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The lubricant retaining effect of micro-dimples on the sliding surface of PDMS

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ABSTRACT

The frictional behavior of elastomers is characterized by compliance of asperities, special surface chemistry, and wetting properties. The objective of this paper is to investigate the coupled influence of surface texture and wettability on the lubrication of an elastomer contact. Patterns of micro-dimples were fabricated on disks of a polymer material, PDMS. An oxygen plasma treatment was used to hydrophilize the disk surfaces. Friction tests of the disks sliding against a spherical pin of PDMS were carried out. The experimental results indicate that the effect of surface texture is different for PDMS with different wetting properties.

1. Introduction

The quality of the interface between moving parts is often of the utmost important for correct function [1]. For example, the longitudinal ribs on shark skin reduce drag and friction forces dramatically [2]. The microstructure of hexagonal cells separated by deep channels enables tree frogs to cling to smooth surfaces without slipping, even under wet conditions [3]. These observations in nature suggest that intricate interface designs could alter the surface performance significantly.

There is a long history of improving tribological and adhesive properties of interfaces through the creation of micro-geometries on the contact surfaces, which is called surface texturing. The cross-hatch pattern resulting from the honing process has been used on the cylinder walls of reciprocating engines since the early part of the last century [4]. Recently, there has been increasing interest in the design of surface texture to improve the efficiency of engine components [5], to prevent stiction of computer hard disks during start up [6], etc. Grooves and dimples at the micro-scale are commonly used geometric features for patterns on tribo-surfaces. The advantages of surface texture include: reserving lubricant to improve anti-seizing ability [7], trapping wear debris to prevent further abrasive wear [8], decreasing the contact area to reduce adhesion [6], and generating hydrodynamic pressure to provide additional lift [9,10]. The disadvantages include increased surface roughness and contact stress at their geometric edges [11].

The effect of surface texture on contact between soft materials has been investigated recently. Salant [12] indicated that the micro-geometry on the lip surface in the sealing zone is critical for achieving sufficient reverse pumping rates for rotary lip seals. Hadinata and Stephens [13] conducted a numerical analysis to investigate the elasto-hydrodynamic effect of deterministic micro-asperities on the shaft of a lip seal. The microasperities on the shaft surface lead to a significant reduction in friction and an increase in the reverse pumping rate. Based on the assumption of full hydrodynamic lubrication, Shinkarenko et al. [14] developed a theoretical model for the analysis of the lubrication between a textured, rigid surface and a smooth, elastomeric material. It was found that the optimal aspect ratio (depth over diameter ratio) depends exclusively on the stiffness index. On the experimental front, He et al. [15] carried out dry friction tests on a textured PDMS surface using a nanoindentation–scratching system with loads on the micro-Newton scale and found the friction coefficient of a pillar-textured surface to be much lower than that of a smooth surface. Hsieh et al. [16] proposed a plasma-induced patterning method for PDMS as well as the micromolding technique.

In addition to topology and microstructure, surface wettability is another important feature significantly influencing the performance of biosurfaces [17]. The influences of surface wettability are complex because they are coupled with the microstructure of the surface. To make biomimetic design of an interface practical, it is essential to uncover the mechanisms of friction and adhesion, and in particular, the coupled effect of the type of contact, deformation scale, and interface chemistry, such as hydrophobicity.

The above issues are all involved in the friction and lubrication of polymers. On one hand, deformation of the contact region plays

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a significant role in determining fluid film properties when lubricated. Thus, even liquids with extremely low viscosity and low pressure–viscosity coefficients, such as water, can be used as lubricants. On the other hand, the low surface energy of the polymer surface could result in the exclusion of the lubricant, inducing significant adhesion between surfaces [18]. Furthermore, the surfaces of polymers can be modified by various chemical and physical means to suit a particular application. Similar to biosurfaces, these complexities provide opportunities and choices for interface design to obtain desired surface performance. The knowledge obtained in this field would benefit surface texture design for soft tribological contacts, such as the following: robot artificial skin and its surroundings, automobile wipers and windscreens, lip seals and shafts, and vehicle tyres and the ground.

The purpose of this paper is to investigate the coupled influence of surface texture and surface wettability on the lubrication of elastomer contact. An elastomer, PDMS, with different levels of hydrophobicity was used for the test specimens. Patterns of micro-dimples with different dimple diameters and area densities were fabricated on the surface of PDMS disks by lithography and replica techniques. The frictional properties of these PDMS disks sliding against a spherical PDMS pin were investigated and compared to the properties of an untextured contact.

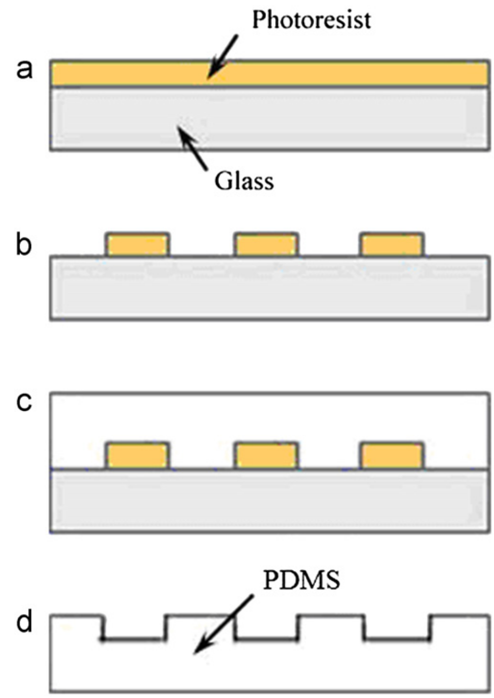

Fig. 1. Procedure of disk preparation and surface texturing for PDMS.

