is usually very small, but the whole adhesion force will be large enough due to the cumulative effect. It was found that the whole adhesion force of such a micro-pillar arrayed surface could be tuned by the external magnetic field.

In the present paper, a flat substrate is adopted to investigate the interaction force between deformed micro-pillar array and this flat substrate. First, the single micro-pillar is assumed to be a cantilever beam, whose elastic large bending deformation induced by an applied magnetic field is derived. Based on the bending configuration of the beam, closed-form solutions to adhesion strength of a single micro-pillar and a micro-pillar arrayed surface are further obtained. The effects of the micro-pillar cross section shape, size, intervals between neighboring pillars and the distribution pattern on the adhesion strength are analyzed in details. Comparison of the theoretical prediction and the experimental measurement is carried out finally. The results in the present paper should be helpful for further precise design of adhesion-tunable surfaces and devices.

2. Large bending deformation of a micro-pillar induced by a magnetic field

According to the experimental sample [34], the schematic of a magnetic particle reinforced PDMS micro-pillar arrayed surface is shown in Fig. 1(a), in which the height and width of each pillar are denoted as H and a, respectively. The interval between neighboring pillars is b. In Drotlef et al.'s experiment [34], the NdFeB micro-particles were provided by a commercial company. The shape and size of the particles cannot be absolutely identical. The NdFeB particles have platelet- or flake-like shape with an average size of 5μm [34]. For a theoretical model, even for a finite element model, the micro-particles in such a case are commonly assumed to be spherical ones with the same size without loss of generality.

In the experimental sample [34], all the magnetic particles in a micro-pillar are assumed to distribute continuously and uniformly in the height direction and be magnetized vertically. The externally applied magnetic field is exerted horizontally as shown in Fig. 1(a). The magnetic moment $\mathbf{p}_m$ that quantifies magnetization of one particle can be expressed as [36]

$$\mathbf{p}_m = \frac{\mu_r - 1}{\mu_0 \mu_r} v \mathbf{B}_R \tag{1}$$

where $\mu_0 = 4\pi \times 10^{-7} \,\mathrm{N \cdot A^{-2}}$ is the permeability of vacuum, μ_r, v, $\mathbf{B}_R$ are the relative permeability, volume and remanence of the particle, respectively. In the applied magnetic field, each magnetic particle gets a force moment, which can be

expressed as the cross product of the magnetic moment $\mathbf{p}_m$ and the magnetic flux

density $\mathbf{B}$ [34]

$$\mathbf{M} = \mathbf{p}_m \times \mathbf{B} \qquad (2)$$

Each pillar is subjected to continuously distributed force moment and produces

large bending deformation as shown in Fig. 1(b).

According to Drotlef et al.'s experiment [34], the aspect ratio of each micro-pillar is

about 5, which can be reasonably assumed as an Euler-Bernoulli cantilever beam.

Under the magnetic field, the tilting angle of each micro-pillar can reach to

approximately 90°. Therefore, geometrical large-deformation theory should be used to

analyze the bending deformation of the micro-pillar.

Considering large elastic deformation of the pillar, a curvilinear coordinate system

(s, θ) and a rectangular coordinate system (x, y) are introduced in Fig. 2(a) with the

coordinate origin fixed at the bottom of the pillar, respectively. s denotes the arc

length of the neutral axis from the origin, θ is the rotation angle of each point on the

neutral axis at s. The relation between the two coordinate systems is $\mathrm{d}x = \mathrm{d}s \cos\theta$

and $\mathrm{d}y = \mathrm{d}s \sin\theta$.

Substituting Eq. (1) into Eq. (2) yields $\mathbf{M} = \dfrac{\mu_r - 1}{\mu_0 \mu_r} v\mathbf{B}_R \times \mathbf{B}$. At the initial moment

when the magnetic field is acted, the micro-pillar will keep a vertical configuration.

The direction of the remanence of the particle $\mathbf{B}_R$ is perpendicular to the applied

magnetic flux density $\mathbf{B}$. Thus, the force moment is a constant $M = \dfrac{\mu_r - 1}{\mu_0 \mu_r} VB_R B$,

which distributes uniformly along the micro-pillar. When the bending deformation of the micro-pillar occurs, the angle between the two vectors $\mathbf{B}_R$ and $\mathbf{B}$ is $\pi/2 - \theta$ as shown in Fig. 1(c). In this case, the force moment becomes

$$M(s,\theta) = \frac{\mu_r - 1}{\mu_0 \mu_r} V B_R B \cos\theta \qquad (3)$$

where V is the particle volume per unit arc length. Due to the bending deformation, the rotation angle θ is a function of the arc length s. From Eq. (3), it is easy to find that the force moment M varies with the arc length s along the deformed micro-pillar.

The principle of minimum potential energy, as a basic method, is widely adopted to achieve the deformation of structures [37-39]. In the present paper, the principle of minimum potential energy is used to find the bending profile of each micro-pillar induced by the magnetic field.

The potential energy of a single micro-pillar can be written as

$$\Pi = \frac{1}{2} \int_0^H \bar{E} I \theta'^2 \mathrm{d}s - \int_0^H \mathrm{d}s \int_0^\theta M(s,\theta) \mathrm{d}\theta + \int_0^H \lambda_1 (x' - \cos\theta) \mathrm{d}s + \int_0^H \lambda_2 (y' - \sin\theta) \mathrm{d}s \qquad (4)$$

where the first term on the right-hand side is the elastic bending energy, $\bar{E}I$ is the bending stiffness of the pillar. It should be noted that here $\bar{E}$ denotes the effective Young's modulus of the pillar, which is actually a particle reinforced polymer matrix composite. The second term is the potential of the force moment $M(s,\theta)$ induced by the magnetic field. λ_1 and λ_2 are two Lagrange multipliers enforcing the additionally geometrical conditions $\mathrm{d}x = \mathrm{d}s \cos\theta$ and $\mathrm{d}y = \mathrm{d}s \sin\theta$.

The boundary conditions at the fixed end of the pillar can be expressed as

$$\theta(0)=0, \ x(0)=0, \ y(0)=0 \tag{5}$$

The variation of Eq. (4) and the principle of minimum potential energy lead to

$$
\begin{aligned}
\delta\Pi = {} & \int_0^H \left[-\bar{E}I\theta'' - M(s,\theta) + \lambda_1\sin\theta - \lambda_2\cos\theta \right]\delta\theta\,ds - \int_0^H \lambda_1'\delta x\,ds - \int_0^H \lambda_2'\delta y\,ds \\
& + \int_0^H (x' - \cos\theta)\delta\lambda_1\,ds + \int_0^H (y' - \sin\theta)\delta\lambda_2\,ds \\
& + \left(\bar{E}I\theta'\delta\theta + \lambda_1\delta x + \lambda_2\delta y \right)\Big|_0^H \\
= {} & 0
\end{aligned}
\tag{6}
$$

Given the arbitrariness of the variation and considering the boundary conditions in Eq.

(5) yield

$$\bar{E}I\theta'' + M(s,\theta) - \lambda_1\sin\theta + \lambda_2\cos\theta = 0 \tag{7}$$

$$\lambda_1' = 0, \ \lambda_2' = 0 \tag{8}$$

$$x' - \cos\theta = 0, \ y' - \sin\theta = 0 \tag{9}$$

with additional boundary conditions

$$\theta'(H) = 0, \ \lambda_1(H) = 0, \ \lambda_2(H) = 0. \tag{10}$$

Combining Eqs. (8) and (10) results in vanishing λ_1 and λ_2. The governing

equation (7) and the boundary conditions in Eqs. (5) and (10) can be rewritten in a

dimensionless form

$$
\begin{aligned}
& \bar{\theta}''(\bar{s}) + \bar{B}\cdot\cos\bar{\theta}(\bar{s}) = 0 \\
& \bar{\theta}(0) = 0, \ \bar{\theta}'(1) = 0
\end{aligned}
\tag{11}
$$

where $\bar{B}(\bar{s},\bar{\theta}) = \dfrac{(\mu_r - 1)B_R B}{\mu_0\mu_r}\dfrac{VH^2}{\bar{E}I}$ is the dimensionless magnetic field strength and

$\bar{\theta}$ stands for the tangential angle with $\bar{s} = s/H$. Eq. (11) belongs to a typical

boundary value problem of nonlinear ordinary differential equation, which can be solved numerically with a standard shoot method.

