Article

The Friction Properties of Firebrat Scales

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Abstract: Friction is an important subject for sustainability due to problems associated with energy loss. Recent years, surface micro- and nanostructures have attracted much attention to reduce friction; however, suitable structures are still under consideration. Many functional surfaces are present in nature, such as the friction reduction surfaces of snake skins. In this study, we focused on firebrats, *Thermobia domestica*, living in narrow spaces such as under bark, so their surface frequently contacts with surrounding surfaces. We speculate that their body surface would be adapted to reduce friction. To investigate the firebrat surface functions, firebrat surfaces were observed by using a field-emission scanning electron microscope (FE-SEM) and a colloidal probe atomic force microscope (AFM), respectively. Results of surface observations by the FE-SEM revealed that firebrats are entirely covered with scales, whose surfaces have micro groove structures. Scale groove periods around the firebrat's head are almost uniform within a scale but vary between scales. AFM friction force measurements revealed that firebrat scale reduces friction by decreasing contact area between scales and a colloidal probe. The heterogeneity of groove periods of the scales suggest that it is difficult to fix the whole body in particular rough surfaces and that lead to be "fail-safe".

Keywords: Firebrat; Friction; AFM; Colloidal probe; Scale; Microstructure

1. Introduction

Friction is an important issue for saving energy and preventing the wear of parts in a wide variety of fields, such as the automobile industry[1] and medicine[2]. Nowadays, lubricants are mainly used for reducing friction forces; however, other technologies are now in demand because lubricants generally lead to pollution of the environment[3]. In recent years, surface nano- and microstructures have attracted attention to reduce friction force[4-6]. Although there are a lot of reports on friction reduction by nano- and microstructures, most effective textures remain under consideration as friction is a complex phenomenon affected by atomic-level structures[7,8]. In nature, the surfaces of living organisms have been adapted to their environments during their evolution process, and various functions have been generated by surface nano- and microstructures: the superhydrophobic self-cleaning surfaces of lotus leaves[9], anti-reflection surfaces of moth eyes[10,11], drag reduction surfaces of shark skins[12,13], and so on[14,15]. Some friction control surfaces of animals have been also reported. The snake reduces friction force on its body in order to decrease damage by using surface microdimple structures[16]. The grasshopper has hexagonal microstructures on its foot to controls stick-slip motion on dry surfaces, and to maintain friction force

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on wet surfaces for preventing a hydroplaning effect[17]. In this report, we focused on the firebrat, *Thermobia domestica* [18-21], a type of primitive wingless insect belonging to the order *Zygentoma*. Because firebrats live in narrow spaces such as openings of bookshelf, so that the body surface is always in contact, attrited by surrounding surfaces. We speculate that their body surface might have evolved to reduce friction and to protect them from wear. Herein, we present surface observations and friction force measurements of firebrat body surface by a field-emission scanning electron microscopy (FE-SEM) and a colloidal probe atomic force microscopy (AFM) [22-24] as part of their surface frictional properties. These results will contribute to the development of novel frictional surfaces applicable to a wide variety of industrial fields.

2. Materials and Methods

2.1. *Animal materials*

Firebrats, *Thermobia domestica* (Zygentoma, Lepismatidae), were bred and maintained in our laboratory, and fresh adults were also collected for this research. Firebrats were kept in a refrigerator for 1 hr in a state of suspended animation, sacrificed using ethyl acetate (Fujifilm Wako Pure Chemical Industries, Ltd., Japan) vapor.

2.2. *Observations and analysis of firebrat surface*

Surface observations of firebrats were carried out by a laser microscope (OLS4000, OLYMPUS CORPORATION, Japan), and FE-SEM (5 kV, 90 μA, JSM-7800F, JEOL, Japan) after sputtering with Pt to a thickness of about 6 nm (30 mA, 80 s, JEC-3000FC, JEOL, Japan). Thereafter, groove periods of firebrat body scale surfaces were analyzed by the methods of periodicity detection using autocorrelation [25]. By taking the SEM images of scales as two-dimensional signals, their autocorrelation could be calculated, where autocorrelation is a mathematical representation of the degree of similarity between a given signal and a spatially lagged version of itself. The autocorrelation has peaks at integer time of the periods of the target two-dimensional signal. Thus, by finding the first peak from the autocorrelation, the groove period could be detected from the target scales. We call this groove period detection method "periodicity detection using autocorrelation". Note that 298 scales from a male firebrat were used for calculating the groove periods (target scale numbers of each position are; head: 40, pronotum: 100, metanotum: 80, 8th abdominal tergum: 35, and 9th abdominal tergum: 43, respectively).