2. Experimental method

2.1. Specimen and surface texturing

To avoid the unsteady state of friction caused by material transferring between surfaces made of different materials, the tribopairs – the spherical pins and disks – were both made of the same commercially available elastomer, Polydimethylsiloxane (PDMS), called Sylgard 184 by Dow Corning Corp. Patterns of evenly distributed dimples were fabricated on the surface of each disk. The detailed procedure of the disk texture fabrication technique is shown in Fig. 1 and is listed as follows:

(a) Coat a layer of photoresist on a glass substrate;
(b) Fabricate the opposite mold of the photoresist on the glass substrate by the lithography process;
(c) Mix the prepolymer and its curing agent by the ratio of 10:1, pour carefully into the mold fabricated in step (b), and after completely degassing with a vacuum pump, place in a convection oven at a temperature of 70 °C for 12 h for curing;
(d) Peel the PDMS off of the mold after cooling down for 24 h.

Several patterns with different dimple diameters and different dimple area densities were fabricated in this study. The dimple depth was kept constant at the thickness of the photoresist, around 5 μm. As a result of the fabrication process, the dimple side walls were nearly perpendicular to the bottom surface. The surface roughness of the disk depended on the surface of the mold. As measured with an optical profiler, the flat area on the disk had a surface roughness Ra around 2–5 nm. The diameter of the disk of PDMS was 36 mm, and the thickness was 5 mm. Table 1 lists the patterns used in this research.

Using a spherical mold, the spherical pin of PDMS was prepared following a procedure similar to that used for preparing the disks. In this research, we fabricated spherical pins with a radius of 6.35 mm and a surface roughness of around 20–30 nm.

Fig. 2(a) shows the images of the tribopair; Fig. 2(b) shows an optical microscope image of the dimple pattern with a dimple diameter d of 100 μm, dimple depth h of 5 μm, and an area density r of 15.5%; Fig. 2(c) and (d) shows 3D profiles of a dimple and a pattern obtained by an optical profiler. Fig. 3 shows the optical microscope images of several patterns used in this study.

Table 1
Parameters of the dimple patterns.

	Dimple diameter d (μm)	Pitch l (μm)	Depth h (μm)	Area density r (%)
1	50	275–70	5	2.6–40.1
2	100	550–140	5	2.6–40.1
3	200	1100–280	5	2.6–40.1

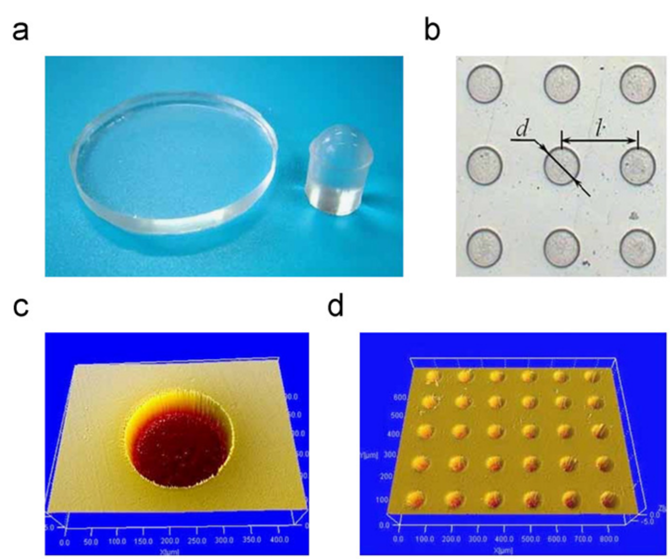

Fig. 2. (a) Image of the tribopair, (b) optical microscope image of a dimple pattern, (c) 3D profile of a dimple and (d) 3D profile of a pattern.

2.2. Mechanical and surface properties of PDMS SPECIMENS

The hardness of PDMS was measured with a Shore-A-type sclerometer per the Dow Corning CTM 0099 (Dow Corning Corp.,