The deformed neutral axis of a micro-pillar induced by different applied magnetic fields is shown in Fig. 2(b), in which the deflection of the micro-pillar increases with increasing magnetic field strength.

3. Adhesion force of a deformed micro-pillar under a magnetic field

Fig. 3(a) shows a deformed micro-pillar arrayed surface interacting with an approaching flat substrate, which is different from the spherical indenter in the experiment [34].

In fact, in order to consider the adhesion problem of an elastic fiber or fiber arrays and a substrate, two kinds of model can be adopted. The first one is the contact model with a bilateral crack at the contact interface and an external load is assumed to pull or push two contact solids, which can be regarded as a model based on the continuum mechanics [13, 40-47]. In this model, the interface adhesive energy is introduced. Contact mechanics and fracture mechanics are used to find the interfacial stress field. Griffith fracture criterion is then adopted to find the relation between the external force and the contact size, from which the pull-off force of the adhesive interface can be achieved. Sometimes, the stress intensity factor is found from the fracture mechanics manual and the Griffith criterion is directly used to study the size effect of contact elements. Or the concept of interface flaw tolerance is adopted directly for a fiber in adhesive contact with a substrate, if the diameter of the fibers is less than a critical size.

Then, the interfacial traction can be regarded as a uniformly distributed force and has nothing to do with the tip shape or deformation. The interface strength achieves the theoretical one. The second kind of model is mainly to find the interaction force between two approaching solids from the atomic interaction point of view. External load does not exist and only atom-atom interaction works between two approaching solids. Volume integral of L-J potential is usually used to find the whole interaction between the two approaching solids. In this kind of model, the effect of the deformation of the two approaching solids on the interaction force is often neglected due to the very small atomic lattice deformation and the difficulty of obtaining an exact solution under atom-atom interactions.

In this paper, we adopt the second kind of model to investigate the interaction between a deformed micro-pillar and a flat substrate, in which no external load exists and only the atom-atom interaction does. In addition, it is assumed that the magnetic force induced by the magnetic field is much larger than the van der Waals force acted on each micro-pillar, so that the deformation of a micro-pillar induced by the magnetic force is considered and the subsequent deformation of a bended micro-pillar induced by the van der Waals force is neglected.

With the above discussion and assumption, the adhesion force between two approaching solids can be achieved with the help of the following Lennard-Jones (L-J) potential [48]

$$w(r) = 4\varepsilon\left[\left(\frac{\sigma}{r}\right)^{12} - \left(\frac{\sigma}{r}\right)^{6}\right] \tag{12}$$

where ε is a parameter determining the depth of the potential well, r is

atom-to-atom distance, and σ is a length scale parameter that determines the

position of the zero potential.

The adhesion between a vertical pillar and a flat surface has been studied in [49]

using the L-J potential method. For a bending pillar, the adhesion behavior is different

from that of a vertical one because of different contacting surface morphologies.

Furthermore, micro-pillars with flat tip but with different shaped cross sections will

be considered in the present paper. According to the usually fabricated experimental

samples, cases of square and circular cross sections are investigated. The bending

deformation of the magnetic particle reinforced micro-pillar results from the applied

magnetic field, which has been analyzed in section 2. Considering the effective

interaction distance of van der Waals force, the interaction between the micro-pillar

and the substrate is mainly contributed by the near-top volume of the micro-pillar.

Contribution of the part far from the contact surface is relatively very weak. Therefore,

for simplicity and without loss of generality, the bending micro-pillar can be treated as

a tilting one as shown in Fig. 3(b) and Fig. 3(c), where the curvature effect of the

bending micro-pillar is neglected, but the tilting angle φ at the top of the tilting

pillar takes the real rotation angle from the result of a deformed pillar under a

magnetic field, i.e., $\varphi = \bar{\theta}(1)$.

3.1 Adhesion force of a deformed pillar of a square cross section

The adhesion model between a pillar of a square cross section with a tilting angle φ and a substrate is shown in Fig. 3(b), in which the space between the pillar and the substrate is D. The tilting angle φ takes the real rotation value at the top of the magnetic particle reinforced pillar induced by an applied magnetic field.

After tedious derivation of the volume integration of L-J potential, the adhesion energy $W(D)$ between the tilting pillar and the substrate can be obtained as

$$
\begin{aligned}
W(D) &= \int_V w(r)\mathrm{d}V \\
&= \frac{4\pi\varepsilon\rho_1\rho_2 a}{\sin\varphi\cos\varphi}\left\{\left[\frac{1}{315}\left(1-\xi^7\right)-\frac{1}{360}\left(1-\xi^8\right)\right]\frac{\sigma^{12}}{D^7}-\left[\frac{1}{6}\left(1-\xi\right)-\frac{1}{12}\left(1-\xi^2\right)\right]\frac{\sigma^6}{D}\right\} \\
&\quad + \frac{4\pi\varepsilon\rho_1\rho_2 a^2}{\cos\varphi}\left[\frac{1}{360}\left(\xi^8-\eta^8\right)\frac{\sigma^{12}}{D^8}-\frac{1}{12}\left(\xi^2-\eta^2\right)\frac{\sigma^6}{D^2}\right]
\end{aligned}
$$

(13)

where ρ_1 and ρ_2 denote the atomic densities of the pillar material and substrate material, respectively. a is the side-length of the square cross section, and $\xi = D/(D+a\sin\varphi)$, $\eta = D/(D+a\sin\varphi+H)$ are two dimensionless parameters.

It should be noted that, in the present paper, the magnetic particle reinforced micro-pillar is considered as a continuum material. An effective atomic density $\rho_1 = v_m\rho_m + v_p\rho_p$ is adopted to denote the atomic density in the particle reinforced micro-pillar, where v_m and v_p are the volume fractions of the matrix and the particles in the composite material, ρ_m and ρ_p are the atomic densities of the pure matrix and particles, respectively.

The adhesion force between the deformed pillar of a square cross section and the

substrate can then be obtained as

$$F_{ad} = \frac{\partial W}{\partial D} = 4\pi\varepsilon\rho_1\rho_2 a^2\left(-\alpha\frac{\sigma^{12}}{D^9} + \beta\frac{\sigma^6}{D^3}\right)$$

(14)

where the two parameters are expressed as

$$\alpha = \frac{1}{\cos\varphi}\left\{\frac{\xi}{1-\xi}\left[\frac{1}{40}\left(1-\xi^8\right)-\frac{1}{45}\left(1-\xi^9\right)\right]+\frac{1}{45}\left(\xi^9-\eta^9\right)\right\}$$

$$\beta = \frac{1}{\cos\varphi}\left\{\frac{\xi}{1-\xi}\left[\frac{1}{4}\left(1-\xi^2\right)-\frac{1}{6}\left(1-\xi^3\right)\right]+\frac{1}{6}\left(\xi^3-\eta^3\right)\right\}$$

(15)

3.2 Adhesion force of a deformed pillar of a circular cross section

The adhesion model between a pillar of a circular cross section with a tilting angle φ and a substrate is shown in Fig. 3(c), where the diameter of the cross section of the pillar is a. D denotes the distance between the pillar and the substrate. Similar to the square cross section case, the adhesion energy between the titling circular pillar and substrate can be achieved as

$$W(D) = \frac{4\pi^2\varepsilon\rho_1\rho_2}{\cos\varphi\sin^2\varphi}\left\{\begin{array}{l}\left[\begin{array}{l}\xi^6\left(\frac{33}{8}F(13)-\frac{63}{8}F(11)+\frac{35}{8}F(9)-\frac{5}{8}F(7)\right)\\-\eta^6\left(\frac{33}{8}G(13)+\frac{63}{8}G(11)-\frac{35}{8}G(9)+\frac{5}{8}G(7)\right)\end{array}\right]\frac{\sigma^{12}}{360D^6}\\-\left[F(1)-G(1)\right]\frac{\sigma^6}{12}\end{array}\right\}$$

(16)

where $F(n) = \left[1-(1-\xi)^2\right]^{-n/2}$ and $G(n) = \left[1-\eta^2(1-\xi)^2/\xi^2\right]^{-n/2}$ with parameters $\xi = D/(D+a\sin\varphi/2)$ and $\eta = D/(D+a\sin\varphi/2+H)$.

