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Adhesion and sliding of wet snow on a super-hydrophobic surface with hydrophilic channels

T. KAKO
RCAST, The University of Tokyo, 4-6-1 Komaba, Meguro-ku, Tokyo 153-8904, Japan
A. NAKAJIMA
Advanced Systems of Technology Incubation, Honson, Chigasaki-shi,
Kanagawa 253-8577, Japan
H. IRIE
RCAST, The University of Tokyo, 4-6-1 Komaba, Meguro-ku, Tokyo 153-8904, Japan
Z. KATO, K. UEMATSU
Nagaoka University of Technology, 1603-1 Kamitomioka-cho, Nagaoka 940-2188, Japan
T. WATANABE, K. HASHIMOTO
RCAST, The University of Tokyo, 4-6-1 Komaba, Meguro-ku, Tokyo 153-8904, Japan
E-mail: Kazuhito@fchem.chem.t.u-tokyo.ac.jp

Adhesion and sliding of wet snow on a superhydrophobic surface with hydrophilic channel were investigated. Two different alignment (two dimensional and three dimensional) of the hydrophilic channels in a superhydrophobic surface were prepared and compared with merely a superhydrophobic surface and a hydrophilic surface. Both alignment samples exhibited intermediate level of wet snow adhesion between merely a superhydrophobic surface and a hydrophilic surface. Although the three dimensional sample also showed intermediate level for the wet snow sliding behavior, the two dimensional sample exhibits poorer snow sliding behavior than a superhydrophobic surface. Based on the experiments using a water-hollow glass beads composite, water movement to hydrophilic parts from wet snow occurs on both samples. It is deduced that the poor sliding behavior on the two dimensional sample was due to the increase of viscosity of wet snow on superhydrophobic parts as a result of the water movement to hydrophilic parts. © *2004 Kluwer Academic Publishers*

1. Introduction

If the adhesion of snow to the surfaces of structures or materials (solid objects) can be prevented or if the sliding of snow off such surfaces can be controlled, the living environment in cold districts would become safer and more comfortable. Various materials and structures have been proposed to overcome the problems caused by the adhesion and sliding of snow [1–10]. Snow is a mixture of ice and water. The way wet snow with a high water content adheres to or slides off a solid surface is greatly different from the way dry snow with a low water content does [9, 10]. It was reported that the water content of snow depends on the ground temperature and snow became dry below −1 or −2°C and wet over −1 or −2°C [9, 10].

In the previous report, we conducted experiments and gathered data on the adhesion and sliding of snow, and based on the data we evaluated the hydrophobic characteristics of the solid surfaces relative to the adhesion and sliding characteristics of wet and dry snow [10]. As a result, it was found that superhydrophobic materials excel in preventing the adhesion of dry and wet snow, facilitating the sliding of dry snow, while hydrophilic materials with smooth surfaces excel in facilitating the sliding of wet snow. Superhydrophobic materials, which are made by providing a low-energy surface with surface roughness [11–17], are superior in anti-snow adhesion performance, as described above, because there is less interaction between the surface and water or ice due to the low surface energy and the small number of contact points between the surface and the water or ice due to the minute-size surface roughness. We also conducted an experiment using simulated snow made by mixing hollow glass beads and water. Based on the data obtained from this experiment, it was found that the water in wet snow moves to the solid surface, a water film forms between the snow and the solid surface, wet snow slides on the water film, and consequently it slides off the solid surface. Because hydrophilic material with a smooth surface can develop a water film easily, it was considered to be superior to other materials in letting wet snow slide off the solid surface. As is clear from the foregoing, it is extremely difficult to control the behavior of wet or dry snow based on a single wettability criterion. A surface with a hydrophobic property repels water and therefore it is difficult for wet snow to slide because water hardly moves from wet snow to the solid surface [10]. Therefore, in the case of a surface with a hydrophobic property, whether or not snow slides off the surface of a solid object depends on the viscous resistance of a patch of snow. Snow should not adhere and techniques for preventing snow from adhering are usually required. On the other hand, snow should or should not slide based on the circumstances, so techniques for preventing snow from sliding sometimes become necessary although those for facilitating the sliding of snow are generally required.

In pursuing the present study, we took into consideration all the above-mentioned factors and examined the possibility of controlling the sliding of snow while at the same time utilizing the superb anti-snow adhesion performance of a superhydrophobic surface. We conducted experiments on the four samples shown below to verify the anti-snow adhesion and snow sliding performance of each individual sample:

(1) Sample with a hydrophilic surface.
(2) Sample with a superhydrophobic surface.
(3) Sample with a two-dimensionally treated hydrophilic-superhydrophobic surface (two-dimensional alignment of the hydrophilic channels in a superhydrophobic surface).
(4) Sample with a three-dimensionally treated hydrophilic-superhydrophobic surface (three-dimensional alignment of the hydrophilic channels in a superhydrophobic surface).

