Adhesive Force of a Spider Mite, *Tetranychus urticae*, to a Flat Smooth Surface*

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The adhesion of a spider mite to a surface of a flat smooth plate is investigated as a model for micromachine parts to adhere to and move on such surfaces. The measurement of adhesive force is carried out under various conditions in which plate material, surface roughness of a plate and environmental humidity are differed. The adhesion mechanism is also discussed. Of the forces acting between a spider mite and a surface, one from dispersion interaction is the most dominant because (1) there is a high correlation between the adhesive force and the dispersion force component of surface energy with adhesive forces of 8.2 μN for glass, 9.7 μN for mica, 9.9 μN for silicon and 12.1 μN for gold, and because (2) high humidity and high surface roughness reduce the adhesive force. For strong adhesion based on work of adhesion, spider mites have tenten hairs with a bell-shaped end.

**Key Words:** Micromachine, Tribology, Spider Mite, Surface Roughness, Tenent Hair, Adhesive Force, Work of Adhesion, Surface Energy

1. Introduction

Reaction force is applied to a machine when it exerts a force on others. To endure the reaction force, it must be firmly fixed on the ground. It is, however, not easy to fix a machine on a smooth surface without protrusions to be grasped. Finding a fixing mechanism is necessary for micromachines because large friction force is not expected due to their small weights. Such mechanisms have been reported that enable a closed formation of reaction forces by overhanging leg-like elements symmetrically to the internal wall of a tube(1) or by connecting machine elements to form a loop around a tube(2). However, there have been few mechanisms that work on a flat smooth surface. On the other hand, in the natural world, not a few small animals exist that can climb any flat smooth wall. We have then noticed one of them, a piece of spider mite (*Tetranychus urticae*), which is approximately 0.5 mm in body length and 0.02 mg in weight, to investigate the adhesion mechanism to a smooth surface. A preliminary investigation has shown that a spider mite can run at a speed of several times the body length per second and exert adhesive force of several ten times its weight on a glass plate(3). A spider mite obviously has these two contradictory functions, transfer and adhesion, by utilizing two kinds of force, body force and surface force, the former of which is dominant in large size, and the latter in small size. Therefore a key to finding a mechanism to fix a machine on a smooth surface can be found in the spider mite.

The present study examines the adhesive force of spider mites to a flat smooth surface under various conditions in which plate material, surface roughness of a plate and environmental humidity are differed, and discusses the adhesion mechanism by taking into consideration adhesive force, spider mites’ leg-tip morphology and leg motion, and the results of calculation using adhesion models including suction, liquid meniscus, intermolecular force and work of adhesion.

2. Spider Mite (*Tetranychus urticae*)

Spider mites belong, in the animal taxonomy, to Arthropoda, subphylum Chelicerata, Arachnida, and Acarina(4). They have four pairs of legs but no feather unlike insects as shown in Fig. 1. The spider mites used in the ex-
experiment were bred by using bean trees. They are usually on the backsides of leaves and suck leaf sap. After sucking the sap of one leaf, they actively move to another leaf of even another trunk or tree. The average body length of the spider mites was determined to be approximately 0.5 mm, which was represented by the maximum body length from the top view (see Fig. 1). Their average weight was determined to be 0.023 mg by using an electron balance.

3. Measurement of Adhesive Force

3.1 Method

The measurement of adhesive force was carried out using an experimental set up shown in Fig. 2. The setup was placed on the stage of a microscope. A spider mite attached to the tip of a glass pipette using instantaneous adhesive was placed on the flat test plate. It was held there for several seconds to sufficiently adhere to the plate and then lifted off. In this process, the cantilever, at the end of which the flat plate had been mounted, bent until the spider mite released the plate. The time-dependent vertical displacement of the plate was recorded and converted to adhesive force. Figure 3 is an example of the time charts of adhesive force obtained from the signal of a micro-displacement detector (Microsense 3401-HR-02, ADE Corp.), indicating that the plate was first lowered, then pulled up until the highest point, and finally in damped oscillation. The adhesive force was obtained by multiplying the maximum displacement with the spring constant of the cantilever (0.98 ± 0.12 N/m).

