LUBRICATION SCIENCE
Lubrication Science 2013; **25**:67–78
Published online 17 October 2011 in Wiley Online Library (wileyonlinelibrary.com). DOI: 10.1002/ls.168

Dimple patterns design for different circumstances

Haiwu Yu, Wei Huang and Xiaolei Wang*,†

School of Mechanical & Electrical Engineering, Nanjing University of Aeronautics & Astronautics, Nanjing 210016, China

ABSTRACT

The appealing and enigmatic properties of biological surfaces inspire people that a smooth surface is not always the best. Currently, the patterns of microdimples have attracted more attentions since such closed texture cells are supposed to generate hydrodynamic pressure easily. The advanced manufacturing techniques provide precision and freedom for the fabrication of microdimples, which enables the optimisation of dimple geometry and distribution to obtain better tribological performances. Over the past decade, experiments were carried out to investigate the effects of microdimples on various materials under different operating conditions. Analytical models were established to evaluate the hydrodynamic effect of the dimple patterns. The results suggest that the design of dimple pattern following hydrodynamic principle would obtain good tribological performance under high-speed low-load conditions; however, for the case of low-speed high-load conditions, shallow and small dimples would have more obvious friction reduction effect than those designed based on hydrodynamic pressure generation. Copyright © 2011 John Wiley & Sons, Ltd.

Received 28 April 2011; Accepted 19 August 2011

KEY WORDS: surface texture; microdimple; sliding; friction; hydrodynamic

INTRODUCTION

Through aeons of life evolution, biological surfaces exhibit appealing and enigmatic properties for specific purposes. The longitudinal ribs on shark skin reduce drag and friction force dramatically. The microstructures and nanostructures on lotus leaves represent self-cleaning surfaces to avoid fluid-dynamic deterioration by the agglomeration of dirt.[1,2] These nature facts remind people that a smooth surface is not always the best.

The surface texture, such as microdimples or grooves, has been a well-known approach to improve tribological performances of sliding surfaces. Reserving lubricant to prevent seizure should be the earliest understanding of the lubricating mechanism of surface texture. Hence, the cross

*Correspondence to: Xiaolei Wang, School of Mechanical & Electrical Engineering, Nanjing University of Aeronautics & Astronautics, Nanjing, 210016, China.
†E-mail: wxl@nuaa.edu.cn

hatch by horning process has been successfully used for cylinder liner of combustion engines so far.[3] In the 1960s, Hamilton *et al*. indicated that micro-irregularities are able to generate the additional hydrodynamic pressure to increase the load-carrying capacity of the surfaces.[4] This theory has been well accepted and promoted, particularly from 1990s by Etsion's group, who developed a series of theoretical models to construct the theory of laser texturing for mechanical seals.[5,6] Although new mechanisms such as 'inlet suction'[7] and new modelling method[8] are proposed continually, microhydrodynamic effect is regarded as the most dominant effect of surface texture at the conditions of high speed and low load.[9–13] At this condition, the texture design concept is mainly according to fluid dynamics.

At the extreme case of 'dry' contact condition, it is known that the surface texture could trap wear debris to prevent further abrasive wear,[14] and decreases the contact area to reduce the adhesive force between the disk and the slider of magnetic storage devices.[15]

The surface texture design in mixed lubrication is complicated, particularly for condition with low speed and high load, where full fluid film could not be established easily; a portion of the surface is in contact so that the friction was determined by how surface texture influences boundary lubrication.

The advanced manufacturing techniques such as laser and reactive etching provide precision and freedom for the fabrication of surface texture. However, in order to obtain better tribological performance, the most important point is that we should know what the principle of surface texture design for different circumstances is.

Over the past decade, experiments were carried out to investigate the effects of microdimples on various surfaces including silicon carbide, metals and elastomer, under high-speed low-load and low-speed high-load conditions, by water and oil lubrication. Numerical and analytical models based on Reynolds equation were used to evaluate the hydrodynamic effect generated between contacting surfaces. This paper will summarise several approaches to enhance the effects of surface texture for different circumstances. The data come from our previous published papers (about ceramics and metals), our current work on polymer and contribution by other researches.