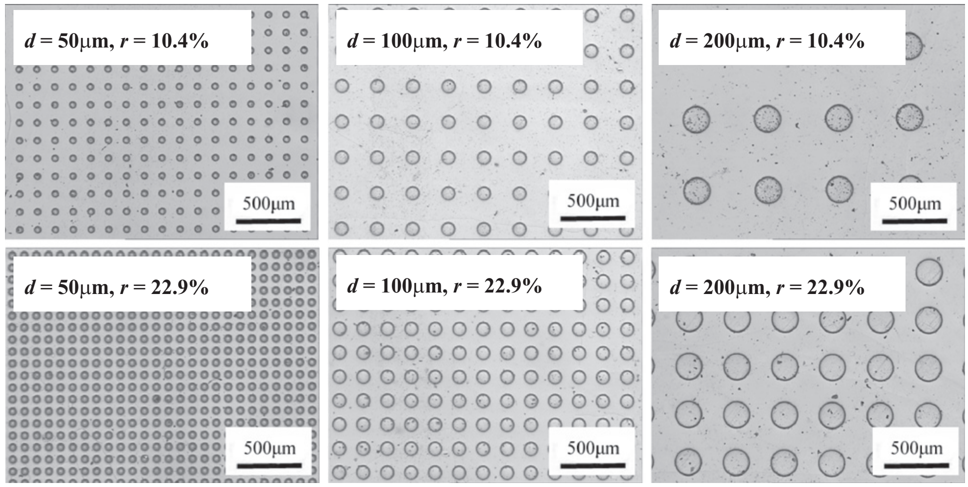

Fig. 3. Optical microscope images of several patterns used in this study.

Midland, MI, USA) standard. In accordance with the ASTM D 575-91 standard, the modulus of compression was calculated from the stress and strain data obtained with the universal mechanical tester UMT-CETR. The measurements show that the hardness of PDMS (prepolymer/curing agent mass ratio of 10:1) was 50 ± 2 Shore A, and the compression elastic modulus E was 1.036 ± 0.038 MPa.

The untreated surface of PDMS is hydrophobic, with a water contact angle of 112 ± 2 degrees. By exposing it to oxygen plasma, the surface can be temporarily rendered hydrophilic. We treated the surface for 1 min in a plasma cleaner at a pressure of 40 Pa, which resulted in a water contact angle around 5 degrees. Similar to previous documented results [19], this hydrophilic surface is not stable and will return to a hydrophobic state gradually. Keeping the surface in water can retard the hydrophobic recovery process. We placed the test specimens in water just after treatment and performed the experiments within 12 h. This ensured that the contact angle remained in the range of 15–20 degrees.

Two types of contacts were tested in this research: a hydrophobic disk against a hydrophobic pin, and a hydrophilic disk against a hydrophobic pin.

2.3. Frictional testing procedure

Friction tests were carried out between the spherical pin and the disk using a pin-on-disk tester as shown in Fig. 4. The spherical pin was stationary, held by the arm. An axial load was applied to the pin with a dead weight. The disk was driven by a motor rotating with a constant speed. The friction force was obtained by measuring the strain of the arm caused by friction. Then, the friction coefficient was calculated as the ratio of the friction force to the normal load applied.

As the viscosity of water is low, a very high sliding speed is required to achieve full fluid lubrication. Hence, a mixture of glycerol and water was also used as a lubricant. Table 2 shows the viscosity measurements made with a NDJ-1 rotary viscometer. With volume fractions of 90% glycerol and 10% de-ionized water, the viscosity of the mixed solution is 90 times higher than that of de-ionized water. The problem with using this solution is that glycerol is highly absorbent of water, so the viscosity will decrease when exposed in ambient moisture. Because each experiment takes less than 15 min, this effect was negligible in this research. The contact angle changed little when using this solution. In the hydrophobic case, the contact angles of the solution and de-ionized water were 110 and 114 degrees, respectively.

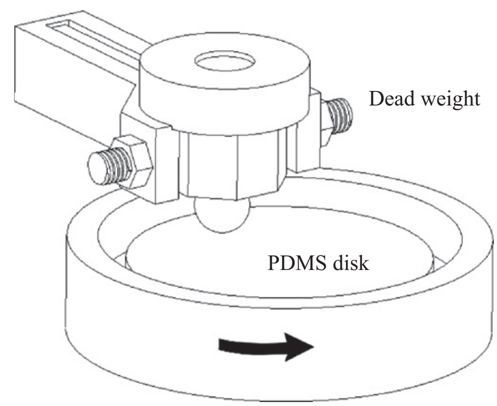

Fig. 4. Schematic diagram of the test setup.

Table 2
Viscosities of deionized water and glycerol solution.

Lubricant	Viscosity η (mPa s)
Deionized water	0.9
90% glycerol solution	84.4

Before the test, the tribopairs were ultrasonically cleaned with isopropyl alcohol and de-ionized water. Then the friction tests were conducted with lubrication from either de-ionized water or the glycerol solution at room temperature, with normal loads of 0.95 N, and with a sliding velocity varying from 0.003 to 0.2 m/s. It was found that the friction between the spherical pin and disk of PDMS was quite stable. So, first, all of the specimens had a running-in distance of 5 m at 0.04 m/s, and then the friction force was obtained by averaging the data over the sliding distance, the next 2 m, at each sliding velocity. The influence of wear on the test was neglected because there was almost no sign of wear for both hydrophobic and hydrophilic surfaces after the above test procedure.

The deformation of PDMS is time-dependent because of its viscoelastic property. Because this article is intended only for qualitative comparison, we used Hertz contact theory to roughly estimate the contact radius so that we could calculate the number of dimples in the contact area. Table 3 lists the number of dimples in the contact area, which had a contact radius around 1.9 mm. In addition, the number of dimples in the contact area will change

Table 3
Number of dimples in the contact area.