The plate materials tested were borosilicate glass used for cover glass, mica for vapor-deposition substrates, silicon for silicon wafers and gold formed on a piece of cover glass by ion beam sputtering with a thickness of approximately 100 nm. The roughness of the plate surfaces was measured by an AFM (Dimension 3100, Digital Instrument) for a square area of 1 µm² and found to be smooth as shown in Table 1. Glass plates of various surface roughnesses were also used to examine the influence of roughness on the adhesive force. The roughness was 0.006 µmRa (original surface), 0.039 µmRa, 0.153 µmRa and 0.338 µmRa (surfaces abraded with alumina powders of #4000, #1500 and #800, respectively).

The temperature was approximately 20°C and the humidity was 20–30% RH. High humid conditions of 70–80% RH were also employed by using a glove box and a humidifier in it.

3.2 Results

Figure 4 shows the distributions of the adhesive forces of spider mites to flat surfaces. Each distribution followed a logarithmic normal distribution. Many reasons can be offered for these distributions, including the individual difference of the spider mites, the number of legs adhering to the surface, the surface conditions, and the difference in the measurement operations. However, they are not fur-
ther discussed here. The result is summarized in Table 2. Of the four kinds of flat surface, the adhesive force was smallest for glass with 8.2 $\mu$N, and largest for gold with 12.1 $\mu$N in spite of its larger roughness. This result indicates that the surface-layer material is one of the key factors affecting adhesion.

The influence of surface roughness on the adhesive force can be seen in Table 3. The adhesive forces for abraded surfaces of glass were almost equal even with a large difference in surface roughness and approximately half that for an unabraded one.

The influence of humidity on the adhesive force is shown in Table 4. The measurement was carried out at (a) high humidity, (b) low humidity and again (c) high humidity, for confirming the reproducibility of the measurement. The adhesive force is lower in high humidity of 70–80% RH.

4. Discussion on Adhesion Mechanism

4.1 Morphology of leg tip

A leg of a spider mite consists of six knots, which are from the basipodite to the tarsus, and the apotele at its tip including tenent hairs and empodiums. A leg tip of a spider mite that had probably been in contact with a flat plane is shown in Fig. 5. The tips of four legs are also shown in Fig. 6. Several characteristics can be seen from these figures: a leg tip responsible for attaching has two pairs of tenent hairs (Fig. 5(c)) that are curved away from the body; empodiums (Fig. 5(b)) between a pair of tenent hairs are curved toward the body; tenent hairs and empodiums couple at their roots with an angle of approximately 90° and compose a joint to a tarsus (Fig. 5(a)); and tenent hairs and empodiums are thinner than a tarsus. The tips of the other legs also have these characteristics. Therefore, it is likely that both tenent hairs and empodiums spreading with an appropriate balance support the body, and that the ends of tenent hairs exert adhesive force. The shanks and expanded ends of tenent hairs are approximately 0.5 $\mu$m and 2 $\mu$m in diameter, respectively. The ends of tenent hairs of each leg are (1) flat, (2) convex, (3) concave or (4) of various shapes. The observation of many individuals showed that there were no clear relationships between the ends’ shapes and the leg position. Figure 7 shows a typical example of concave ends. Such bell-shaped ends can become flat when pushed straight against a flat surface and convex when pushed softly and obliquely. Therefore the ends of tenent hairs shown in Fig. 7 are of the initial force.
shape and probably change into other shapes according to the contact conditions with the surface.