The corresponding adhesion force can then be obtained as

$$F_{ad} = 4\pi\varepsilon\rho_1\rho_2\pi\left(\frac{a}{2}\right)^2\left(-\alpha\frac{\sigma^{12}}{D^9}+\beta\frac{\sigma^6}{D^3}\right)$$

(17)

where the two parameters are

$$
\alpha = \frac{1}{45\cos\varphi}\left(\frac{\xi}{1-\xi}\right)^2 \left\{ \begin{array}{l} \xi^7\left[\dfrac{429}{64}F(15)-\dfrac{231}{16}F(13)+\dfrac{315}{32}F(11)-\dfrac{35}{16}F(9)+\dfrac{5}{64}F(7)\right] \\ -\eta^7\left[\dfrac{429}{64}G(15)-\dfrac{231}{16}G(13)+\dfrac{315}{32}G(11)-\dfrac{35}{16}G(9)+\dfrac{5}{64}G(7)\right] \end{array} \right\}
$$

$$
\beta = \frac{1}{6\cos\varphi}\left(\frac{\xi}{1-\xi}\right)^2 \left\{ \xi\left[F(3)-F(1)\right]-\eta\left[G(3)-G(1)\right] \right\}
$$

$$(18)$$

3.3 Adhesion force with a unified form

Comparing Eqs. (14) and (17), we can write the adhesion force in a unified form

for cases of pillars with different cross sections

$$
\overline{F}_{ad} = \frac{F_{ad}}{4\pi\varepsilon\rho_1\rho_2\sigma^3 H^2} = \overline{A}\left[-\alpha\left(\frac{\sigma}{D}\right)^9+\beta\left(\frac{\sigma}{D}\right)^3\right]
\tag{19}
$$

where

$$
\overline{A} = \begin{cases} \overline{a}^2, & \text{for square pillar} \\ \dfrac{\pi\overline{a}^2}{4}, & \text{for circular pillar} \end{cases}
\tag{20}
$$

and $\overline{a} = a/H$. Dimensionless parameters α and β are expressed in Eqs. (15) for

square pillars and in Eqs. (18) for circular pillars, respectively.

When the applied magnetic field vanishes, the micro-pillar will restore to the

initially vertical configuration, i.e. $\varphi = 0$ and we have $\xi = 1$ and $\eta = D/(D+H)$.

The unified adhesion force in Eq. (19) can be reduced to

$$
\overline{F}_{ad0} = \frac{F_{ad0}}{4\pi\varepsilon\rho_1\rho_2\sigma^3 H^2} = \overline{A}\left[-\frac{\sigma^9}{45D^9}+\frac{\sigma^3}{6D^3}+\frac{\sigma^9}{45(D+H)^9}-\frac{\sigma^3}{6(D+H)^3}\right]
\tag{21}
$$

which is identical to the adhesion force between a flat punch and a substrate [49].

4. Adhesion force of deformed micro-pillar arrays under a magnetic field

On bio-inspired micro-pillar arrayed surfaces, the micro-pillars are always designed to distribute in a regular pattern, such as, triangular, square and hexagonal patterns [29, 50, 51]. The adhesion behavior of a fibrillar array has been widely investigated with the contact mechanics and fracture mechanics method. Significant enhancement in adhesion of such a micro-pillar arrayed surface compared to that of a flat surface has been well explained from different points of view, for example, crack trapping, equal load sharing of each fibril, flaw tolerance [43-45, 51, 52]. In the present paper, the assumption of equal load sharing of each micro-pillar [44] is adopted due to the size of each pillar and the rigid substrate.

Fig. 4 gives three kinds of distribution patterns, i.e., triangular, square and hexagonal patterns for pillars of square and circular cross sections, respectively. Effects of the distribution pattern on the adhesion force will be analyzed. The area density ϕ of each kind of pillar array is defined as the ratio of each pillar's cross section area to the area encircled by a black dashed line as shown in Fig. 4. Thus, the area density ϕ can be expressed as $\phi = \phi_{\max} / (1 + \rho)^2$ [51], where we define $\rho = b/a$, a is the width or diameter of a pillar and b is the interval of neighboring pillars. $\phi_{\max}$ is the maximum area density of a given pillar pattern when the closest neighboring upright pillars begin to contact each other. For the array consisting of pillars of square cross-section, we have $\phi_{\text{squ-3-max}} = \sqrt{3}/2$ for a triangular pattern as

shown in Fig. 4(a), $\phi_{\text{squ-4-max}} = 1$ for a square pattern in Fig. 4(b) and $\phi_{\text{squ-6-max}} = \sqrt{3}/3$

for a hexagonal pattern in Fig. 4(c). It should be noted that not all pillars contact each

other for the cases of $\phi_{\text{squ-3-max}}$ and $\phi_{\text{squ-6-max}}$ since the regular triangle and regular

hexagonal patterns are assumed. For the array consisting of pillars of circular

cross-section, the corresponding maximal area densities are $\phi_{\text{cir-3-max}} = \pi/2\sqrt{3}$,

$\phi_{\text{cir-4-max}} = \pi/4$ and $\phi_{\text{cir-6-max}} = \pi/3\sqrt{3}$, respectively, as shown in Fig. 4(d)-Fig. 4(f). In

order to eliminate the effect of surface area, the adhesion force per unit area of

distribution patterns is adopted,

$$\overline{P}_{\text{ad}} = \frac{\overline{F}_{\text{ad}}\phi}{\overline{A}} = \frac{\overline{F}_{\text{ad}}\phi_{\max}}{\overline{A}(1+\rho)^2} \tag{22}$$

where $\overline{F}_{\text{ad}}$ and $\overline{A}$ are the adhesion force and the cross section area of a single pillar

given in Eqs. (19) and (20), respectively.

5. Results and discussion

In the present paper, the homogenization method is adopted to find the equivalent

mechanical property of particle reinforced composites, including the effective Young's

modulus of composite materials [53, 54]. The effect of ratio of the average particle

diameter to the micro-pillar diameter or side is actually included by the volume fraction

in the homogenization method.

Furthermore, in the experimental samples [34], surface roughness of each

micro-pillar can not be avoided too. However, the aim of the present paper mainly

focuses on the phenomenon of controllable adhesion force of the micro-pillar structure

induced by the magnetic field. The scale of concern is the micro-pillar magnitude

because the large deformation of each pillar is the main factor leading to the

controllable adhesion force. A fine theoretical model considering the effect of

micro-pillar surface roughness will be investigated in the future.

5.1 The case of a micro-pillar under a magnetic field

The tilting angle φ at the top of the tilting pillar depends nonlinearly on the

applied magnetic field $\bar{B}$, which can be found in Fig. 5. The stronger the magnetic

field, the larger the tilting angle will be.

When a flat rigid substrate approaches the tilting micro-pillar, the adhesion force

$\bar{F}_{ad}$ between the pillar and the substrate as given in Eq. (19) would be influenced not

only by the applied magnetic field $\bar{B}$ but also by the distance D/σ between the

tilting pillar and the substrate. The adhesion force for both square and circular pillars

with a given cross section area $\bar{A} = 0.01$ under magnetic fields of different strengths is

given in Fig. 6, where the adhesion force between the pillar and the substrate with

$\bar{B} = 0$ is also given for comparison. It is found that, for both square and circular pillars,

the adhesion force between the pillar and the substrate varies with the separation

distance in a van der Waals potential form. When the separation distance is relatively

small, the interfacial interaction is repulsive. As the separation distance between the

pillar and the substrate surpasses the equilibrium distance, at which the interfacial

interaction vanishes, the interaction becomes attractive. Afterwards, the attractive

force increases to a maximum and then drops quickly with the increasing separation

distance. Finally, the interfacial interaction tends to vanish. When the separation

distance is fixed, it is found that the adhesion force decreases with the increase of

magnetic field strength. The effect of the cross section shape on the adhesion force is

not very obvious only if the dimensionless cross section area $\bar{A}$ keeps the same. In

the case of a vanishing applied magnetic field, the adhesion force of both the square

and circular pillars are identical only if the dimensional cross section area remains the

same as shown in Eq. (21).