2.3. Chemical and wettability analysis of firebrat scales surface

Surface chemistry and wettability of firebrat scales before and after washing with chloroform (Fujifilm Wako Pure Chemical Industries, Ltd., Japan) were measured by infrared spectroscopy (PerkinElmer, Spotlight400 Spectrum100, Japan) and water contact angle analyzer (FAMAS, Drop Master 500, Kyowa Interface Science, Japan). The volume of the ultra-pure water (25 ^{o}C, 18.2 Ω, supplied form Milli-Q Advantage, Merck KGaA, Darmstadt, Germany) was 3.0 μL for measuring water contact angles.

2.4. Friction measurements on a body surface

Surface topology of scales were measured by AFM (AFM5100N, Hitachi High-Technologies Corporation, Japan) with conventional needle-type probe (apex curvature radius = 8 nm, FMR-20, NanoWorld, Switzerland). Surface friction forces were measured in two ways as shown in below; i.e., to measure the friction forces of the scales, including the scale boundaries, a whole firebrat was fixed on a silicon substrate by carbon adhesive tape to keep measuring area horizontal (See Supplementary data, Figure S1). Then, friction forces of the firebrat surface were directly measured by AFM with the conventional needle-type probe and colloidal probes with diameters of 5.0, 10 and 20 μm(CP-CONT-BSG-A, CP-CONT-BSG-B and CP-CONT-BSG-C, sQube, Germany), respectively. The scanning area was 50 μm square, and scan rate 0.3 Hz. Scanning was performed from the scale root to apex, scale apex to root, and lateral directions, respectively.

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2.5. Friction measurements within a scale

For detailed analysis of the relationship between scale surface structures and dimensions of rubbed objects (indenters), a single scale was taken from a firebrat, and fixed on a silicon substrate using poly(vinyl alcohol) (Wako Pure Chemical Industries, Ltd., Japan) as an adhesive. Then, friction forces were measured by AFM with needle and colloidal probes with diameters of 2.0, 3.5 and 6.6 μm(CP-CONT-SIO-A, CP-CONT-SIO-B, and CP-CONT-SIO-C, sQube, Germany), respectively. The scanning was performed from the scale root to apex only (See Supplementary data, Figure S2). The scanning area was 15 μm square, while the other measurement conditions were as described above.

3. Results

3.1. Surface observations and analysis of firebrat

Figure 1 shows the laser microscope and FE-SEM images of the body surface of a firebrat (male, body length of 7.24 mm), respectively. The body surface of firebrats is covered with dense scales, and scales on the head are oriented against the direction of forward movement though growth directions of other parts are forward direction (white arrows in Figure 1(B-E)). FE-SEM observations also revealed that the scale surfaces have periodic groove structures(Figure 1(F-I)). These grooves were formed on only the face, and backside of the scale has ladder-like structures, lower height and regard as almost flat compared with face grooves (Figure 1(J-L)). The groove periods of the firebrat scales seemed to vary between scales on the anterior regions of the body, particularly around the head, although the groove periods are almost uniform within a scale (Figure 1(F)).

To study the groove periods differences more precisely, we analyzed groove periods by periodicity detection using autocorrelation. It was revealed that the groove periods and their standard deviations are clearly smaller from the firebrat's head to the tail. And also, groove periods are become smaller to the tail (Figure 2(A)). Figure 2(B) shows the graphs of groove height from the scale root to apex of 6 scales, which groove periods were ca. 3.5 μm of 3 scales (Black points) and ca. 2.0 μm of 3 scales (Gray points) measured by AFM, respectively. According to the graph, groove heights are almost proportion to the distance from scale root to apex, so the groove heights are also varying within a scale.

3.2. Surface chemical and wettability analysis of firebrat scales

Before measurements of friction forces, we analyzed surface chemistry and wettability of scales. Because if firebrat surfaces are covered by waxy compounds, surface conditions would be changed during friction force measurements. Figure 3 shows IR spectra, FE-SEM images and photographs of water droplets on scales before and after washing by chloroform for 10 min. From these experiments, surface conditions were not changes, so firebrat scale surfaces are not covered by waxy compounds (In this study, we did not consider the possibility of a existence of molecular lubricant layer directly fixed on the body surface, such as a snake[26]).