SURFACE TEXTURE FOR HIGH SPEED AND LOW LOAD

Generating additional hydrodynamic pressure is well accepted as the most important effect of surface texture under relative high speed and low load. Each cell of surface texture works as a microstep bearing so that the load-carrying capacity could be increased. The analytical results based on Reynolds equation could explain the experimental results in most cases.

Area ratio, depth and diameter

Dimple diameter, depth and area ratio are the major parameters of evenly distributed dimple patterns. Many researchers have contributed to the investigation of the effects of above parameters on friction or load-carrying capacity of sliding surfaces. As early as 1999, Etsion suggested that the depth over diameter ratio is the most important parameter for high load-carrying capacity.[9] Nowadays, people also agree that the area ratio of microdimples is another important factor for the pattern of microdimples.[16,17] Orthogonal studies indicated that area ratio is more significant for the tribological performance than the depth or diameter of dimples.[18]

DOI: 10.1002/ls

Without consideration of the negative effects such as the decrease of contact area and the contact stress caused by dimple edge, the analytical models usually suggest that the area ratio of 20%–40% would be preferable since the total hydrodynamic pressure is maximised within this range.[19,20] However, the optimal values of area ratio obtained by experiments were usually not as high as the theoretical results. Figure 1 is an example, which shows the load-carrying capacity map of the textured surface of silicon carbide sliding in water. With the optimised parameters of the dimples, which is only 4.9% for area ratio, and 0.01–0.02 for depth over diameter ratio, the load-carrying capacity could be increased more than two times. On the other hand, as shown in Figure 2, the analytical solution also shows a high hydrodynamic lift region at proper area ratio and depth over diameter ratio. But the optimal value of the area ratio is much higher than that obtained by experiments.[10]

For the sliding surfaces of metals, the optimal area ratio seems to be slightly higher than that for silicon carbide. Several studies support that 5%–15% is the preferable value.[18,21] For example, the pattern of dimples (diameter 80 μm, depth 5.5 μm, 12%) is beneficial for expending the range of the hydrodynamic lubrication regime.[22]

The optimal value of area ratio could become higher if the material has relative lower Young's modulus. As shown in Figure 3, the experiments show that area ratio as high as 29% presented low friction and low wear rate for the contact between a soft material ultra-high-molecular-weight polyethylene and a stainless steel under water lubrication.

This is probably due to the contact stress caused by the edge of surface texture. High stress would be generated at the edge of dimples, particularly at the side perpendicular to the sliding direction.[23] The stress would be higher for harder materials with sharper edges. Therefore, the optimal value of the area ratio obtained by experiment is usually lower than that obtained by theoretical analysis only based on Reynolds equation, and the optimal value of the area ratio for ceramics is lower than that for metals and polymers.

However, if the anti-seizure ability is the high priority, particularly at the starved lubrication condition, high area ratio may result in good tribological performance even for hard materials.[24] This is because that relative high area ratio is helpful to retain lubricant. The data of laser texturing on metals show that the pattern of dimples (φ 90 μm, depth 2–20 μm, 25%) could increase the maximum product of contact pressure and sliding speed (PV) value of the mechanical seal obviously.[25] And the dimple pattern with the area ratio of 15% shows an obvious increase of the critical load for SiC sliding in water.[26]

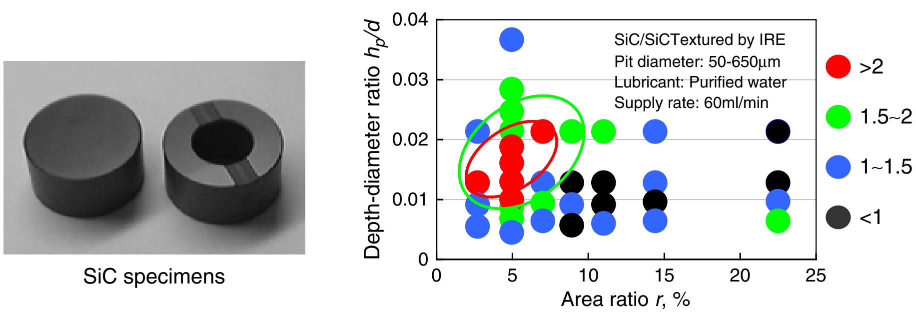

Figure 1. The effect of dimple parameters on the increment of load-carrying capacity of SiC sliding in water.[10]