2. Experimental method

2.1. Preparation

(1) Sample with a hydrophilic surface

An acrylic plate ($20 \times 20 \times 0.3$ cm^3; Mitsubishi Rayon Co., Japan) was coated with a primer (Ishihara Sangyo Co., Japan, ST-K300) by a spin coating at a rotational speed of 1500 rpm for 10 s and subsequent drying at 70°C for 1 h in an oven.

The acrylic plate was then coated by a spin coating at 1500 rpm for 10 s, with a titania-silica coating solution(Ishihara Sangyo Co., ST-K211), which was diluted to 10 parts isopropyl alcohol (Wako Pure Chemicals Industries Co., a super high-grade IPA). The acrylic plate was dried at 70°C for 1 day.

(2) Sample with a super-hydrophobic surface

An acrylic plate of the same size was coated with the same primer (ST-K300) by a spin coating at 1500 rpm for 10 s, and subsequent drying at 70°C for 1 h in an oven. About 10 cc of a commercially available hydrophobic coating solution (NTT-AT Co., Japan, HIREC-1550) was sprayed on the acrylic plate for 5 to 10 s. The acrylic plate was then dried at 70°C for 1 h. This step of spraying and drying was repeated twice. The acrylic plate was dried at 70°C for 1 day to form a superhydrophobic surface.

(3) Sample with a two-dimensionally treated hydrophilic-superhydrophobic surface

Stripes of masking tape (Nitto Denko Co., Japan, N-380), each 1 mm in width, were affixed at intervals of 1 mm on the acrylic plate with a hydrophilic surface, which is the sample with a hydrophilic surface mentioned above in (1). The same hydrophobic coating solution that was mentioned above in (2) was sprayed on the acrylic plate, and the acrylic plate was then dried at room temperature for 1 h. This step of spraying and drying was repeated twice. The stripes of masking tape were peeled off and the acrylic plate was dried at 70°C for 1 day. Using a blacklight bulb (Toshiba Lighting & Technology Co., Japan), the surface of the acrylic plate was irradiated with an ultraviolet light of 1.5 mW/cm^2 to form a two-dimensionally treated hydrophilic-superhydrophobic surface.

Note: Because striped hydrophilic and superhydrophobic parts of surfaces are formed on the same plane in this surface structure, it is called a "two-dimensionally treated hydrophilic-superhydrophobic surface."

(4) Sample with a three-dimensionally treated hydrophilic-superhydrophobic surface

Straight grooves, each 1 mm in depth and 1 mm in width, were milled into an acrylic plate at intervals of 2 mm. The same primer (ST-K300) that was mentioned above in (1) was spin-coated on this acrylic plate at 1500 rpm for 10 s. This acrylic plate was dried at 70°C for 1 h. Strips of masking tape, each 1 mm in width, were affixed on the uncut portions of the acrylic plate. The same hydrophobic coating solution that was mentioned above in (2) was sprayed on the acrylic plate, and the acrylic plate was then dried at 70°C for 1 h. This step of spraying and drying was repeated twice. In this step, the cut grooves (depressions) were made superhydrophobic. The strips of masking tape were peeled off and the acrylic plate was dried at 70°C for 1 day. The uncut parts (projections) of the acrylic plate were brought into contact with the above-mentioned titania-silica coating solution in a Petri dish to form hydrophilic surfaces.

Note: Because hydrophilic and super-hydrophobic samples whose top was hydrophilic and bottom was super-hydrophobic were formed on different planes in this surface structure, it is called a "three-dimensionally hydrophilic-superhydrophobic surface."

2.2. Evaluation

Water contact angle by 1 μL droplet was measured by a contact angle meter (Kyowa Interface Co., CA-X) and a CCD camera that is equipped with this contact angle meter (CA-X) was used to observe the shapes of water drops on the surfaces of these samples. Water drops 0.9 to 15 mg in weight were applied to the surfaces of samples to observe their shapes. Hollow glass beads (1.1 mg/ml in density, each 2 to 20 μm in particle size; Polyscience Co., USA) were mixed with water according to a specified mix proportion. Water drops of this mixture, each 30 mg in weight, were applied to the surfaces of each sample in order to observe the sliding angle at which they began to slide off the surfaces by using the sliding angle measurement system (Kyowa Interface Co., SA-11). Before performing the sliding angle measurement, ionized air generated by a static eliminator (Hakko 495) was blow on the surface of each sample to remove the electrostatic charge. A scanning electron microscope (SEM; Hitachi Co, Japan, S-4200) was used to observe the microstructure of the samples. A laser microscope (Keyence Co., Japan, VF-7500) was used to measure the surface roughness and the film thickness. Outdoor exposure tests were conducted in Nagaoka and Iwamizawa City, both in Japan. Specifically, these samples were set at a fixed angle of 45° and their anti-snow adhesion and snow slide facilitating performance were observed. Gathered data were evaluated in terms of the snow adhesion ratio and the snowfall weight at the start of snow sliding, as in the case of our previous report [10]. In gathering data on the snow adhesion ratio, samples were left outdoors for more than 1 h with their surfaces facing down to keep them clear of snow. They were then set with their surfaces facing up at an angle of 45°. After 30 min, pictures of adhering snow were taken using a digital camera and the images were dichromatically colored using the image analytical software "Scion Image" (Scion Co., USA) to distinguish between the area where there was adhering snow and the area where there was no adhering snow. Specifically, the number of pixels in the area where there was adhering snow and that in the area where there was no adhering snow were counted and the snow adhesion ratio was calculated using the following equation:

$$R = Sa/(Sa + Sn), \tag{1}$$

where R is snow adhesion ratio and Sa and Sn are area where there is adhering snow and area where there is no adhering snow, respectively.