4.2 Motion of legs attaching to surface

The leg motion of a spider mite on the surface of a glass plate was observed through the plate. A spider mite fluttering its legs when being drowned off is shown in Fig. 8. The spider mite was attached to the plate in the same manner as mentioned in section 3. This fluttering was performed by bending legs at a frequency of approximately 5 Hz. During fluttering, re-adhesion of a leg occurred as shown in Fig. 8 (b). The adhesion point was close to the body with the legs bending, while the points that the leg tips of a walking spider mite touch were away from the body with the legs extending.

The footprints of spider mites attaching to the surface of a glass plate were examined. In this experiment, spider mites were put in a small vessel with a clean glass plate as the ceiling. After one day, the plate was observed using a phase-contrast light microscope. Figure 9 shows an example of the results. Some point-like traces with a size of approximately 1 µm were observed, but not so many. The traces indicate that spider mites walked upside down on the glass. The size of the traces corresponds to that of the expanded ends of tentent hairs. Hence, the ends of tentent hairs likely secrete adhesive material or are soft enough to be easily detached from the surface.

4.3 Model of adhesion

Several mechanisms enabling small animals to attach to smooth surfaces have been discussed, including suction,
friction, electrostatic attraction, liquid meniscus force and intermolecular force\(^{(5)-(7)}\). Intermolecular force was proposed as the dominant factor in adhesive force for geckoes\(^{(5)}\) and liquid meniscus force for blowflies\(^{(7)}\). Similarly, several mechanisms are here examined for spider mites by calculating adhesive force based on each model described in the following.

We assume that the expanded end of a tenent hair is a disk of radius \(R (= 1 \mu m)\) in touch with a flat surface.

**4.3.1 Suction model**  Pressure difference \(P\) between the contact area and others exists. The adhesive force by suction \(F_s\) is expressed as

\[
F_s = \pi R^2 P
\]

**4.3.2 Liquid meniscus force model**  Liquid (surface tension \(\gamma\)) cross-links between a disk and a flat surface with a thickness \(h\), and forms a meniscus of radius \(R_m (= 0.5 h)\) and \(R\); the Laplace pressure \(P\) in the liquid attracts the disk. The adhesive force by this liquid meniscus model \(F_m\) is\(^{(8)}\)

\[
F_m = \pi R^2 \gamma \left( \frac{1}{R_m} - \frac{1}{R} \right)
\]

**4.3.3 Intermolecular force model**  A disk and a flat surface are almost in touch with each other with a slight distance \(D\) and van der Waals force works between them. The adhesive force by this model \(F_i\) is\(^{(9)}\)

\[
F_i = \frac{A R^2}{6D^3}
\]

where \(A\) is Hamaker constant.

The results of calculation are as follows. (a) If the pressure difference is 1atm \((P = 0.1 \text{ MPa})\), \(F_s\) is 0.3 \(\mu\)N. (b) If the surface tension of the secretion of a spider mite is the same as that of a blowfly \((\gamma = 30 \text{ mN/m})\) and the liquid thickness is larger than the surface roughness of a gold film \((2R_m > 14 \text{ nm})\), \(F_m\) is 10 \(\mu\)N \((R_m = 10 \text{ nm})\) or 2 \(\mu\)N \((R_m = 50 \text{ nm})\). (c) Assuming that the contact clearance is equal to or bigger than a typical atomic distance \((D \geq 0.4 \text{ nm})\) and using a typical Hamaker constant for both solid and liquid \((A = 10^{-19} \text{ J})\), \(F_i\) is 260 \(\mu\)N \((D = 0.4 \text{ nm})\) or 33 \(\mu\)N \((D = 0.8 \text{ nm})\).

A spider mite can exert, for example, eight times the above forces under a condition where its four of eight legs work for adhesion using half of the four tenent hairs per leg. In the above three types of force, liquid meniscus force, \(8F_m\), is in the same order of the magnitude as that for the measured adhesive forces. Additionally taking \(F_m \ll F_i\); into consideration, it is likely that the rupture of the contact region when pulled off occurs not at the solid-liquid interface but in liquid. The adhesive force therefore depends on the characteristics of liquid. However, this cannot explain the difference in the measured adhesive forces between the surfaces of various materials with, for example, the force for gold 1.5 times that for glass. We then introduce the following model.