DOI: 10.1002/ls

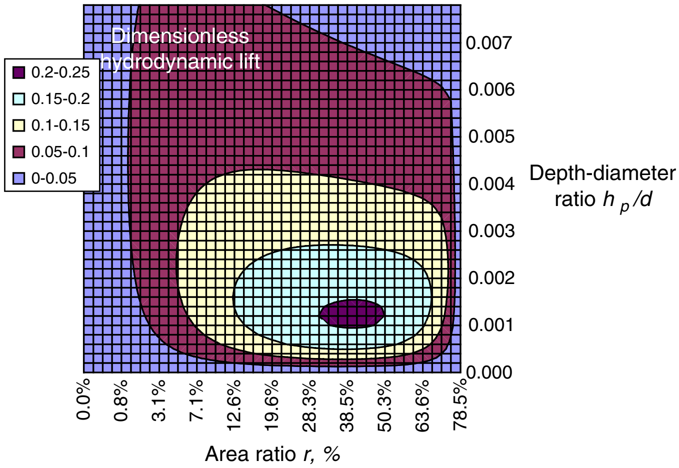

Figure 2. Dimensionless hydrodynamic lift as a function of the area ratio and depth over diameter ratio of the dimples.[10]

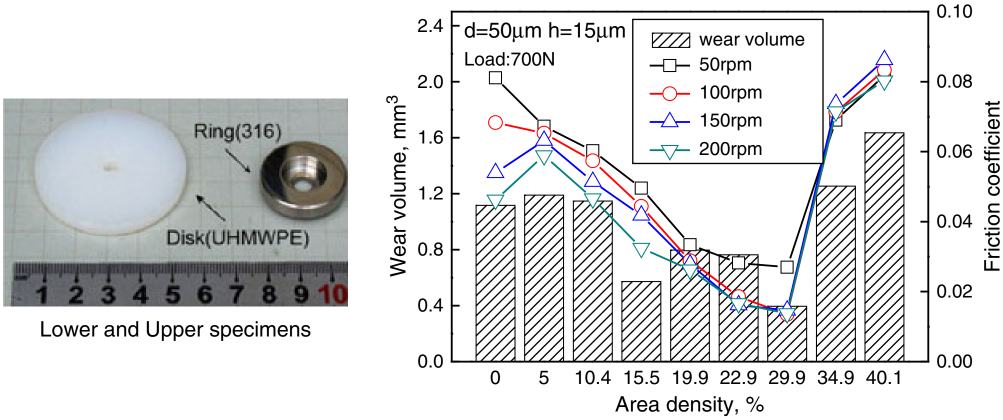

Figure 3. The effect of area ratio on the friction coefficient between ultra-high-molecular-weight polyethylene (UHMWPE) and stainless steel.

Diameter and depth of the dimples do not seem to be as important as the area ratio at high-speed low-load conformal contact condition. Analytical model suggests that 100–300 μm is a good range for the dimple diameter, and the dimple depth near the clearance between surfaces is better for obtaining high hydrodynamic pressure. However, analytical model agrees with the experimental data that the parameter of depth over diameter ratio is very important to the tribological performance of sliding surfaces. Etsion *et al*. suggests that the preferable value of it is in the range of 0.01–0.05, and higher velocity or smaller clearance (by higher load) would result in smaller value of the optimal depth over diameter ratio.[9] This is confirmed by experiments of SiC lubricated by water as shown in Figure 1.