	$d=50$	$d=100$	$d=200$
$r=2.6\%$	150	38	9
$r=10.4\%$	601	150	38
$r=15.5\%$	895	224	56
$r=22.9\%$	1323	331	83
$r=29.9\%$	1727	432	108
$r=40.1\%$	2316	579	145

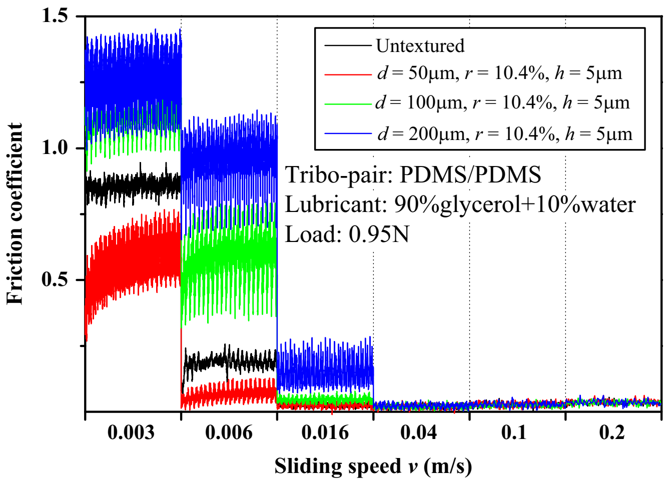

Fig. 5. Friction coefficients of untextured and textured PDMS (hydrophobic) with different dimple diameters as a function of sliding speed.

while sliding. For example, for the pattern with a dimple diameter of 200 μm and an area density of 2.6%, the number of dimples in the contact area may vary between 8 and 12, resulting in a relative large variation (−11.1% to 33.3%). For the patterns with smaller diameters, the relative variation is smaller.

3. Experimental results

3.1. Frictional properties of untextured and textured PDMS

Fig. 5 shows the raw data of friction coefficients measured from untextured and textured PDMS disks sliding against a PDMS pin at a normal load of 0.95 N and different sliding velocities and with lubrication from the glycerol solution. Both the pins and disks were hydrophobic. Because the viscosity of the glycerol solution was much higher than that of water, it was easy to obtain friction coefficients greater than 1.0 or less than 0.1 by varying the sliding velocity.

It has been reported that the friction coefficient of PDMS can be higher than 1 with water lubrication at low sliding velocities [17]. In Fig. 5, the highest average friction coefficient of the untextured specimen was around 0.86, obtained at a sliding velocity of 0.003 m/s. The reason for this result is that the lubricant has a higher viscosity than that of water, so that a mixed lubrication regime was achieved in this case. By increasing the sliding velocity, the friction coefficients of the untextured specimen decreased obviously at 0.006 m/s, and decreased to less than 0.1 at 0.016 m/s, exhibiting a transition to a full fluid lubrication regime.

Only the data for the specimens with an area density of 10.4% are presented in Fig. 5. It is shown the patterns of dimples are capable of modifying the friction performance at low sliding velocities. Compared to the untextured PDMS, the patterns with dimple diameters of 200 μm increased the friction coefficient to values as high as 1.2 and 1.0 at sliding velocities of 0.003 m/s and 0.006 m/s, respectively, which is around 1.4 and 4.0 times higher than that of the untextured surface, respectively.

Conversely, the pattern with a dimple diameter of 50 μm reduced friction. The friction coefficient could be decreased to around 0.6 and 0.2 at sliding velocities of 0.003 m/s and 0.006 m/s, respectively, which is 69% and 50% that of the untextured surface, respectively.

As reported by Vicente et al. [20], the lubricating properties of such soft contacts are determined solely by the product of the sliding velocity v and the viscosity η of the lubricant. The full Stribeck curve, exhibiting boundary, mixed, and elasto-hydrodynamic lubrication (EHL) conditions, could be presented by the data under the lubrication for both water and the glycerol solution. As shown in Fig. 6, the sphere and disk mainly have boundary lubrication with water as the lubricant. The friction coefficients were always above 1 regardless of the sliding speed. With the glycerol solution, the friction coefficient decreased rapidly, indicating mixed lubrication and then approached the lowest value, around 0.02, showing the transition to elasto-hydrodynamic lubrication.

Fig. 7 shows several Stribeck curves for textured and untextured surfaces with hydrophobic and hydrophilic PDMS. Clearly, the curves of the hydrophobic contacts and hydrophilic contacts are on different orders of magnitude. At the same value of $v\eta$, the friction coefficients of the hydrophilic surfaces are only one-tenth to one-hundredth that of the hydrophobic surface, indicating the importance of the surface hydrophilicity. Another interesting phenomenon is that different degrees of wettability could induce different effects from the surface texture. For the hydrophobic surface, surface texture has the effect of moving the Stribeck curve horizontally, which means the transition value of $v\eta$ changes. On the other hand, for the hydrophilic surface, surface texture has the effect of shifting the Stribeck curve vertically. This shift is most likely related to the fluid film thickness.