**4.3.4 Work of adhesion model**  We assume that the adhesive force comes from the surface energy of a flat plane that can interact with the end of a tenent hair. Here the surface energy is evaluated.

To begin with, a liquid of surface tension \(\gamma_2\) was dropped on a flat surface of surface tension \(\gamma_1\) and the contact angle between the droplet and the surface \(\theta\) was measured. The work of adhesion between them per unit area \(W_{12}\) can be calculated using Young-Dupré equation\(^{(8)}\) as

\[
W_{12} = \gamma_2 (1 + \cos \theta)
\]

An acrylic solution (NOA65, Norland Products Inc.; surface tension = 36.4 mN/m and viscosity = 1 200 cps) was dropped on the surfaces of various materials. The photographs of its droplets on the surfaces and the contact angles \(\theta\) are shown in Fig. 10. The surface tension of the acrylic solution is mainly dependent on dispersion force because it hardly has polar groups. Because the dispersion force is dominant in such a case, \(W_{12}\) is\(^{(8)}\)

\[
W_{12} \approx 2 \sqrt{\gamma_1^d \gamma_2^d}
\]

where \(\gamma_1^d\) and \(\gamma_2^d\) are the contribution of dispersion force to surface tension.

If the end of a tenent hair also has surface tension that is dependent only on dispersion force, the work of adhesion between the end and the surface, \(W_{13}\), which is normalized by that for glass surface, \(W_{13(\text{glass})}\), is expressed as

\[
W_{13}/W_{13(\text{glass})} \approx 2 \sqrt{\gamma_1^d/2 \gamma_1^d(\text{glass}) \gamma_2^d} = 2 \sqrt{\gamma_1^d/2 \gamma_1^d(\text{glass}) \gamma_2^d} \approx W_{12}/W_{12(\text{glass})}
\]

With the measured adhesive forces normalized by that for glass surface in the same way, the relation between them and the work of adhesion was examined. The result is shown in Fig. 11. They are strongly correlated with a correlation coefficient of 0.98.

From the above discussion we summarize the adhesion mechanism as follows. The adhesive force of a spider
mite to a smooth flat surface is determined according to the characteristics of the weaker part in the contact region, which is the end of a tenent hair (secretion is included, if it exists) or the interface between the end and the plate. With the fact that the adhesive force is large on a surface with a large surface energy and decreases with the presence of steam of a small dispersion force, the adhesive force is probably strongly controlled by the characteristics of the interface based on the dispersion interaction among molecules in the end of a tenent hair and the plate. Because the actual contact area for the interface is much smaller than the apparent contact area, in order to increase the actual contact area, a spider mite employs deformable bell-shaped ends of tenent hairs that allow the ends to follow the surface configuration, and the leg motion for strongly pressing the ends to the surface. Although the force calculated from the suction model is smaller than the measured ones, suction force has the possibility of sucking out adhesive secretion to the end of a tenent hair.

5. Conclusions

(1) The adhesive force of a spider mite to a smooth flat surface varies with surface materials and is high for materials of larger surface energy based on the dispersion interaction between molecules. It is 8.2 μN (37 times the average weight of spider mites) for glass, 9.7 μN for mica, 9.9 μN for silicon and 12.1 μN for gold.

(2) The adhesive force is low with high humidity or large surface roughness.

(3) The adhesion to a surface is carried out using deformable bell-shaped ends of tenent hairs with an extended length of approximately 2 μm that allow the ends to follow the configuration of the contact area.

(4) The most promising model for the adhesion is the work of adhesion model in which adhesive force is controlled by the characteristics of the interface based on the dispersion interaction between molecules in the end of a tenent hair and the surface layer of the contact area.

References