DOI: 10.1002/ls

Table I. Geometry parameters of the patterns of dimples.[29]

	Depth (μm)	Radius (μm)	Area of a dimple (μm^2)	Pitch (μm)	Area ratio (%)
Circle	8	75	17 671	500	7
Ellipse	8	150/37.5	17 671	500	7
Triangle	8	202 (side length)	17 671	500	7

On the contrary, for the contact of ball-on-flat or cylinder-on-flat, the diameter of dimples would become important for the tribological performance. Several documented studies reported that Hertz contact width might be a critical value. The dimples with diameter larger or smaller than the contact width may result in significant difference in film thickness or load-carrying capacity.[27,28]

Dimple shape

Although circular dimples are low cost and easy for fabrication, modern micromanufacturing techniques are able to fabricate the dimples with other shapes. This enables the optimisation of dimple geometry to obtain better tribological performance of sliding surfaces. Table I lists a group of specimens that have dimples with same depth, individual area and area ratio, but different shapes.

Experiments of conformal contact under oil lubrication were carried out to evaluate the shape and orientation effects of these dimples. Figure 4 shows the Stribeck curves of these specimens. It was

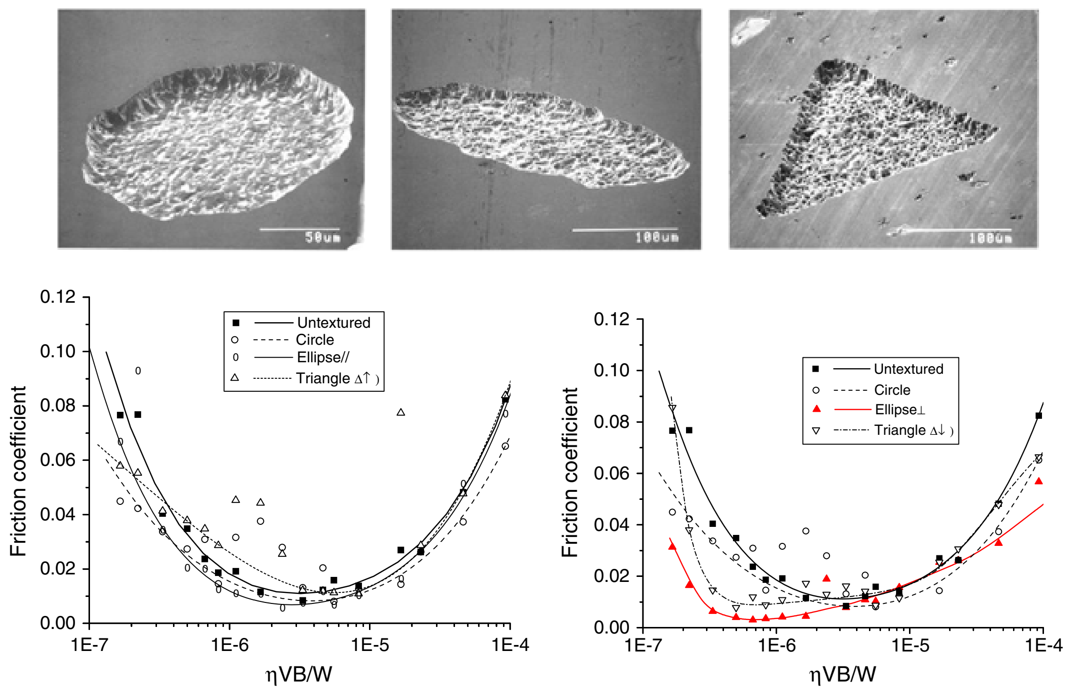

Figure 4. Stribeck curves of the surface textures parallel (left) and perpendicular (right) to the direction of sliding (η is the viscosity of the lubricant, *V* is the sliding speed, *B* is the contact width and *W* is the normal load).[29]

DOI: 10.1002/ls

found that, for the triangle dimple, the sliding direction that lubricant driven toward the base of the triangle was better than that toward the apex, and the elliptical dimple perpendicular to the sliding direction showed the better effect on the load-carrying capacity than the cases of circular dimple and elliptical dimple parallel to the sliding direction. This is similar to the case of microgrooves, which shows good hydrodynamic lubrication while the grooves are perpendicular to the sliding direction.[30] Based on Reynolds equation, the dimensionless hydrodynamic pressures generated by different dimples were calculated and averaged as shown in Figure 5. It explained the experimental results in Figure 4 very well.[29] Similar results were also obtained by other researchers.[31]