Furthermore, Fig. 6 shows that the maximal adhesion force decreases when the

applied magnetic field strength increases. Denote the maximal adhesion force as

$\bar{F}_{\text{strength}}$, the effect of the magnetic field strength on the maximal adhesion force is

depicted in Fig. 7 for both the square and the circular pillars of different cross section

areas $\bar{A}$, in which the parameter $\bar{\sigma} = \sigma/H = 3 \times 10^{-3}$ is adopted. It exhibits that the

maximal adhesion force increases with the increase of the pillar's cross section for a

fixed magnetic field strength. However, for a determined cross section area, the

maximal adhesion force decreases drastically with the increasing applied magnetic

field strength. Furthermore, the maximal adhesion force in all cases of different cross

section areas would approach zero only if the applied magnetic field strength is large

enough. All the results are mainly due to the effective interfacial interaction area,

which varies with the variation of the applied magnetic field strength. Bending

deformation of the micro-pillar would happen under an applied magnetic field, which

subsequently induce the rotation of the pillar top. As a result, the real interacting area

of the pillar with the substrate would decrease with the increase of the applied

magnetic field strength. Such a magnetism-induced tunable contact configuration

leads to tunable adhesion of a single pillar. Generally, the maximal adhesion force in

the case of a circular cross section is a little bit smaller than that in the case of a

square cross section when the dimensionless cross section area keeps the same.

5.2 The case of a micro-pillar array under a magnetic field

For a micro-pillar arrayed surface, the deformation of micro-pillar arrays will

influence the adhesion ability of the surface since the adhesion force of the surface

comes from the interaction between each pillar and the substrate. According to Eq.

(22), many parameters would show influence on the adhesion force of a micro-pillar

arrayed surface, such as the width or diameter of pillar a and the interval b

between neighboring pillars (i.e. the value of $\rho = b/a$), the dimensionless cross

section area $\bar{A}$, and the distribution pattern.

The maximal adhesion strength $\bar{P}_{\text{strength}}$ is introduced, which is defined as the

maximal adhesion force per unit area, i.e.,

$$\bar{P}_{\text{strength}} = \frac{\bar{F}_{\text{strength}}\phi}{\bar{A}} = \frac{\bar{F}_{\text{strength}}\phi_{\max}}{\bar{A}(1+\rho)^2} \tag{23}$$

Here, one can see that the maximal adhesion strength is a function of $\bar{A}$, ρ (i.e., $\bar{a}$

or $\bar{b}$), $\phi_{\max}$ and the maximal adhesion force.

For a micro-pillar with a square or circular cross section, once the width or

diameter of the pillar $\bar{a}$ is given, the cross section area $\bar{A}$ is determined. Then, the

value of $\rho = \bar{b}/\bar{a}$ for a micro-pillar arrayed surface in any kind of pattern depends

only on the interval $\bar{b}$. Since the maximal adhesion force of the surface is influenced

by the applied magnetic field strength, the relation between the maximal adhesion

strength and the applied magnetic field strength can be achieved for cases of different

intervals as shown in Fig. 8(a) for a square pillar arrayed surface in a square pattern

and Fig. 8(b) for the circular one in a square pattern, respectively, where the

parameters are $\bar{a} = 0.1$ and $\bar{\sigma} = \sigma/H = 3 \times 10^{-3}$. It is obvious that the maximal

adhesion strength decreases with the increase of the applied magnetic field strength in

the case of a certain interval $\bar{b}$. Furthermore, the maximal adhesion strength is

reduced by the increase of the interval of neighboring pillars in the case of a

determined applied magnetic field strength. Such a result should be very easily

understood since the larger the applied magnetic field strength, the larger the rotation

angle of each pillar's top is; and the larger the interval of neighboring pillars, the

smaller the area density of the pillar arrays is. As a result, the maximal adhesion force

would be reduced by the increase of the applied magnetic field strength or the interval

between neighboring pillars.

If the interval between neighboring pillars is fixed, the effect of the pillar's width

or diameter $\bar{a}$ on the maximal adhesion strength of the micro-pillar arrayed surface

in a square pattern can be obtained. Figs. 9(a) and 9(b) show the relation between the

maximal adhesion strength and the applied magnetic field strength for the square

pillar arrayed surface case and the circular one, respectively, where $\bar{b} = 0.1$ and

$\bar{\sigma} = \sigma/H = 3 \times 10^{-3}$. It is found that the maximal adhesion strength increases with the

increase of the pillar's width or diameter, especially for the case with a relatively weak

applied magnetic field strength. It means that the adhesion strength is proportional to the area density of pillar arrays. However, the maximal adhesion strength becomes insensitive to the pillar's width or diameter when the applied magnetic field strength is relatively large. It is due to the large deformation of pillars and the large rotation angle at pillar tips, both of which are induced by a strong applied magnetic field strength.

All the above effects of the width or diameter of pillars and the interval of neighboring pillars on the maximal adhesion strength are also true for micro-pillar arrayed surfaces in other distribution patterns.

The effect of distribution pattern of micro-pillar arrayed surfaces on the maximal adhesion strength is further investigated. Three kinds of distribution patterns as shown in Fig. 4, i.e., triangular, square and hexagonal ones, are taken into consideration for both square and circular micro-pillar arrayed surfaces. The relation between the maximal adhesion strength and the applied magnetic field strength is given in Fig. 10 for cases of different distribution patterns. All the parameters adopted in Fig. 10 are $\rho = 1$ with $\bar{a} = \bar{b} = 0.1$ and $\bar{\sigma} = \sigma/H = 3 \times 10^{-3}$. It is found that no matter what the distribution pattern of micro-pillar array is and what shape of each pillar's cross section is, the maximal adhesion strength always decreases with the increase of the applied magnetic field strength. However, the distribution pattern in cases of micro-pillars of different cross sections will show influence on the maximal adhesion strength of the micro-pillar arrayed surfaces, especially under a relatively weak applied magnetic field strength. For a square pillar arrayed surface, the maximal

adhesion strength in the case of square distribution pattern is much larger than that in

the case of triangular or hexagonal distribution pattern. While for a circular pillar

arrayed surface, the maximal adhesion strength in the case of triangular distribution

pattern is much larger than that in the case of square or hexagonal distribution pattern.

Among all the combining cases, the maximal adhesion strength of a square pillar

arrayed surface in a square pattern achieves the maximum, while the maximal

adhesion strength of a square pillar arrayed surface in a hexagonal pattern is the

smallest. It is interesting to find that the setal mat in geckos' foot is also arranged in a

tetrad pattern [23], which is well consistent with the present results. When the applied

magnetic field strength is relatively strong, difference of the effects of the distribution

pattern is not very obvious. The maximal adhesion in all the cases tends to vanish.

Comparing the maximal adhesion strength under different applied magnetic field

strength finds that there is an order of magnitude difference. It means that tunable

adhesion could be realized on such a bio-inspired micro-pillar arrayed surface by the

applied magnetic field. All the micro-pillars on the surface are vertical under a

vanishing external magnetic field, at which the maximal adhesion strength achieves

the maximum. While all the micro-pillars bend seriously and the maximal adhesion

strength approaches to zero when the applied magnetic field strength is large enough.

The adhesion of such a magnetic particle reinforced micro-pillar arrayed surface can

be well tuned by the applied magnetic field.

In order to attain good tunable adhesion performance, one can design a square

patterned surface consisting of pillars of a square cross section due to the largest area

density if the width and interval are determined. The circular pillar arrayed surface in

a triangular pattern might be also popular due to the second largest area density and

the easily preparation technology [29, 50].

From the theoretical analysis, it is found that the way to enlarge the pillar's width

and to reduce the interval between neighboring pillars at the same time can increase

the upper limit of the maximal adhesion strength. However, the pillar's width and the

interval cannot be adjusted randomly, which should avoid the adhesion between the

neighboring pillars due to the van der Waals interaction. Adhesion of neighboring

pillars may lead to cluster and prevent deformed pillars from restoring the initial

configuration in the absence of magnetic field. Such a problem has been studied by

Gao et al. [13] and Glassmaker et al. [42], respectively. Another issue in the present

investigated magnetic particle reinforced micro-pillar arrayed surface is that bending

deformation of neighboring pillars would happen in the same direction when an

external magnetic field is added. If the interval of neighboring micro-pillars decreases,

one of the pillar's edge would contact another one. Let φ_{cr} denote the critical tilting

angle, at which neighboring pillars contact each other due to the bending

deformation. Then, the contact condition as shown in Fig. 1(b) can be expressed as

$a+b=a/\cos\varphi_{cr}$. Considering $\rho=b/a$ yields the critical ratio $\rho_{cr}=1/\cos\varphi_{cr}-1$.