3.2. Critical parameters of surface texture for PDMS with different wettability

Fig. 5 clearly shows that the dimple diameter obviously influences the friction property of PDMS. Figs. 8 and 9 summarize the effects of dimple parameters. The Y-axis in these figures represents the percentage increase in friction from surface texture

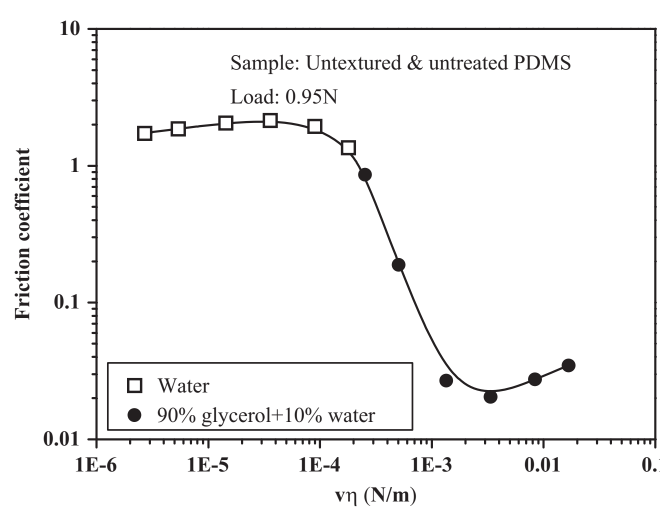

Fig. 6. Stribeck curve of untextured and hydrophobic PDMS with water and glycerol solution lubrication.

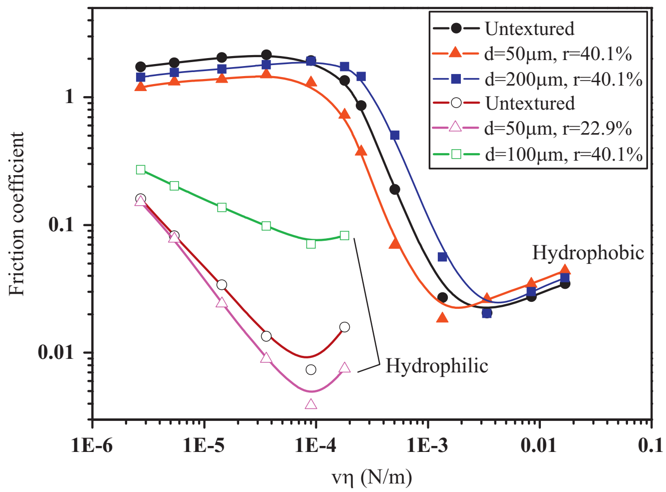

Fig. 7. Stribeck curves of untextured and textured PDMS with different surface wettabilities.

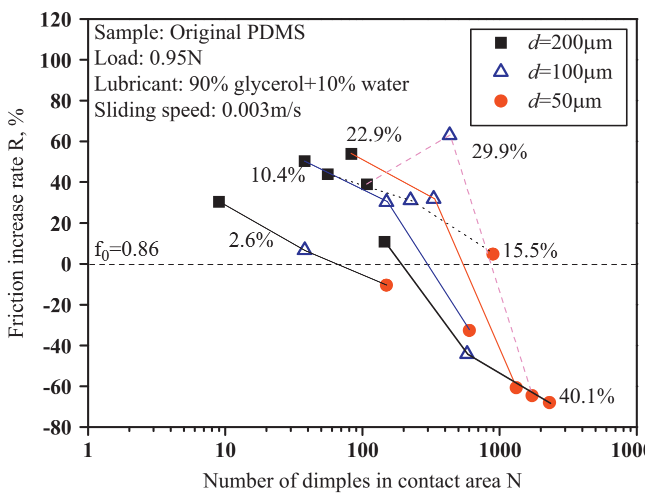

Fig. 8. Surface texture effect on the friction of a hydrophobic PDMS disk sliding against a hydrophobic PDMS pin.

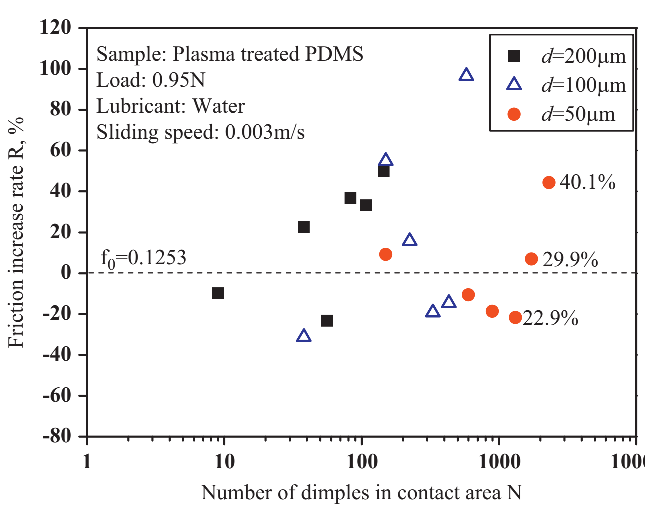

Fig. 9. Surface texture effect on the friction of a hydrophilic PDMS disk sliding against a hydrophobic PDMS pin.