Dimple distribution

Dimples evenly distributed as a square or hexagon array are the normal ways people design the pattern of microdimples. As shown in Figure 5, high hydrodynamic pressure is always generated on the one side of the dimple, as well as low pressure on another side. Analytical simulation indicates that the two adjacent dimples would have interactions for each other on the pressure distribution, particularly, in the direction perpendicular to the sliding while the area ratio is high. Hence, optimisation of dimple distribution is another approach to enhance the hydrodynamic effect on the whole surface. Figure 6 shows the dimple distribution effect on the dimensionless hydrodynamic pressures. The top is the regular dimple pattern, in which the dimples distribute as a square array; the column is perpendicular to the line of the dimples. By shifting the lines of the dimples to the right, the column will be at an angle of α to the line of the dimples, and the area ratio will remain identical. A model based on

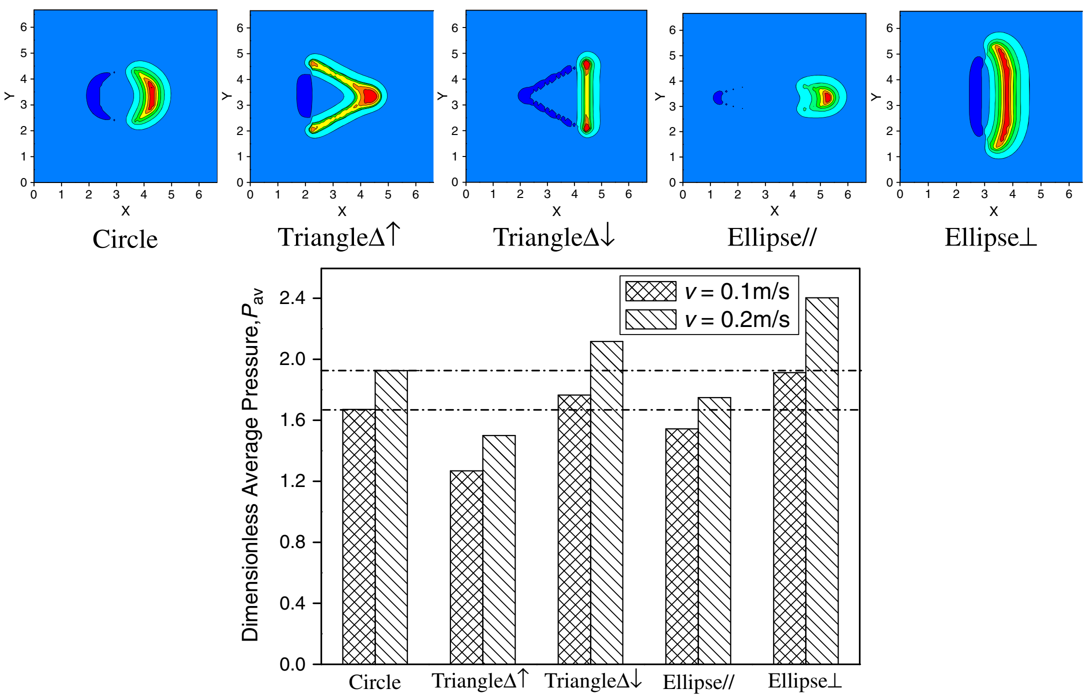

Figure 5. Average pressure P_{av} of different textural shapes and orientations at the speed of 0.1 and 0.2 m s^{-1}.[29]