If adhering snow slid off the surfaces of samples in less than 30 min, the data collected were not used to calculate the snow adhesion ratio. In gathering data on the snowfall at the start of snow sliding, all samples were set at an angle of 45°, as in the case of gathering data on the snow adhesion ratio, and were left until snow began to slide off their surfaces. Specifically, the bulk density of snow and the amount of change in the height of accumulated snow were measured every hour and these two parameters immediately before snow began to slide were used as data to be input into the following equation:

$$W = d \times Sa \times h \tag{2}$$

Here, W is snowfall weight at the start of snow sliding and d and h are the bulk density of snow and the height of accumulated snow when snow begins to slide, respectively.

3. Results and discussions

3.1. Microstructures of sample surfaces and wettability characteristics

Fig. 1 shows the microstructures of sample surfaces. Fig. 1(1) shows the microstructure of the hydrophilic surface. It should be noted that the hydrophilic sample has a uniform surface structure and minute roughness. Fig. 1(2) shows that of superhydrophobic sample. It should be noted that the superhydrophobic surface consists of particles, each hundreds of nanometers in size, and that the average surface roughness of this superhydrophobic film 10 μm in thickness is 800 nm. Figs 1(3) and 1(4) show those of two- and three-dimensionally treated hydrophilic-superhydrophobic surfaces. It should be noted that hydrophilic and superhydrophobic stripes have the same 1 mm width and are arranged with the same 1 mm pitch and that they have a uniform microstructure similar to the microstructures observed with samples having only hydrophilic or superhydrophobic surfaces. It was found that the average surface roughness and the film thickness of the hydrophilic film were 100 nm and 2 μm, respectively, and that the average surface roughness and the film thickness of the superhydrophobic surface were 800 nm and 10 μm, respectively.

Fig. 2 shows the shapes of water drops on the surfaces of these samples. In the case of the sample with only a hydrophilic surface, the initial contact angle with the water drops was 45°, as shown in Fig. 2(1). This sample was left outdoors for one hour under a cloudy sky and the contact angle was measured: When the sample was set with its surface facing up and down, the contact angle was 38° and 45°, respectively. And the UV light intensity was measured by UV power meter (Topcon Co., RD-2, R-36) and the irradiated UV intensity of samples with their surfaces facing up and down was 0.3 and 0.01 mW/cm^2, respectively. When the same sample was irradiated with an ultraviolet light of 1.5 mW/cm^2 for one hour using a black-light bulb, the contact angle decreased to 29°. In the case of the sample with a superhydrophobic surface, the water drop was spherical and the contact angle was 158°, as shown in Fig. 2(2). In the case of the sample with a two-dimensionally treated hydrophilic-superhydrophobic surface, the water drops spread to the hydrophilic parts only if there were a small size of water drops on the surface. As the size of water drops increased, although the water drops spread to the hydrophilic parts, they were blocked by the adjacent superhydrophobic parts and did not spread further. The same phenomenon were found by Lipowsky *et al.* when they observed a hydrophilic-hydrophobic MgF_2 film form on the surface of a hydrophobic silicon-rubber substrate to verify the wettability relative to the increase in the amount of condensed water [18]. As the size of the water drops increased, the water drops spread to both the hydrophilic and superhydrophobic parts. When observed from the direction parallel to the cut grooves, it was found that the contour of each water drop was smoothly distorted where solid, water and air form a mutual interface line (three phase line), as shown in Fig. 2(3). Drelich *et al.* formed alternate hydrophilic and hydrophobic stripes