The relationship between the critical ratio ρ_{cr} and the applied magnetic field

strength $\bar{B}$ is further shown in Fig. 11, in which the critical curve divides the plane

into two regions: one is the no bundling (no contact) region of the upper left and another is the bundling (contact) region of the lower right. With the increase of the magnetic field strength $\bar{B}$, a relatively large interval b is needed and the width or diameter of the pillar a can not be arbitrarily large in order to avoid neighboring contact, which apparently contradicts with the condition of achieving strong and tunable adhesion. In fact, it gives a limiting condition on all the above results and discussion. Therefore, in practical fabrications and applications, comprehensive design of the ratio ρ is needed. It should be noted that all the values of ρ taken in the present work are valid in the no bundling region.

5.3 Comparison of the theoretical result and the experimental measurement

Corresponding to the present theoretical model, similar experiments have been well done by Drotlef et al. [34], in which the effect of magnetic field on the adheison of NdFeB micro-particle reinforced PDMS micro-pillar arrayed surfaces was investigated. Under an applied magnetic field, large bending deformation of the micro pillars was observed via microscopy. The adhesion force varying with the tilting angle of the pillars was measured with the help of adhesion tester with a spherical probe. It was found that the adhesion force decreased with an increasing tilting angle induced by the applied magnetic field (please see Fig. 3C in ref. [34]). Comparison of the experimental measurement and the present theoretical prediction as given in Fig. 12 shows good qualitative agreement.

It should be noted that quantitative comparison between the present theoretical

model and the experimental result can not be carried out due to several aspects: the first one is the adhesion force in experiment was measured between the micro-pillar arrayed surface and a spherical probe, while a flat substrate is adopted for simplicity in the present theoretical model; as a result the real interaction area between a micro-pillar arrayed surface and a spherical probe is difficult to obtain. The second one is some material parameters in experiments were not given, for example, the effecive Young' modulus of the pillar, the magnetic flux density, the bending stiffness of the pillar, etc. Besides the van der Waals force, the electrostatic and capillary interactions between the micro-pillar array and substrate are hardly to avoid in experiment [55], which is not considered in the present theoretical model. However, similar mechanism underlying the magnetic field actuated tunable adhesion of a micro-pillar arrayed surface found in experiment can be reasonably predicted in the present theoretical analysis and qualitative prediction of the adhesion force and adhesion strength influenced by several factors in the theoretical model should be helpful for further precise designs of reversible or tunable adhesive sensors.

6. Conclusions

Inspired by tunable adhesion of a magnetic particle reinforced PDMS micro-pillar arrayed surface actuated by an applied magnetic field, we establish theoretical models to analyze the mechanical mechanism of tunable adhesion and the main influencing factors of adhesion. Large deformation of each pillar is considered and surfaces consisting of micro-pillars of square and circular cross sections are investigated. The

adhesion mechanism of a single pillar is studied first. The tunable adhesion is mainly

due to the varying rotation angle of the pillar's tip, which results from the large

deformation of pillars induced by the applied magnetic field. Further analysis of

micro-pillars of different cross sections distributing in different patterns is carried out.

It is found that under a fixed magnetic field, the adhesion between a micro-pillar

arrayed surface and a substrate varies with the separation distance in a van der Waals

interaction form, in which a maximum adhesion strength exists. The maximum

adhesion strength in each case decreases with the increase of the applied magnetic

field strength, leading to tunable adhesion. Analysis of the influence of pillar's cross

section shapes, the intervals between neighboring pillars and the distribution patterns

exhibits that the surface consisting of square pillars distributing in a square pattern

would possess the best tunable adhesion feature if the cross section area is fixed. All

the theoretical results agree well with the existing experimental measurements

qualitatively [34] and should be helpful for precise design of bio-inspired functional

surfaces of reversible or tunable adhesion in the future.

Acknowledgements

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Figure captions

Fig. 1   Schematics of the theoretical model. (a) The model of a magnetic particle

reinforced PDMS micro-pillar arrayed surface, in which the height and width

of each pillar are H and a. b denotes the interval of neighboring pillars.

The micro-pillars keep vertical without an applied magnetic field. (b) Under an

applied magnetic field $\mathbf{B}$, large bending deformation happens for

micro-pillars. φ is the rotation angle at the pillar's top. (c) The relation of

vectors of the remanence $\mathbf{B}_R$, the magnetic field $\mathbf{B}$ and the moment $\mathbf{M}$

acting on a single particle. Here, θ is the rotation angle of the pillar where the

particle locates.

Fig. 2   Schematics of large deformed cantilever beam model. (a) A rectangular

coordinate system $(x,\, y)$ and a curvilinear coordinate system $(s,\, \theta)$ are

attached on the initial and deformed configurations, respectively. (b) The

profiles of a deformed cantilever beam under different magnetic field strength.

Fig. 3   Schematics of the interaction between a micro-pillar arrayed surface and a

substrate. (a) Under an applied magnetic field, the deformed micro-pillars are

approached by a substrate, where D is the separation distance and φ is the

rotation angle at the pillar's top. (b) A tilting square shaped micro-pillar

interacts with a substrate, where a is the width of the square cross section. (c)

A tilting circular micro-pillar interacts with a substrate, where a is the

diameter of the circular cross section.

Fig. 4   Top views of micro-pillar's distribution patterns. (a)-(c) Triangular, square and

hexagonal distribution patterns for square pillars; (d)-(f) Triangular, square and

hexagonal distribution patterns for circular pillars. The area surrounded by

dashed lines denotes one cell of the pattern. The maximal area density in each

pattern is given at the bottom of each figure.

Fig. 5   The relation between the rotation angle of the pillar's top φ and the applied

magnetic field strength $\bar{B}$.

Fig. 6   The dimensionless adhesion force $\bar{F}_{ad}$ between a single tilting pillar and a

substrate as a function of the separation distance D/σ under different

magnetic field strength, where the cross section area is taken as $\bar{A} = 0.01$ for

both square and circular pillars. ($\bar{\sigma} = \sigma/H = 3\times10^{-3}$)

Fig. 7   The dimensionless maximal adhesion strength $\bar{F}_{strength}$ varying with the applied

magnetic field $\bar{B}$ for both square and circular cross section cases with the

cross section area of $\bar{A} = 0.01$, 0.0225 and 0.04, respectively.

($\bar{\sigma} = \sigma/H = 3\times10^{-3}$)

Fig. 8   The dimensionless maximal adhesion strength $\bar{P}_{strength}$ as a function of the

applied magnetic field strength $\bar{B}$ for micro-pillar arrays distributed in a

square pattern but with different intervals $\bar{b}$ between neighboring pillars. (a)

For the case of square cross section. (b) For the case of circular cross section.

In both cases, $\bar{a} = a/H = 0.1$ and $\bar{\sigma} = \sigma/H = 3\times10^{-3}$.

Fig. 9   The dimensionless maximal adhesion strength $\bar{P}_{strength}$ as a function of the

applied magnetic field strength $\bar{B}$ for micro-pillar arrays distributed in a

square pattern but with pillars of different widths or diameters $\bar{a}$. (a) For the

case of square cross section. (b) For the case of circular cross section. In both

cases, $\bar{b} = b/H = 0.1$ and $\bar{\sigma} = \sigma/H = 3\times10^{-3}$.