DOI: 10.1002/ls

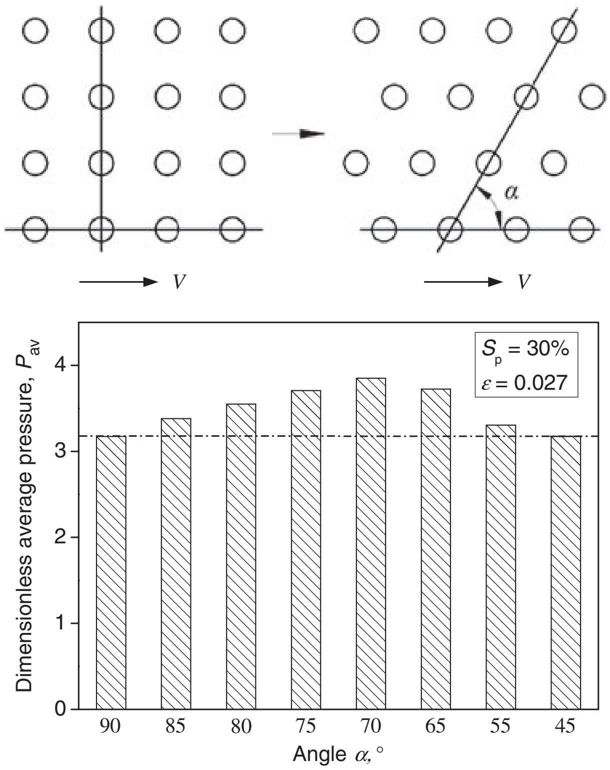

Figure 6. Average dimensionless hydrodynamic pressure as a function of the angle α between line and column of dimples (the area ratio $S_p = 30\%$, the depth over diameter ratio $\varepsilon = 0.027$).

Reynolds equation was established to evaluate the hydrodynamic pressure influenced by the angle α. The results indicated that the dimensionless hydrodynamic pressure could be increased up to 21.7% just by the optimising the angle α, which is around 70° in this case.

SURFACE TEXTURE FOR LOW SPEED AND HIGH LOAD

Since the hydrodynamic effect depends on the sliding speed between two surfaces, the hydrodynamic lift would not be dominant under the condition of low speed and high load. Therefore, the dimples effective at high-speed low-load condition only have limited friction reduction rate at low-speed high-load conditions.

The experimental results in Figure 7 were obtained from the tribo-tests of ball-on-three-flats, which were carried out at the condition of low speed ($0.2\ \mathrm{m\,s^{-1}}$) and high load (203 MPa). It shows that the small and shallow dimple would have an obvious effect of friction reduction compared with other specimens that has the same area ratio and nearly the same depth over diameter ratio.[32] The reason has been well explained with elastohydrodynamic lubrication experiments by Krupka, which showed that a significant increase in lubricant film thickness is induced by a shallow microcavity in the elastohydrodynamic lubrication regime.[33]