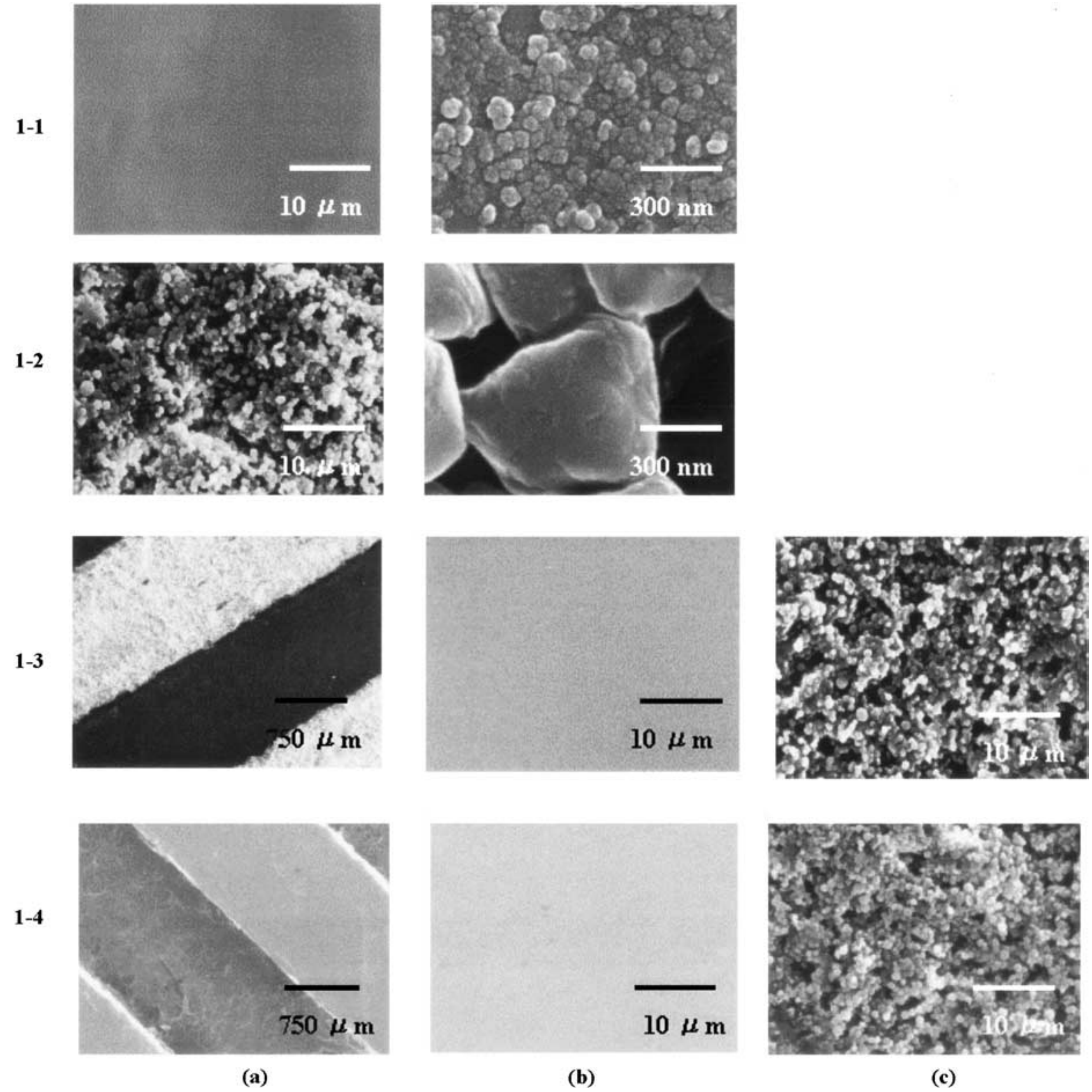

Figure 1 SEM micrographs of samples: (1) Hydrophilic surface, (a) low magnifiction and (b) high magnifiction, (2) superhydrophobic surface, (a) low magnifiction and (b) high magnifiction, (3) two-dimensionally treated hydrophilic-superhydrophobic surface, (a) low magnifiction, (b) super-hydrophobic part and (c) hydrophilic part, (4) three-dimensionally treated hydrophilic-superhydrophobic surface, (a) low magnifiction, (b) hydrophilic part and (c) super-hydrophobic part.

on a gold-thiol film and studied the wettability. They observed the same smoothly distorted water drops and explained that this water drop shape is associated with the line tension along the three phase line [19, 20]. In the case of the three-dimensionally treated hydrophilic-superhydrophobic surface with its raised parts made hydrophilic and recessed parts (cut grooves) made superhydrophobic, the water drops spread through only the hydrophilic parts (raised parts) if they were small in size. If they became large in size, they widely spread through a larger number of hydrophilic parts. A unique phenomenon was observed here: the water drops fully wetted the hydrophilic parts and there was an air space between the substrate and the water, as shown in Fig. 2(4). When observed from the direction parallel to the cut grooves, the contour of each water drop was distorted along the three phase line, as in the case of the two-dimensionally treated hydrophilic-superhydrophobic surface. The shapes of water drops on two- and three-dimensionally treated hydrophilic-superhydrophobic surfaces look alike. This is thought to be associated with the fact that water drop was sustained on the top of grooves made superhydrophobic and the penetration of water into grooves is almost negligible. Fig. 3 shows the schematic illustration of water drops from top view. The water drops are considered to have taken such shapes due to various factors, including the surface energies of solid and water, the ratio of contact with solid to that with water, line tension, and the weight of the water drops. Because it was observed during the experiments that wetting occurs with the hydrophilic parts of these two- and three-dimensionally treated hydrophilic-superhydrophobic surfaces, it is thought that water films for lubrication between