Fig. 10 The dimensionless maximal adhesion strength $\bar{P}_{\text{strength}}$ varying with the

applied magnetic field strength $\bar{B}$ for both square and circular micro-pillar

arrays but with different distribution patterns, where $\rho = 1$ with $\bar{a} = \bar{b} = 0.1$
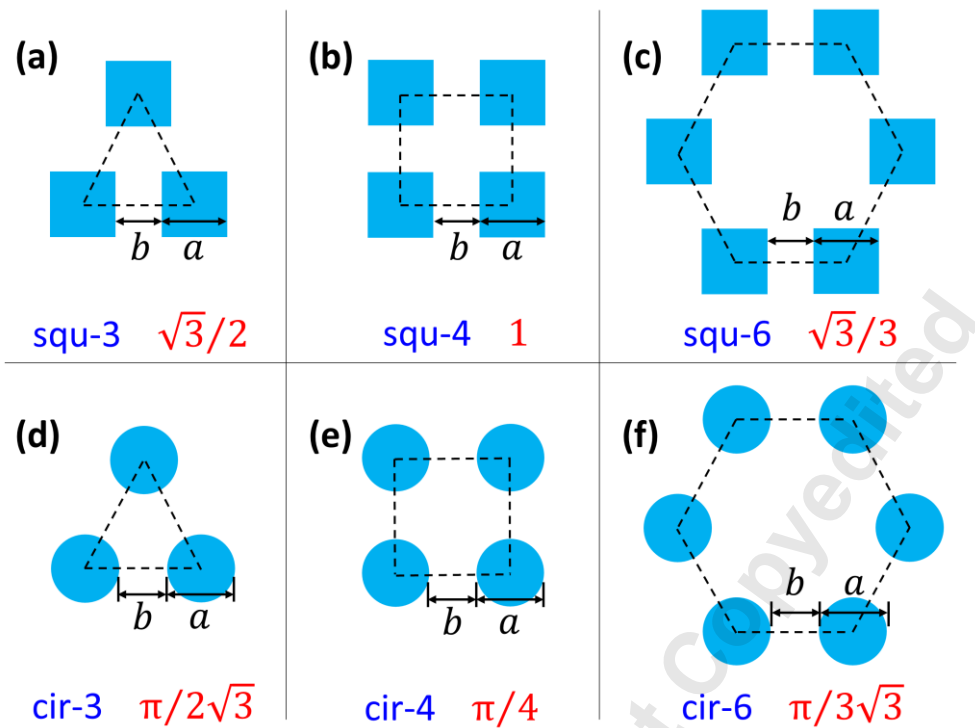
and $\bar{\sigma} = \sigma/H = 3\times10^{-3}$.

Fig. 11 The critical ratio ρ_{cr} as a function of the applied magnetic field strength $\bar{B}$,

which can divide the plane into two regions.

Fig. 12 The maximal adhesion strength $\bar{P}_{\text{strength}}$ varying with the rotation angle of

pillar's top φ for a arrayed surface with circular pillars arranged in square

pattern, in which $\bar{a} = \bar{b} = 0.1$ and $\bar{\sigma} = \sigma/H = 3\times10^{-3}$.

(a)

micropillar array

magnetic

particle

back layer

H

b a

$\mathbf{p}_m$ ↑

(b)

$a + b$

$a/\cos\varphi$

$\mathbf{B}$

b a

(c)

$\mathbf{B}_R$

$\mathbf{M}$

$\pi/2 - \theta$

$\mathbf{B}$

Fig. 1

Fig. 2

Fig. 3

(a)

b a

squ-3 $\sqrt{3}/2$

(b)

b a

squ-4 1

(c)

b a

squ-6 $\sqrt{3}/3$

(d)

b a

cir-3 $\pi/2\sqrt{3}$

(e)

b a

cir-4 $\pi/4$

(f)