DOI: 10.1002/ls

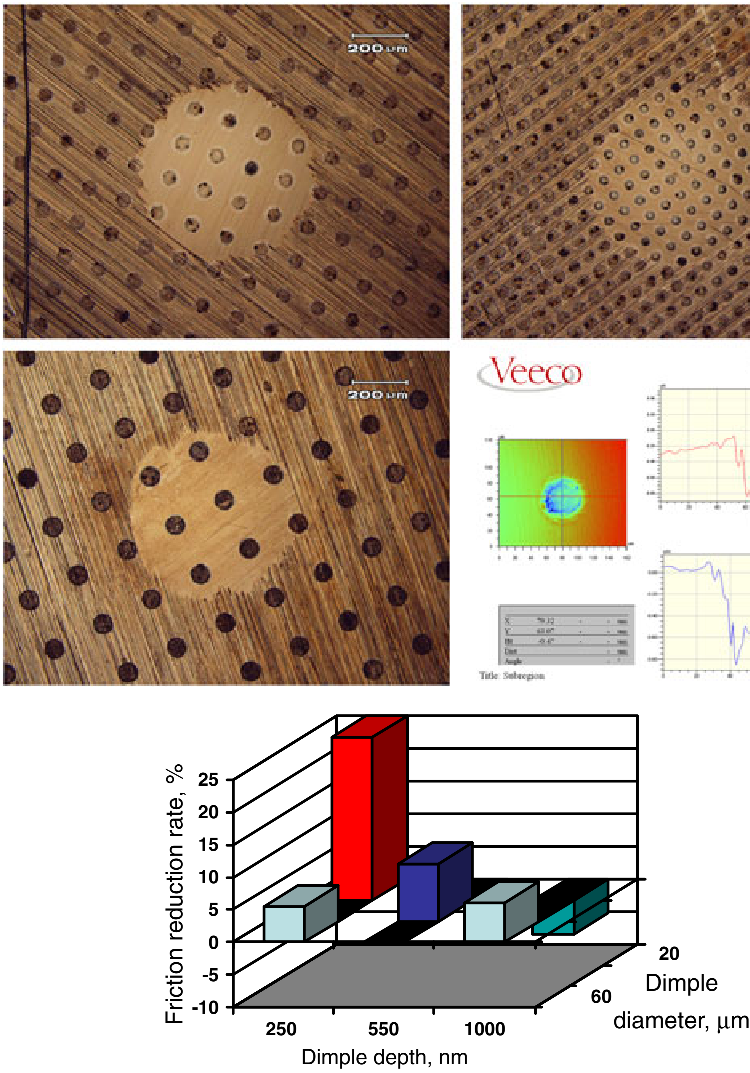

Figure 7. Friction reduction rates of different patterns.[32]

Figure 8 shows the experimental data obtained from the friction tests between soft materials. A PDMS disk (Sylgard 184 silicone elastomer with standard curing process, Dow Corning, Midland, MI, USA) was sliding against a PDMS spherical surface under the lubrication of glycerol solution. μ/μ_0 less than 1 means that the textured surface has a lower friction coefficient than that of untextured specimen. From the results, it could be found that the number of the dimples in the contact area becomes important. Even with the same area ratio, the smaller dimples and larger number of dimples resulted in friction reduction, whereas the larger dimples caused high friction. Clearly, lubricant retaining effect is more important than the hydrodynamic effect in this case. Similar results were also obtained by Pettersson and Jacobson in the case of bearing ball sliding against textured silicon wafer.[34]

DOI: 10.1002/ls

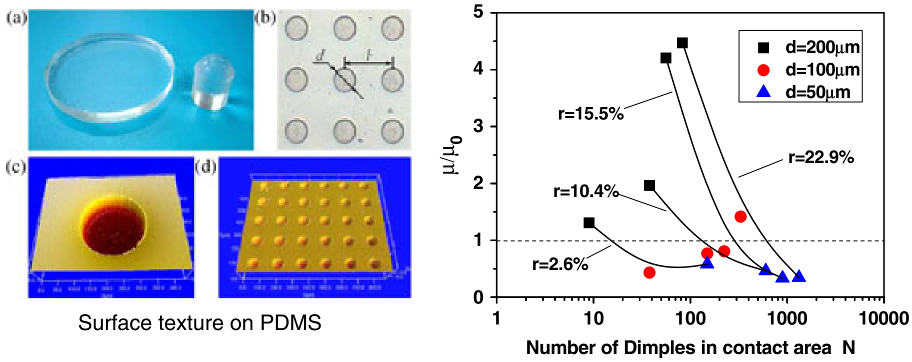

Figure 8. The μ/μ_0 as a function of number of dimples in the contact area (μ is the friction coefficient; μ_0 is the friction coefficient of the untextured specimen).

ADVANCED SURFACE TEXTURE DESIGN

As described above, in order to obtain desirable tribological performance, the surface texture design needs to be conducted according to the type of contact, materials of the interface and, most importantly, operating conditions. However, the typical mechanical components such as piston rings usually work in a complicated lubrication condition, which contains both high and low speed. Therefore, effort is still needed to reveal the mechanisms of the surface texture at different circumstances to develop novel designs of surface texture.

Figure 9 shows an example of a combined surface texture design. The pattern containing both large and small dimples was fabricated on the surface of silicon carbide. This design took the advantages of