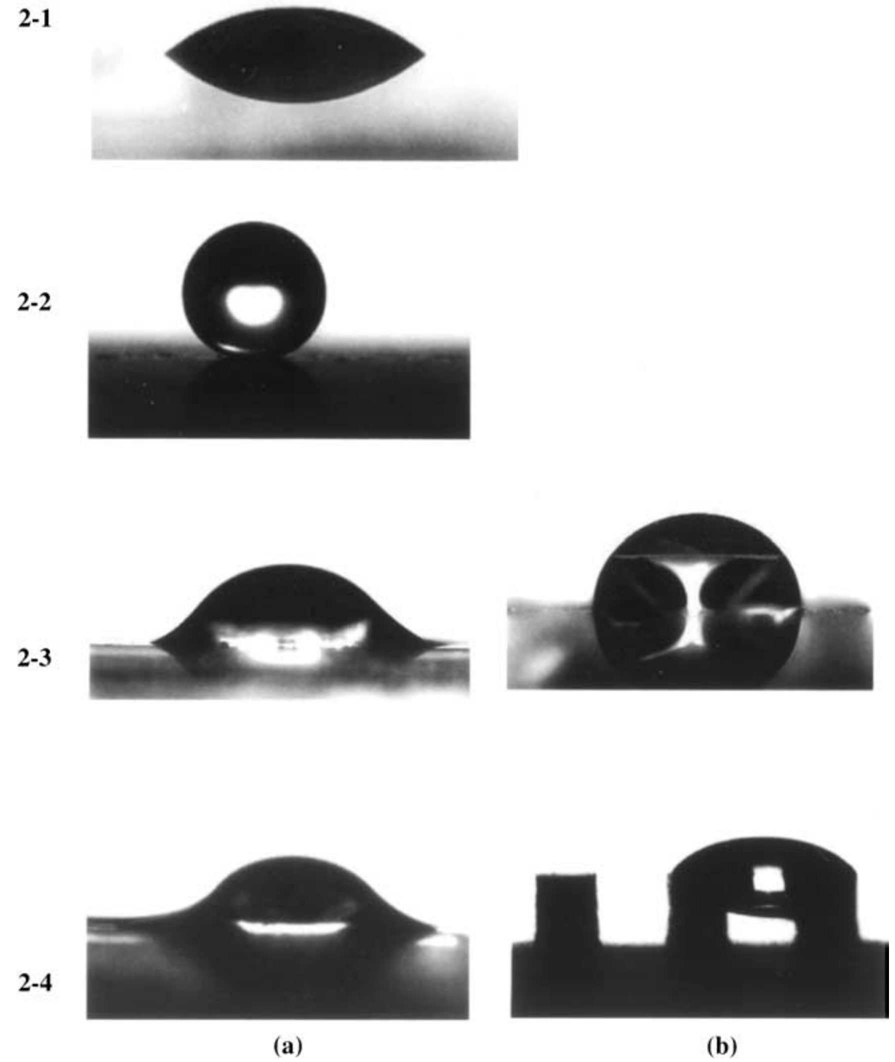

Figure 2 Shapes of water droplets on prepared samples: (1) Hydrophilic surface, (2) super-hydrophobic surface, (3) two-dimensionally treated hydrophilic-superhydrophobic surface, (a) from the parallel direction in the stripes and (b) from the orthogonal direction in the stripes, and (4) three-dimensionally treated hydrophilic-superhydrophobic surface, (a) from the parallel direction in the grooves and (b) from the orthogonal direction in the grooves.

snow and these surfaces were formed on hydrophilic parts.

3.2. Adhesion and sliding characteristics of wet snow

Fig. 4 shows typical experimental data of wet snow adhesion ratios. The wet snow adhesion ratio was smallest with the superhydrophobic surface, while it was largest with the hydrophilic surface. This result

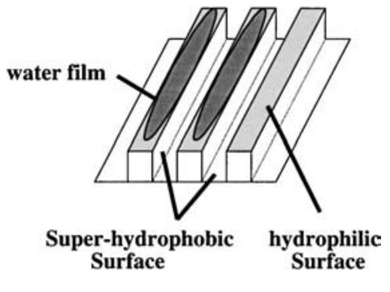

Figure 3 Schematic illustration of droplet shape on the three-dimensionally treated hydrophilic-superhydrophobic surface.