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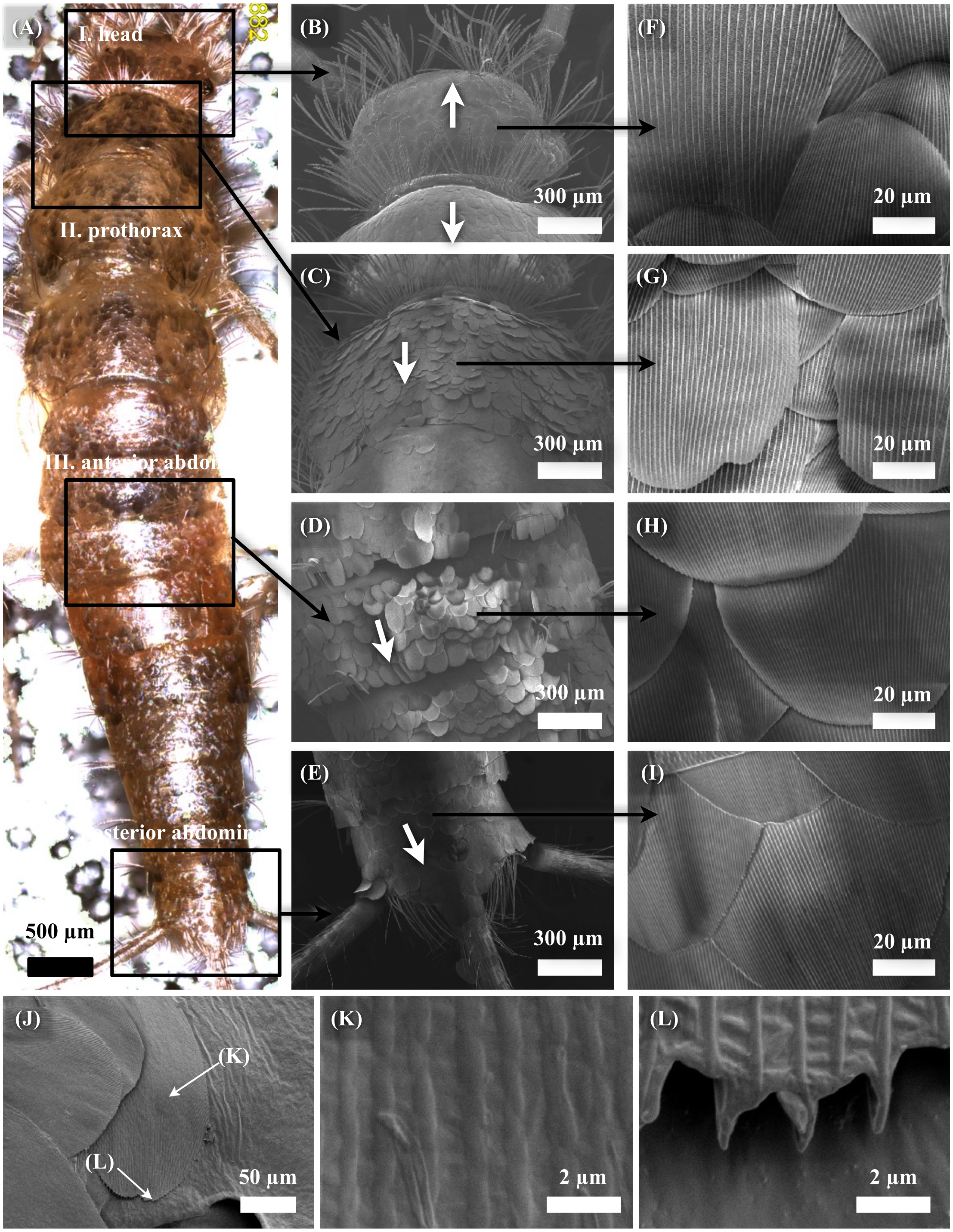

Figure 1. (A) Laser microscope image of a whole firebrat (I -III, V areas correspond to Figure 2, respectively). FE-SEM images of firebrat surfaces. (B-E) Low-magnified images for confirming scale growth direction, (B): head, (C): prothorax, (D): anterior abdominal region, (E): posterior abdominal region. (F-I) Magnification images of (B-E), respectively. (J-L) FE-SEM images of backside of the scales.