b a

cir-6 $\pi/3\sqrt{3}$

Fig. 4

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Fig. 5

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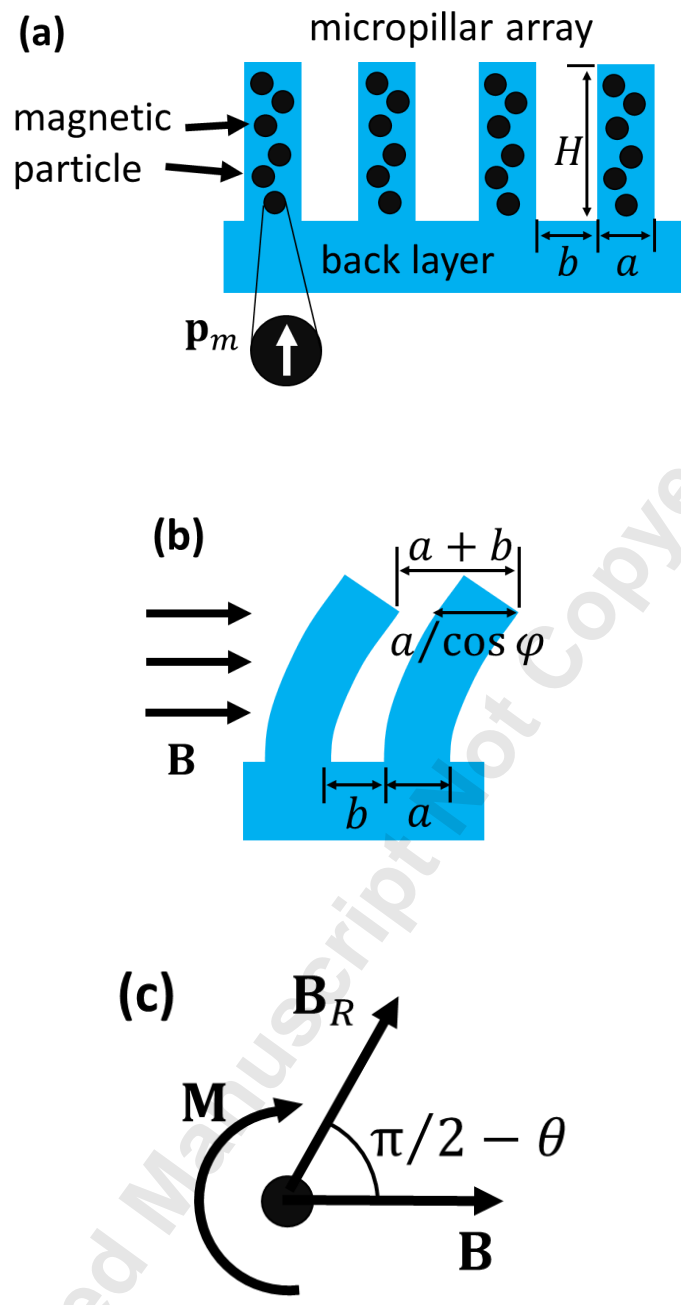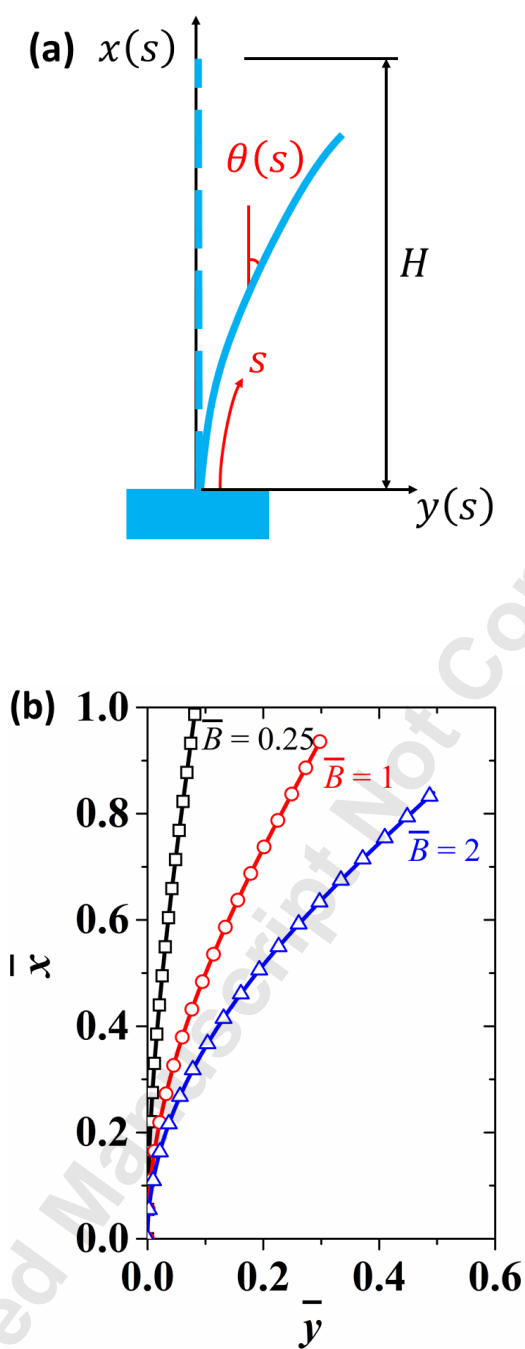