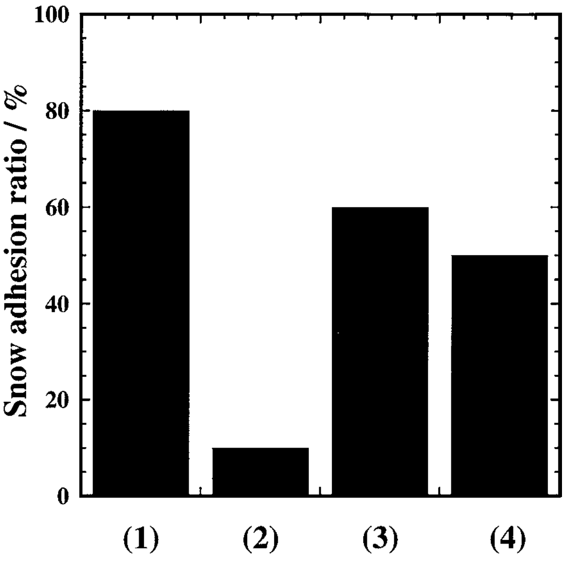

Figure 4 Typical snow adhesion ratio for wet snow on prepared samples: (1) Hydrophilic surface, (2) superhydrophobic surface, (3) two-dimensionally treated hydrophilic-superhydrophobic surface, and (4) three-dimensionaly treated hydrophilic-superhydrophobic surface.

is in agreement with the results of the experiments shown in our previous report [10]. With the hydrophilic-superhydrophobic surface, the wet snow adhesion ratio was medium. More specifically, the wet snow adhesion ratio of the three-dimensionally treated hydrophilic-superhydrophobic surface was slightly lower than that of the two-dimensionally treated hydrophilic-superhydrophobic surface. With the two-dimensionally treated hydrophilic-superhydrophobic surface, hydrophilic and superhydrophobic parts were formed on the same plane and therefore snow bridging occurred across adjacent hydrophilic surfaces more easily than in the case of the three-dimensionally treated hydrophilic-superhydrophobic surface.

Fig. 5 shows typical experimental data on the snowfall weight at the start of wet snow sliding. The snowfall at the start of snow sliding was smallest with the sample with only a hydrophilic surface, while it was medium with the sample with a three-dimensionally treated hydrophilic-superhydrophobic surface. It was largest with the sample with a two-dimensionally treated hydrophilic-superhydrophobic surface. The result that the sample with only a hydrophilic surface is superior in snow-sliding performance while the sample with only a super-hydrophobic surface is inferior in snow-sliding performance is in agreement with the results of experiments shown in our previous report [10]. It should be noted that the sample with a two-dimensionally treated hydrophilic-superhydrophobic surface is inferior in snow-sliding performance to the sample with only a superhydrophobic surface.

Hollow glass beads and water were mixed to make simulated snow. These hollow glass beads were used because their specific gravity (1.1 g/cm^3) is almost the same as that of water, they are so light weight as to remain unaffected by gravity, and are also as hydrophilic as ice. Experiments were conducted using this simulated snow to verify the snow-sliding performance of the four samples. Fig. 6 shows the experiment results. As the concentration of solids (hollow glass beads) in the simulated snow increased, the sliding angle equally increased. This is because the increased viscosity of the simulated snow resulted in an increase in viscous resistance, as indicated in our previous report [10]. When the simulated snow was applied to the sample with a hydrophilic surface or samples with two- or three-dimensionally treated hydrophilic-superhydrophobic surfaces, solids (hollow glass beads) separated from water in low solid concentrations; specifically, the phenomenon that water slides off the surface of the sample while glass beads stay put was observed. It was thought that as the concentration of solids in the simulated snow increases, the proportion of hydrophilic glass beads in the simulated snow increases, hence the movement of water from the mixture to the surface of the sample is restrained, thus making it difficult for solids to separate from water. When the simulated snow was applied to the sample with only a super-hydrophobic surface, the separation of solids from water was not observed, as mentioned in our previous report, and the concentration of solids in the mixture increased in proportion as the snow-sliding performance decreased. It was thought, therefore, that the viscous resistance of the mixture governs the snow-sliding performance.

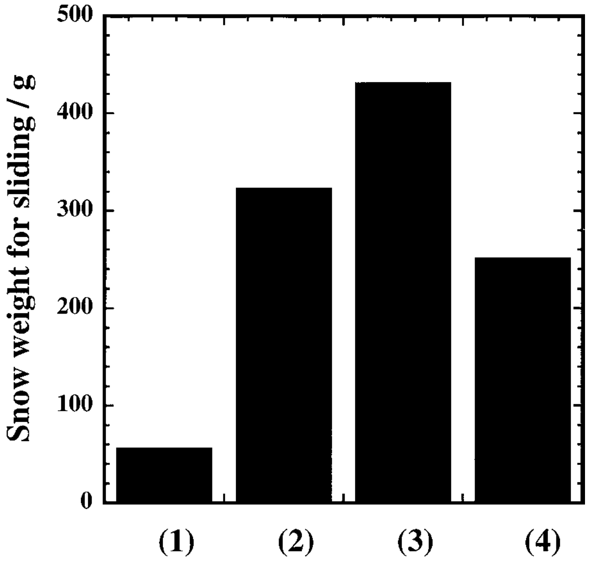

Figure 5 Typical snowfall weight for sliding on the samples for wet snow: (1) Hydrophilic surface, (2) superhydrophobic surface, (3) two-dimensionally treated hydrophilic-superhydrophobic surface, and (4) three-dimensionally treated hydrophilic-superhydrophobic surface.