R, which was calculated by

$$R = 100(f - f_0)/f_0 \quad (1)$$

where f and f_0 are the friction coefficients of the textured and untextured specimens, respectively. The X-axis in these figures is the number of dimples in the contact area, N. The value of N depends on the area density, the dimple diameter, and the size of the contact area.

Fig. 8 shows the effect of surface texture on the friction of a hydrophobic disk sliding against a hydrophobic pin of PDMS. Values above the dashed line mean that friction was increased by the surface texture, and values below mean that friction was decreased. Generally speaking, all of the patterns with a dimple diameter of 200 μm had the effect of increasing friction. On the other hand, most patterns with a dimple diameter of 50 μm had the effect of reducing friction. The symbols connected with lines in this figure are from the patterns that have the same area density but different dimple diameters. Except for the pattern with the dimple diameter of 100 μm and an area density of 29.9%, most of the data exhibit the same trend in that the friction decreases with an increasing number of dimples in contact area, N, for constant area density. In other words, having a large number of small dimples becomes critical for reducing friction on hydrophobic PDMS surfaces. Additionally, high area density reduces friction. The pattern with an area density of 40.1% and a dimple diameter of 50 μm presents the lowest friction, 68% that of the untextured specimen.

Fig. 9 shows the effect of surface texture on the friction of a hydrophilic disk sliding against a hydrophobic pin of PDMS. Compared to the results of the hydrophobic case shown in Fig. 8, there are several remarkable differences. First, with surface hydrophilization, the friction coefficient of the untextured specimen decreased to 0.1253, which is much lower than 0.86, that of the hydrophobic case. This result agrees with that of Lee and Spencer [18] very well. Second, small dimples are not the key issue for friction reduction. Comparing the patterns with dimples of 50 μm, 100 μm, and 200 μm, it is hard to say which diameter is better for low friction. Third, the number of dimples in the contact area is not critical anymore. The patterns with small numbers of dimples in the contact area, such as the pattern (d=100 μm, r=2.6%), and the pattern (d=100 μm, r=15.5%), also resulted in comparatively low friction. Finally, high area density does not reduce friction. For the patterns with a dimple diameter of 50 μm, the area density of 22.9% gave the lowest friction in this study.

3.3. Discussion

The frictional properties of elastomers are complicated because of their low elastic modulus and special surface chemistry [21]. Because Van der Waals and hydrogen bonds formed between the contacting surfaces are followed by junctions developed on the actual contact spots, formation and rupture of the junctions control the adhesion component of friction [22]. Surface roughness has the effect of shifting to a different value of $v\eta$ the transition from the mixed lubrication regime to the EHL regime, but is not very effective owing to the compliance of the asperities on the surface of elastomers [17]. Although the surfaces should have a partial contact and be in a mixed lubrication condition, if the film thickness is small and the viscosity is low, experiments show that the hydrophobic surfaces will suddenly spring together, giving intimate contact over the major part of the contact region [23] so that any liquid between the two surfaces is completely excluded [24]. Therefore, for the hydrophobic tribopairs of PDMS, the friction coefficients of dry and water-lubricated contact are very similar at low sliding velocities, getting closer as the entrainment speed decreases [17].

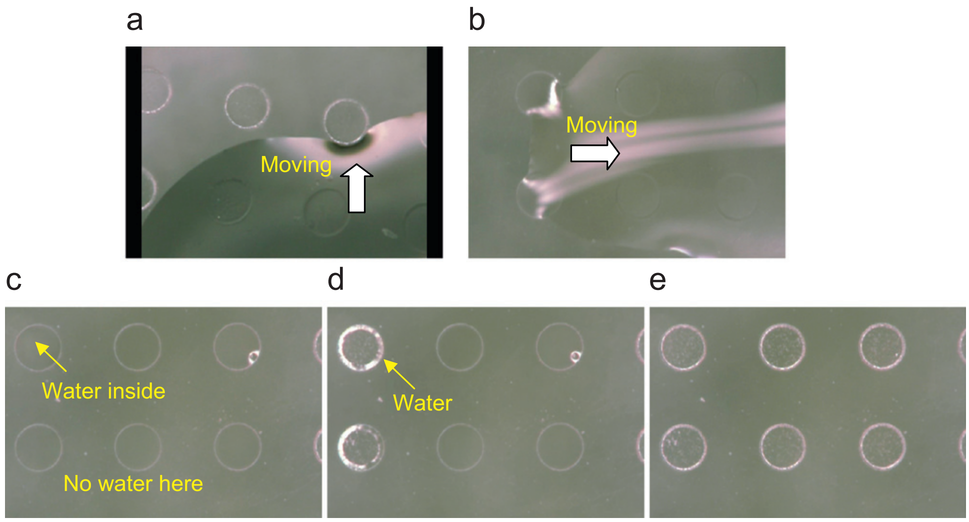

Fig. 10. Behavior of a water drop moving over a textured hydrophobic surface of PDMS.