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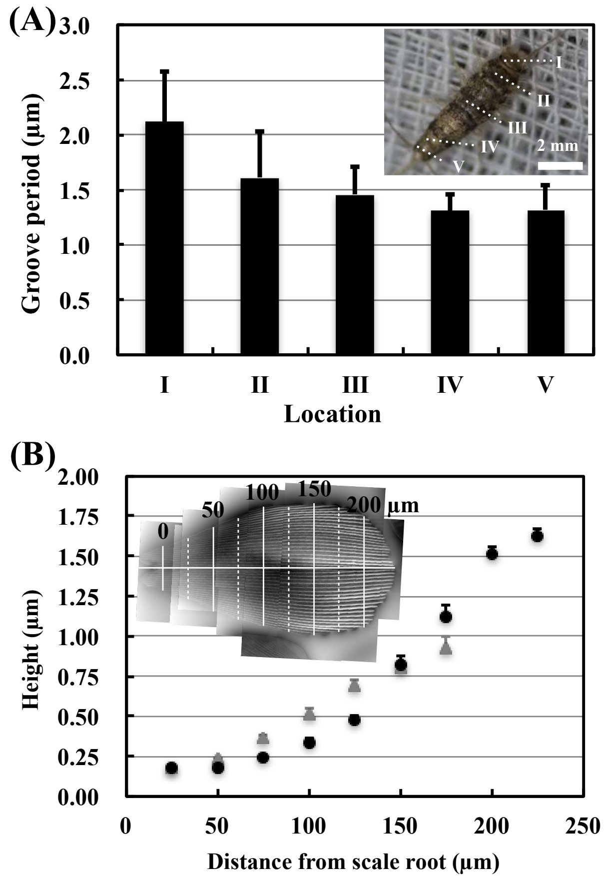

Figure 2. (A) Graph of groove period lengths and their standard deviations for the different body regions. I: head, II: pronotum, III: metanotum, IV: 8th abdominal tergum, and V: 9th abdominal tergum. (B) Graph of groove height from scale root to apex. These points show average height of 3 scales with groove period about 3.5 µm(Black points) and of 3 scales with groove period about 2.0 µm(Gray points), respectively. Error bars mean standard deviations.

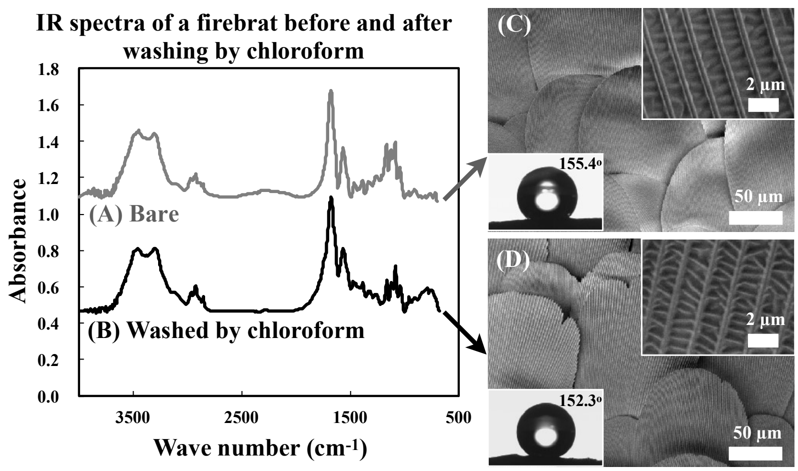

Figure 3. (A, B) IR spectra and (C, D) FE-SEM images and photograph of water droplet on the scales. (A) and (C) indicates bare surface, and black line in (B) and (D) shows after washing by chloroform.

3.3. Friction measurements on a body surface ~ Needle probe

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Friction forces on overlapped scales were measured using AFM with a needle-type probe and three kinds of scanning directions. According to friction force images in Figure 4, friction anisotropy at the boundaries of overlapped scales were appeared. At the scale boundary, friction forces were markedly reduced when examined with scale root to apex scanning direction. In contrast, friction forces were increased at the boundary with scale apex to root scanning. Moreover, friction forces were increased at top of grooves in the case of lateral scanning. Groove structures appear to act as projections; however, this is unconcerned for firebrats as they can not move sideways.