The sample with a two-dimensionally treated hydrophilic-superhydrophobic surface has hydrophilic surfaces that attract water to let it form water films. Nevertheless, it is inferior to the sample with a superhydrophobic surface in snow-sliding performance. This is thought to be due to the fact that the slide inhibitory effects predominate at superhydrophobic surfaces in the two-dimensionally treated surface structure and the amount of water in the snow sitting on super-hydrophobic surfaces decreases after the water moves to hydrophilic surfaces, thus resulting in the increased viscosity of wet snow and the decreased mobility of wet snow. For snow to slide smoothly on the water films formed on a surface having both hydrophilic and superhydrophobic properties on the same plane, it is thought that the water films must be thick enough to match or surpass the repellent force of a coarsely grained structure of a superhydrophobic surface. To obtain satisfactory snow-sliding performance, therefore, the two-dimensionally treated surface requires a water film thicker than that on the three-dimensionally treated surface. On the other hand, there is very little snow sitting on super-hydrophobic surfaces formed on the three-dimensionally treated surface. Therefore, the increased resistance to mobility resulting from the movement of water to hydrophilic films has only a minimal effect and the water films formed on hydrophilic surfaces were able to facilitate the sliding of snow off the surface effectively. The qualitative estimation of the change of the viscosity value in the water-solid composite on the various surface combinations is an intrigue research matter. This value will be governed by both surface character such as surface energy difference or hydrophilic/hydrophobic alignment, and the water migration kinetics in the composite which depends on