Surface texture is a type of patterned surface roughness. In order to understand the effect of surface texture on the lubrication of PDMS surfaces, the behavior of a water droplet moving on the textured, hydrophobic surface of PDMS was recorded using an optical microscope. Fig. 10 shows frames extracted from the video. As the droplet, blown by air, approaches a dimple, its boundary line is bent, as shown in Fig. 10(a), demonstrating that the existence of a dimple seems to obstruct the movement of the droplet. However, after the surface has been wetted and the water droplet has nearly passed, as shown in Fig. 10(b), it is interesting that the water not only still fills the whole dimple, but also seems to encounter a drag force so that the shape of the droplet is deformed considerably. After the water droplet has moved over the dimple, the dimple is still filled with water, as shown in Fig. 10(c), although it is extraordinary that the water can stay in a hydrophobic dimple with a relatively large diameter of 50 μm and a very shallow depth of 5 μm. Because of the surface tension of water, this thin water film does not remain for very long. After a short while, no more than 1 s, the thin water film collapses, and the water shrinks to the circular wall of the dimple. In Fig. 10(d), the water in the left two dimples shrank to their circular wall so that their edges look bright, but the other dimples still have the thin water film inside. Finally, the films of water in all of the dimples collapse, as shown in Fig. 10(e). These observations show that the dimples on the surface of PDMS not only have the effect of resisting the leaving of the water droplet, but also have the ability to retain water.

Because the high friction coefficient of hydrophobic PDMS at low sliding speeds is mainly due to direct contact caused by the extrusion of lubricant, the ability to retain liquid by surface texture would be useful for reducing the friction between hydrophobic PDMS surfaces. The liquid retained in the dimple could be re-supplied to the surrounding area to avoid the direct contact, particularly, while the dimple is squeezed during contacting. From this viewpoint, a higher area density of dimples would improve the lubricant-retaining effect. Smaller dimples diameters would ensure the uniform distribution of larger numbers of dimples in the contact area for the cases with the same area density. On the other hand, it has been reported that small and shallow dimples have a better effect on reducing friction and increasing film thickness for EHL lubrication [25,26], particularly for non-conformal contact [27]. Of course, on the negative side, a higher area density means higher surface roughness, more geometric edges which would result in high contact stresses while the surfaces are in contact and the edges are perpendicular to the sliding direction [11]. However, because PDMS is much softer than materials such as ceramics and metals, these should not be the dominant effects. This would explain why the pattern with the small dimple diameter, 50 μm, and high area density, 40.1%, gave the most friction reduction for hydrophobic PDMS contact.

The hydrophilic case is different from the above situation. A water droplet spreads easily on a hydrophilic PDMS surface. In the case of high hydrophilicity (just after the oxygen plasma treatment), it is hard to recognize the boundary of the water droplet. Therefore, enhanced hydrophilicity facilitates fluid entrainment [17], and the lack of water would not be the dominant factor any more for the hydrophilic surfaces of PDMS.

Because the baseline friction coefficient in the hydrophilic case is much lower than that in the hydrophobic case, some detailed concepts of dimple design for hard materials might also need to be considered for soft-material contact [28]. For example, too high an area density of dimples would induce high friction [29]. It has been reported that preferable aspect ratios of dimples (depth over diameter) for hydrodynamic lift generation is in the range of 0.05-0.01 [30], etc. That might be the reason why the pattern with a dimple diameter of 50 μm and an area density of 40.1% did not have the lowest friction for hydrophilic surfaces of PDMS.

On the other hand, a different area density means a different surface roughness. Bongaerts et al. reported that the surface roughness changes the minimum friction coefficient in the Stribeck curve [17]. Of course, the shift of the Stribeck curves of hydrophilic PDMS in the vertical direction might have other explanations [31]. The total friction should be the balance of surface roughness, hydrodynamic effect, contact stress, uniformity of lubrication film, etc.

4. Concluding remarks

In this paper, we have investigated the coupled influence of surface texture and surface wettability on the lubrication of elastomer contact. The lithography and replica processes were used for surface texture fabrication on the surfaces of PDMS specimens. Dimple patterns with a dimple depth of 5 μm, diameters of 50, 100, and 200 μm, and area densities from 2.6% to 40.1% were fabricated. An oxygen plasma treatment was used to hydrophilize the surface of the PDMS. The friction tests of the PDMS disks sliding against a spherical pin were carried out using both water and a glycerol solution for lubrication. The conclusions are as follows:

(1) The frictional behavior of surface texture is different for surfaces of PDMS with different wetting properties.
(2) For the hydrophobic surface, high area density and a large number of dimples become critical for reducing friction. In this study, the smallest dimples (with a diameter of 50 μm) and highest area density (40.1%) reduced friction the most. This was not the case with a hydrophilic surface, though.
(3) From observations of the behavior of a water droplet moving on the PDMS surface with a dimple pattern, it appears that the dimples could provide both a drag force resistant to lubricant exclusion and the ability to act as a lubricant reservoir, which is important for reducing friction between hydrophobic surfaces.