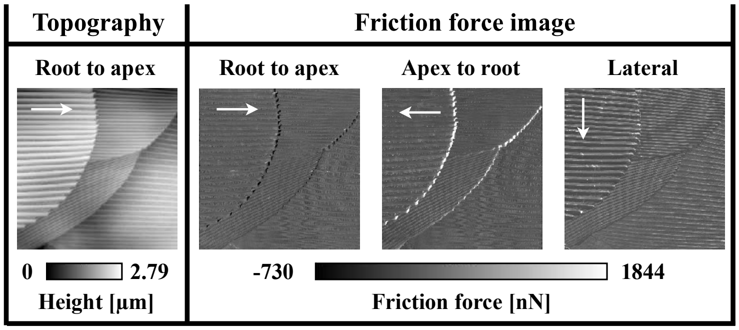

Figure 4. Topography and friction force images obtained by AFM with a needle probe. White arrows show scanning direction. The body part measured was the pronotum, and scanning area was 50 µm square.

3.4. Friction measurements on a body surface ~ Colloidal probe

We next focused on groove structures on scales. Since we predicted that a property of groove structures was friction reduction by reducing contact area, friction forces were measured by using AFM with 3 types of colloidal probes, which diameters are larger than groove periods in substitution for environmental roughness. As results of AFM measurements (Figure 5), contact area is decreased with increasing probe diameter in topographies; becoming difficult to distinguish small groove

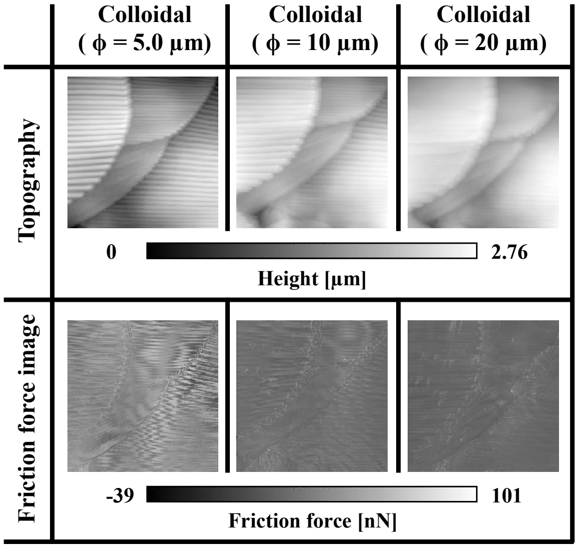

Figure 5. Topographies and friction force images obtained by AFM with 3 types of colloidal probe. Scanning directions are scale root to apex only. The body part measured was the same as Figure 4.

structures in topographies. Because when indenters became larger, the contact areas of the indenters regard as a plane surface, negating the effects of the groove structures. In the same manner, friction

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forces were reduced with increasing probe diameter. This result suggests friction force is proportional to the contact area.

3.5. Friction measurements within a scale

Figure 6 shows the topographies and friction force images obtained by AFM with needle probe and colloidal probes with diameters of 2.0, 3.5, and 6.6 μm, respectively. In this case, scales with a groove period of ca. 3.5 μm were selected for these measurements, so diameters of colloidal probes are almost same size of the groove period. Comparing topographies, the colloidal probes with larger diameters were not able to reach the groove bottom. And friction forces were the largest for the colloidal probes of 3.5 μm in diameter. According to these friction measurements, there are relationship between groove period and colloidal probes when their sizes are similar; friction forces were not simply becoming larger with decreasing diameters of colloidal probes as with Figure 4.