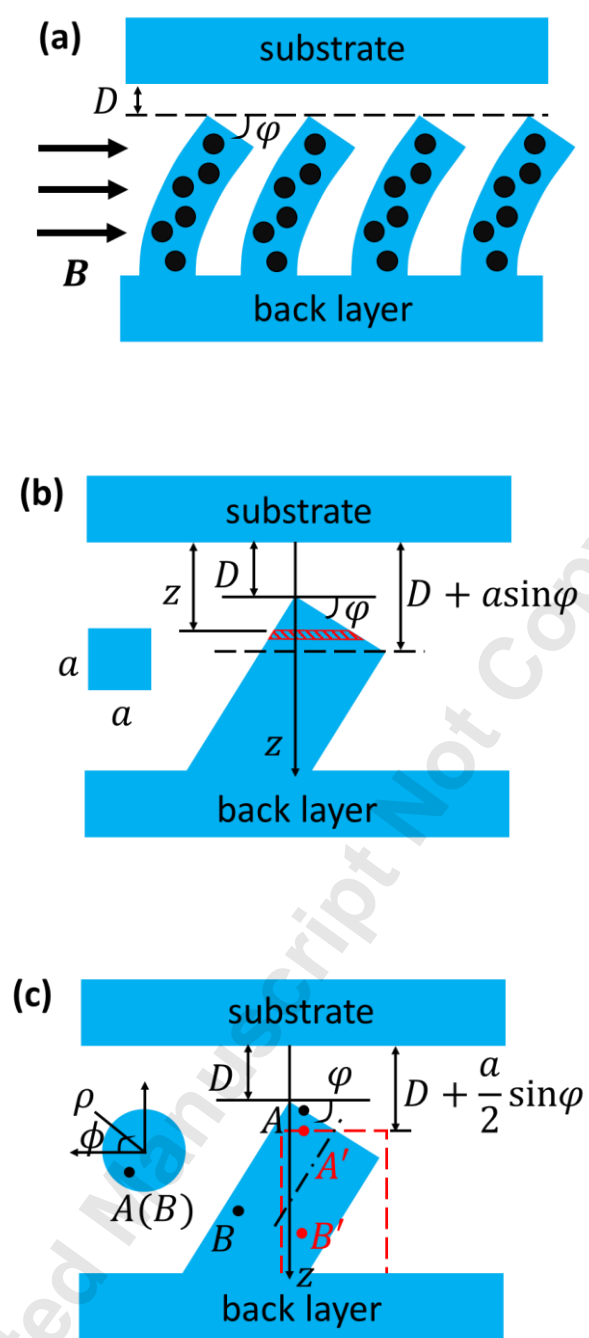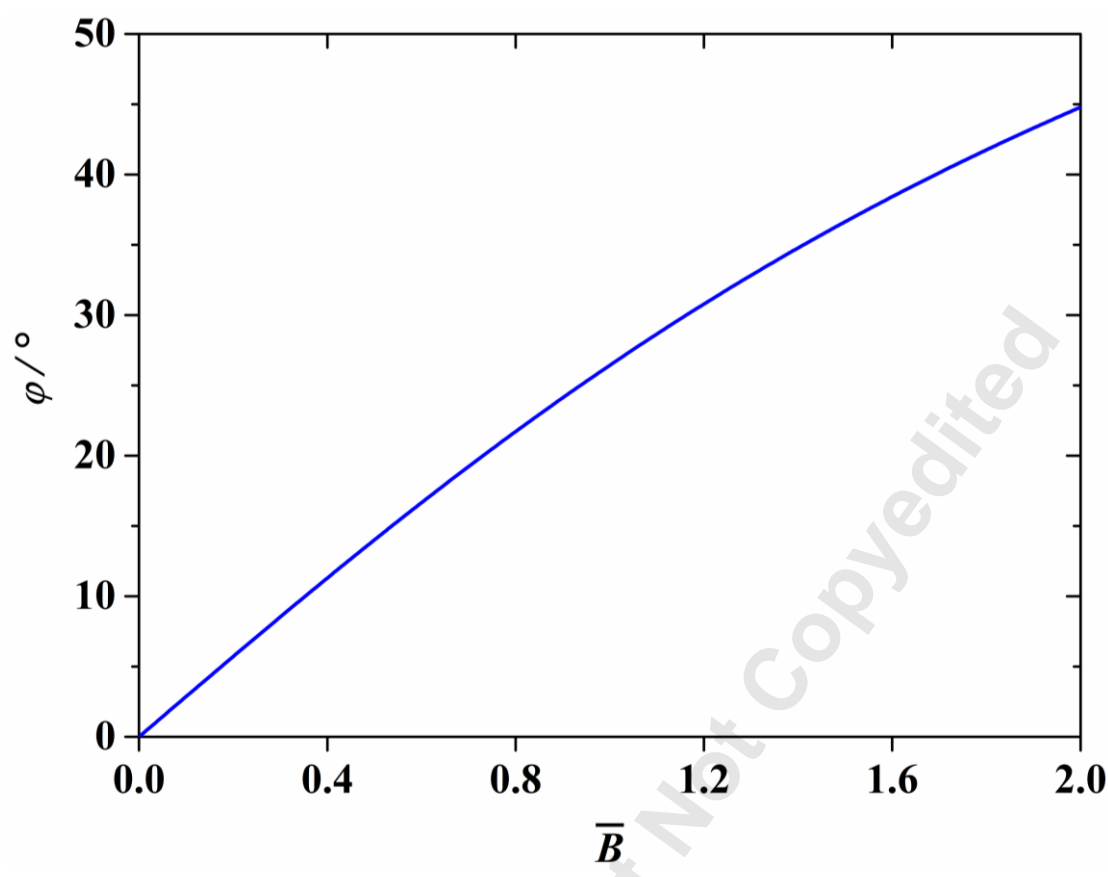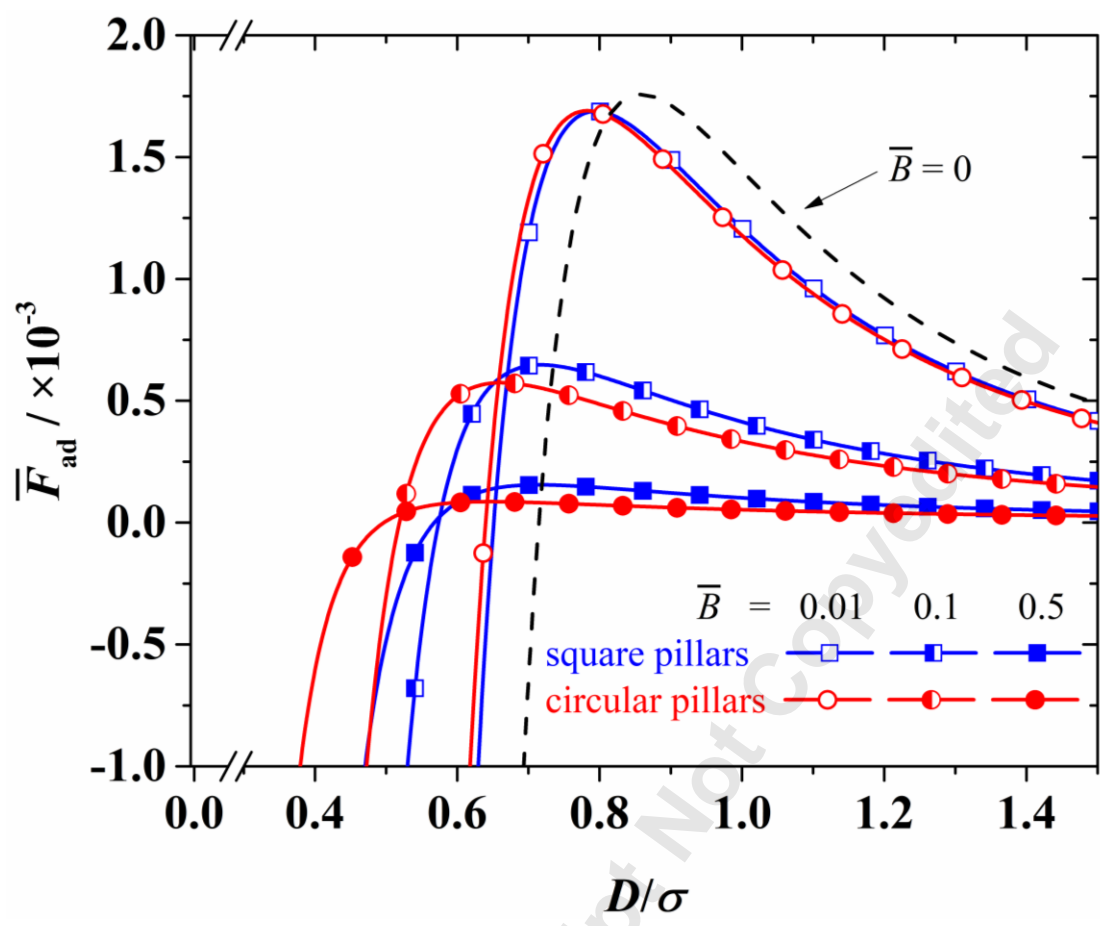
Fig. 6
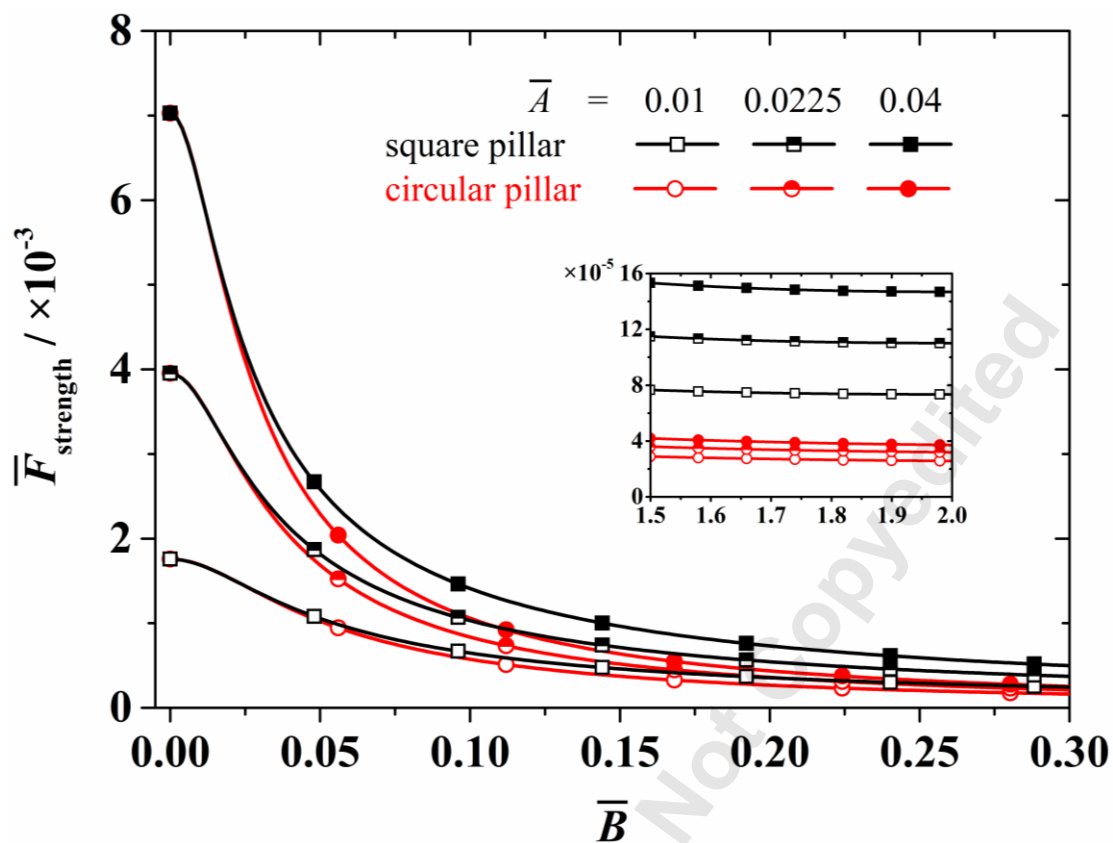
Fig. 7
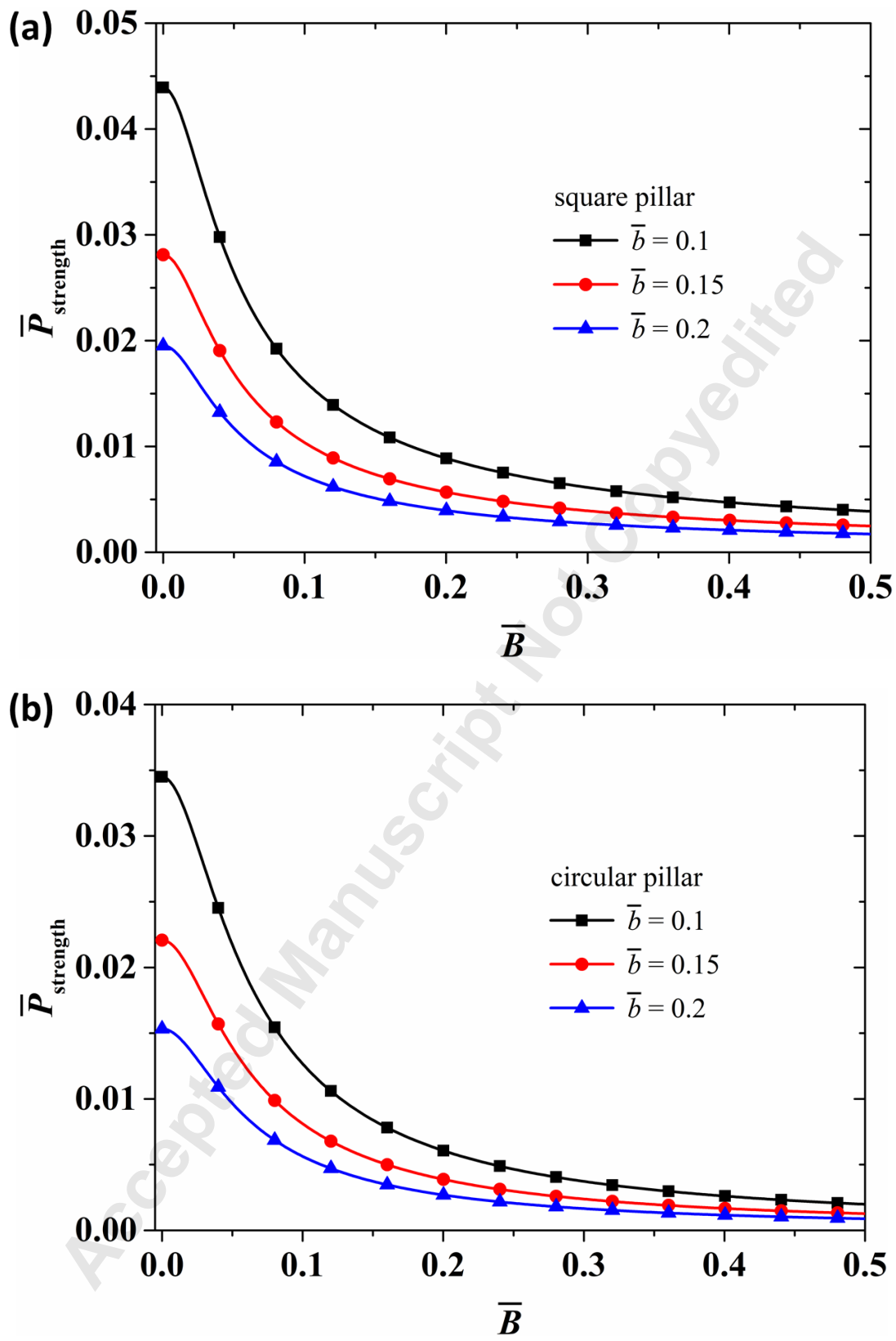
Fig. 8

Fig. 9

Fig. 10

Fig. 11

Fig. 12