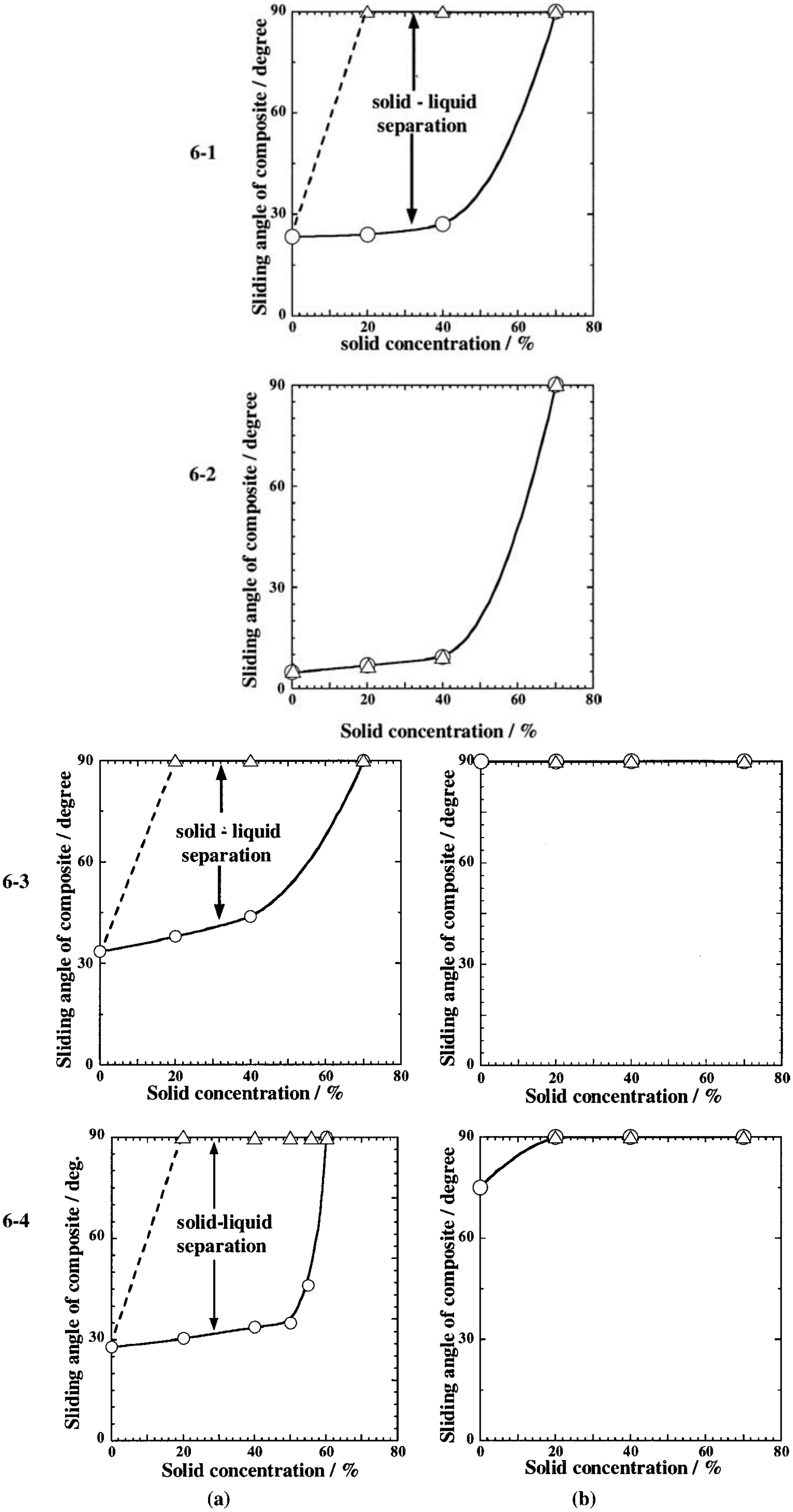

Figure 6 Solid concentration dependence of the sliding angle of the mixture of water and glass beads on prepared samples (○: Sliding angle of liquid and △: Sliding angle of solid): (1) Hydrophilic surface, (2) superhydrophobic surface, (3) two-dimensionally treated hydrophilic-superhydrophobic surface, (a) to the parallel direction in the stripes, and (b) to the orthogonal direction in the stripes, and (4) three-dimensionally treated hydrophilic-superhydrophobic surface, (a) to the parallel direction in the grooves, and (b) to the orthogonal direction in the grooves.

water/solid ratio, solid surface area, the degree of solid hydrophilicity, and atmosphere temperature. This subject is now under investigation, and will be reported elsewhere near future. The simulated snow was let to slide off the surface of the sample in the direction perpendicular to the grooves. It was found that the simulated snow did not slide even at an angle of inclination of 90° or more degrees if the ratio of solid to water in the simulated snow was larger than 20%.

When the simulated snow was let to slide in the direction parallel to the grooves, it spread downward rather slowly while wetting the hydrophilic parts. These phenomenon is thought to be associated with a large potential barrier that water drops must overcome to separate themselves from hydrophilic surfaces and to slide vertically along the grooves.

In this study, it has been verified that a two-dimensionally treated hydrophilic-superhydrophobic surface is superior to a surface with only a hydrophilic surface in anti-snow adhesion and anti-snow sliding performance though it is outperformed by a merely superhydrophobic surface when handling wet snow. It also has been verified that anti-snow adhesion and snow-sliding performance of a three-dimensionally treated hydrophilic-superhydrophobic surface are in the middle between the performance of a hydrophilic surface and that of a super-hydrophobic surface. It is thought that these performance characteristics will vary depending on the pitch, the ratio of cut grooves to uncut parts, the depth of grooves, the surface energy, and so forth. Four different surfaces were evaluated with regard to wet snow in this study. With regard to dry snow, snow anti-adhesion and snow-sliding performance are determined by interactions between solids and the number of contact points, not by the water film forming process. If the same experiments are conducted on the four different surfaces by applying dry snow to them, it is estimated that their performance would be in the middle between the performance of a hydrophilic surface and that of a superhydrophobic surface. The relationship between snow quality and snow characteristics is another research subject that needs to be studied in the future.

4. Conclusion

Hydrophilic channels were formed on the superhydrophobic surface by combining hydrophilic and superhydrophobic films two- and three-dimensionally (samples with raised parts made hydrophilic and recessed parts made superhydrophobic) to evaluate anti-snow adhesion and snow-sliding performance with regard to wet snow. Unique water drop shapes were observed on the surface of each sample, and they were thought to be associated with the surface energies of solid and water, the ratio of contact with solids to that with water, line tension, and the weight of the water drops. The snow adhesion ratio of the sample with the hydrophilic-superhydrophobic surface was in the middle between the snow adhesion ratio of the sample with only the hydrophilic surface and that of the sample with only the superhydrophobic surface. Specifically, the snow adhesion ratio of the sample with the two-dimensionally treated hydrophilic-superhydrophobic surface was slightly larger than that of the sample with the three-dimensionally treated hydrophilic-superhydrophobic surface. This was thought to be attributed to the fact that the hydrophilic and superhydrophobic surface are formed on the same plane and therefore snow bridging occurs more easily.

The snow-sliding performance of the sample with the three-dimensionally treated hydrophilic-superhydrophobic surface was in the middle between that of the sample with only the hydrophilic surface and that of the sample with only the superhydrophobic surface. Water films were formed on the sample with the two-dimensionally treated hydrophilic-superhydrophobic surfaces. The snow-sliding performance of this sample, however, was lower than that of the sample with only the super-hydrophobic surface. This was thought to be attributed to the fact that the slide inhibitory effects predominated at superhydrophobic surfaces in this particular surface structure and the amount of water in the snow sitting on superhydrophobic surfaces decreased after water moved to hydrophilic surfaces, thus resulting in the increased viscosity of wet snow and decreased mobility of wet snow. It has been demonstrated in this study that the sliding behavior of wet snow can be controlled by introducing hydrophilic channels to a superhydrophobic surface and that slide inhibitory effects can be obtained by combining hydrophilic and superhydrophobic channels two-dimensionally while slide-facilitating effects can be obtained by combining them three-dimensionally. It is expected that the characteristics of hydrophilic-superhydrophobic surfaces can be further improved by optimizing the width and pitch, the ratio of projections to depressions, the difference in surface energies, and so forth depending on the type of snow quality. We hope that the concept presented in this paper can be used as an important guideline for designing surfaces that can handle wet snow effectively and efficiently.

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