Acknowledgments

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References

[1] Evans CJ, Bryan JB. Structured, textured or engineered surfaces. Annals of the CIRP 1999;48:541–56.
[2] Bechert DW, Bruse M, Hage W, Meyer R. Fluid mechanics of biological surfaces and their technological application. Naturwissenschaften 2000;87: 157–71.
[3] Federle W, Barnes WJP, Baumgartner W, Drechsler P, Smith JM. Wet but not slippery: boundary friction in tree frog adhesive toe pads. Journal of the Royal Society Interface 2006;3:689–97.
[4] Willis E. Surface finish in relation to cylinder liners. Wear 1986;109:351–66.
[5] Ben-Tsur L. Reduced friction using a nanolayer-based environmentally friendly technology. MTZ 2008;69:28–33.
[6] Ranjan R, Lambeth DN, Tromel M, Goglia P, Li Y. Laser texturing for low-flying-height media. Journal of Applied Physics 1991;69:5745–7.
[7] Wang XL, Kato K. Improving the anti-seizure ability of SiC seal in water with RIE texturing. Tribology Letters 2003;14:275–80.
[8] Suh NP, Mosleh M, Howard PS. Control of friction. Wear 1994;175:151–8.
[9] Etsion I. State of the art in laser surface texturing. Journal of Tribology-Transactions of the ASME 2005;127:248–53.
[10] Wang XL, Kato K, Adachi K, Aizawa K. Loads carrying capacity map for the surface texture design of SiC thrust bearing sliding in water. Tribology International 2003;36:189–97.
[11] Yuan S, Huang W, Wang X. Orientation effects of micro-grooves on sliding surfaces. Tribology International 2011;44:1047–54.
[12] Salant RF. Modelling rotary lip seals. Wear 1997;207:92–9.
[13] Hadinata PC, Stephens LS. Soft elastohydrodynamic analysis of radial lip seals with deterministic microasperities on the shaft. Journal of Tribology 2007;129:851–9.
[14] Shinkarenko A, Kligerman Y, Etsion I. The effect of surface texturing in soft elasto-hydrodynamic lubrication. Tribology International 2009;42:284–92.
[15] He B, Chen W, Wang QJ. Surface texture effect on friction of a microtextured poly(dimethylsiloxane) (PDMS). Tribology Letters 2008;31:187–97.
[16] Hsieh S, Cheng Y-A, Hsieh C-W, Liu Y. Plasma induced patterning of polydimethylsiloxane surfaces. Materials Science and Engineering B 2009;156:18–23.
[17] Bongaerts JHH, Fourtouni K, Stokes JR. Soft-tribology: lubrication in a compliant PDMS—PDMS contact. Tribology International 2007;40:1531–42.
[18] Lee S, Spencer ND. Aqueous lubrication of polymers: Influence of surface modification. Tribology International 2005;38:922–30.
[19] Lawton R, Price C, Runge A, Dohertyiii W, Saavedra S. Air plasma treatment of submicron thick PDMS polymer films: effect of oxidation time and storage conditions. Colloids and Surfaces A: Physicochemical and Engineering Aspects 2005;253:213–5.
[20] Vicente Jd Stokes JR, Spikes HA. Soft lubrication of model hydrocolloids. Food Hydrocolloids 2006;20:483–91.
[21] Maeda N, Chen N, Tirrell M, Israelachvili JN. Adhesion and friction mechanisms of polymer-on-polymer surfaces. Science 2002;297:379–82.
[22] Myshkin N, Petrokovets M, Kovalev A. Tribology of polymers: adhesion, friction, wear, and mass-transfer. Tribology International 2005;38:910–21.
[23] Roberts AD, Tabor D. The extrusion of liquids between highly elastic solids. Proceedings of the Royal Society A: Mathematical, Physical and Engineering Sciences 1971;325:323–45.
[24] Chaudhury MK, Whitesides GM. Direct measurement of interfacial interactions between semispherical lenses and flat sheets of poly(dimethylsiloxane) and their chemical derivatives. Langmuir 1991;7:1013–25.
[25] Wang X, Zhang H, Hsu SM. The effects of dimple size and depth on friction reduction under boundary lubrication pressure. ASME/STLE international joint tribology conference. San Diego, California, USA; 2007. pp. 909–11.
[26] Mourier L, Mazuyer D, Lubrecht AA, Donnet C. Transient increase of film thickness in micro-textured EHL contacts. Tribology International 2006;39: 1745–56.
[27] Wang XL, Liu W, Zhou F, Zhu D. Preliminary investigation of the effect of dimple size on friction in line contacts. Tribology International 2009;42: 1118–23.
[28] Yu H, Huang W, Wang X. Dimple patterns design for different circumstances. Lubrication Science 2012. http://dx.doi.org/:10.1002/ls.168.
[29] Yan D, Qu N, Li H, Wang X. Significance of dimple parameters on the friction of sliding surfaces investigated by orthogonal experiments. Tribology Transactions 2010;53:703–12.
[30] Etsion I, Kligerman Y, Halperin G. Analytical and experimental investigation of laser-textured mechanical seal faces. Tribology Transactions 1999;42: 511–6.
[31] Wang XL, Kato KJ, Adachi K. The critical condition for the transition from HL to ML in water-lubricated SiC. Tribology Letters 2004;16:253–8.