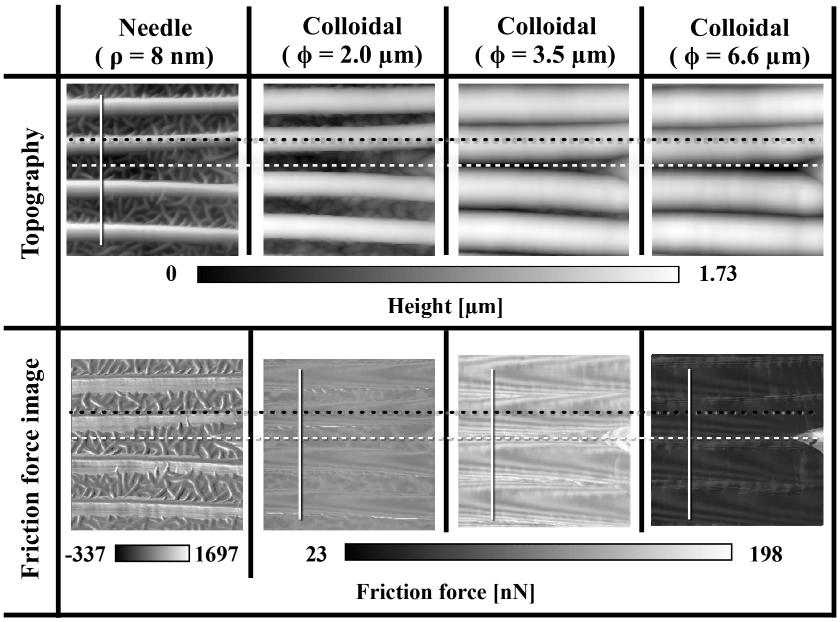

Figure 6. Friction force images obtained by AFM. Black dotted lines show the top of the grooves and white broken lines represent the bottom of grooves. White lines show the height profile and friction force extraction point of Figure 7. The scanning direction was the same (left to right), and the scanning area was 15 μm square. Within this figure, same scale spot was measured by 4 different probes.

4. Discussion

4.1. Observations and analysis of firebrat scales

According to the FE-SEM observations and analysis, firebrats are densely covered with scales with periodic groove structures on a face side and almost flat surface on a backside, and only scales on the head are oriented against the direction of forward movement (Figure 1). The groove periods of scales are varied between scales on the anterior regions of the body, although the groove periods are almost uniform within a scale. And the scale periods are becoming smaller and uniformly toward the tail (Figure 2(A)). Furthermore, groove heights are almost proportion to the distance from scale root to apex, so the groove heights are also varying within a scale(Figure 2(B)). As results of above observations, we found three unclear points; one is deferent scale growth direction at the firebrat's head, which is against forward movement since it is easily supposed to interfere their movement. Second is groove structure on scale surfaces, and last one is groove period and height unevenness.

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For clearing these points, we measured friction forces on the scale surfaces using AFM because we speculate that their surface scales might have evolved for reducing friction to adapt their lifestyle.

4.2. Meaning of scale growth directions

To investigate meaning of scale growth orientations, friction forces on overlapped scales were measured using AFM with a needle-type probe and three kinds of scanning directions (Figure 4). As results, friction forces are larger or smaller at the scale boundaries depending on scanning directions. This suggests that scale orientation on the trunk or thoracic and abdominal regions prevents sticking during forward movement into a narrow space. Meanwhile, we inference firebrat use “high friction” generated at the head scale apexes (edges), which growth direction are against the forward movement, as mechanosensor to determine whether they can enter small spaces (the head is smaller than the trunk).

4.3. Effect of groove structures on scales

We measured friction forces by AFM with 3 different size of colloidal probes to study effects of groove structures on scales. In Figure 5., topographies and friction force images indicate that firebrat use scale groove structures for reduction of friction force by reducing contact area to surroundings. In fact, the firebrat’s scale backside, which is always contacted to a scale face is nearly flat surfaces. These results suggest firebrat utilize scales with groove structures for reduction of friction.

4.3. Reasons of groove periods and heights unevenness

Generally, the groove periods on scales are the same over the body of insects such as butterflies. In butterflies, uniform groove periods on scales are used for the generation of optical properties referred to as structural color[27]. We, therefore, speculated that this groove period unevenness may have frictional property because firebrats live in narrow spaces, such as under bark, and optical properties are unnecessary. Moreover, the standard deviations of the groove periods on the head that frequently come into contact with their surroundings are large whereas those on parts that have little contact, such as the posterior abdomen or the tail, are small. This suggests that the firebrat has evolved uneven groove periods for a specific purpose.

To investigate effects of groove period unevenness, friction forces on 3.5 μm groove period were performed by using AFM with 3 different diameter colloidal probes, which sizes are similar dimensions to the scale groove period (Figure 6). As results, friction forces were not simply becoming larger with decreasing diameters of colloidal probes, friction forces were largest when a diameter of a colloidal probe and a groove period are same. To estimate this relationship between groove structures and colloidal probes, the height profile of groove structures and friction forces were extracted from Figure 6 (selected positions are shown in Figure 6 as white lines). Figure 7(A) shows the height profile of groove structures (black line) obtained from the topography and friction forces (colored lines) obtained from the friction force images in Figure 5, respectively. Figure 7(B-D) presents schematic illustrations of the groove structures and colloidal probes of 3 different diameters, respectively. In the case of the 2.0 μm diameter probe, the friction force was larger at the bottom and sides of the grooves (displayed as “B” in Figure 7(A, B)) as the colloidal probe made contact with two surfaces. In the case of the 3.5 μm diameter probe, which was similar in size to the groove periods, the friction forces were largest and became larger toward to center of the grooves (displayed as “F” in Figure 7(A, C)). When the diameter of the colloidal probe was 6.6 μm, the friction forces were increased at the center of grooves for the same reason as described above. However, as the contact areas were small, the friction forces were smaller than those for the other probes. These results clearly suggest an increment in contact area causes larger friction forces. In particular, if the probe diameter and groove periods are the same size, the probe sticks in the grooves, leading to larger friction force. Same trends were obtained in case of 2.0 μm groove period (See Supplementary data, Figure S3). According to these results, groove structures are definitely thought to influence friction, and

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inhomogeneous groove periods may prevent high levels of friction with rough surfaces of specific size by preventing fixation of all the scales.

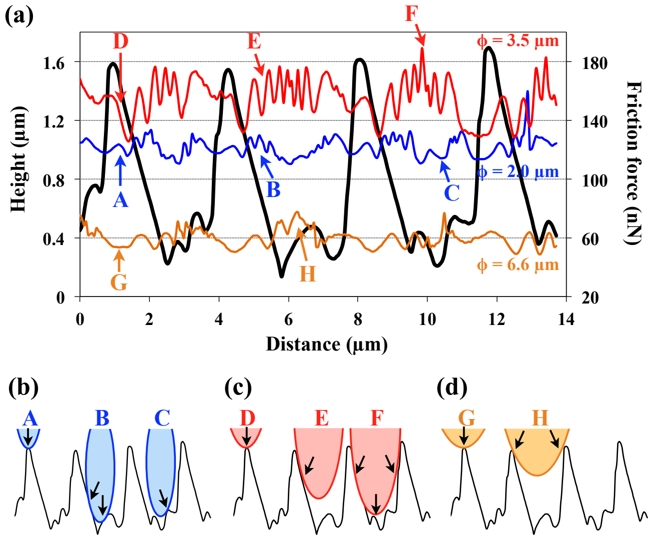

Figure 7. (A) Height profiles of the groove structures (black line) and friction forces (colored lines). The data were extracted from the white lines on the friction force images in Figure 4. (B-D) shows schematic illustrations of the relationship between groove structures and the 2.0 μm (B), 3.5 μm (C), and 6.6 μm (D) diameter colloidal probes, respectively.

5. Conclusions

We observed the body surface of firebrats, which is covered in dense scales, by FE-SEM and measured friction force by colloidal probe AFM as part of our investigation of the properties of firebrat scales. The scales of firebrats are equipped microgrooves. Detailed observations and analysis revealed that the groove periods vary by body part, although the groove periods are almost uniform within respective scales. Friction measurements suggest that firebrat scales may have five properties; one is the scale itself. Though we are not describing above, when a scale was injured or trapped by something including spider net, firebrat removes the scale to escape (scales are regenerated by molt). The second is the direction of scale growth on the trunk or thoracic and abdominal regions. This prevents the firebrat from becoming lodged during movement in narrow spaces. The third one is growth direction of the head scales. The head scales act as a mechanosensor to identify whether they can enter a narrow space. The fourth is groove structures, which reduces contact area, and it leads reduction of friction forces. The final property is the heterogeneous groove periods. Due to changes in groove period for respective scales, it is difficult to fix the whole-body scales at a time. If some scales are stuck to something, the firebrat can easily escape by removing only the trapped scales. These are also suggested by the standard deviations of groove periods, which are larger toward to the anterior portion of the body, which is frequently in contact with the environment, and smaller on the body parts, such as the tail, that have little external contact. From our research, it appears that firebrats adapt their scales to their habitat. Based on this knowledge of firebrat scales, we can develop novel less-frictional surfaces applicable to a wide variety of industrial fields[28,29].

Supplementary Materials:

Figure S1: Photograph of a firebrat specimen used for AFM measurements (direct measurement of the friction forces of scales).

Figure S2: Photographs of scales fixed on a silicon substrate for AFM measurements (detailed measurement of the friction forces of scales).

Figure S3: Friction force images obtained by AFM. A scale period is ca. 2.0 μm. The scanning direction was the same (left to right), and the scanning area was 15 μm square.

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