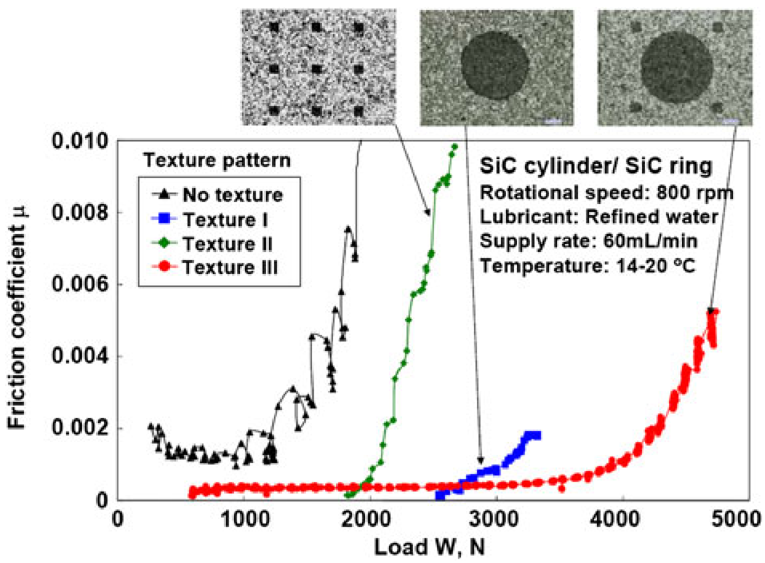

Figure 9. The friction coefficient of the patterns with only large, only small and both large and small dimples.[35]

DOI: 10.1002/ls

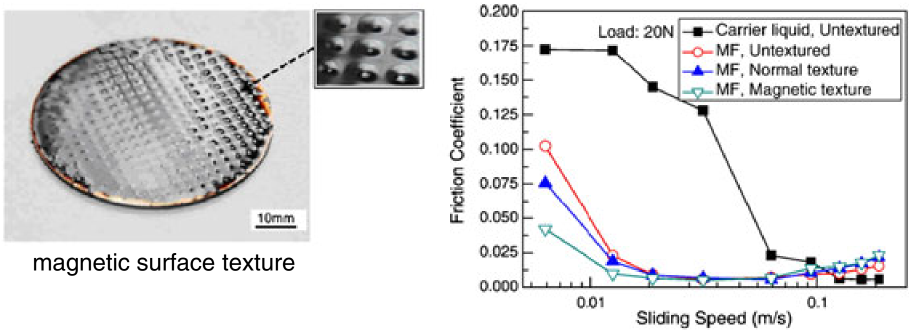

Figure 10. The magnetic surface texture and its friction properties at different speeds (MF: magnetic fluid).[36]

both large and small dimples, namely the hydrodynamic pressure-generating ability by large dimples, and the lubricant-retaining ability by small dimples. As results, the load-carrying capacity was obviously improved compared with both the patterns with only large or small dimples.[35]

Figure 10 shows a design of 'magnetic surface texture'. A microscale dimple pattern was initially fabricated on the surface, and then a permanent magnet material CoNiMnP was electrodeposited into these dimples. Therefore, there are both geometric surface texture and periodic distribution of magnetic field on the surface (magnetic surface texture). When the surface was lubricated by magnetic fluid, it would be controlled and shaped by the magnetic surface texture as shown in the figure. As results, load-carrying capacity could be generated even under very low sliding velocity.[36]

SUMMARY

As an effective approach, surface texture provides various ways to improve the tribological properties of sliding surfaces. Experimental and analytical studies carried out by different researchers suggest that in order to obtain desirable tribological performance, the surface texture design needs to be conducted according to the type of contact, materials of the interface and, most importantly, operating conditions. The design of dimple pattern following hydrodynamic principle would obtain good tribological performance under high-speed low-load conditions; however, for the case of low-speed high-load conditions, shallow and small dimples have more obvious friction reduction effect than those designed based on hydrodynamic pressure generation.

Effort is still needed to reveal the mechanisms of the surface texture at different circumstances to develop novel designs of surface texture.

ACKNOWLEDGEMENTS

The authors are grateful for the financial support provided by the National Natural Science Foundation of China (51175246, 50875125) and Jiangsu Innovation Program for Graduate Education (CX10B_093Z-05).

REFERENCES

1. Barthlott W, Neinhuis C. Purity of the sacred lotus, or escape from contamination in biological surfaces. *Planta* 1997; **202**:1–8.
2. Bechert DW, Bruse M, Hage W *et al*. Fluid mechanics of biological surfaces and their technological application. *Naturwissenschaften* 2000; **87**:157–171.

DOI: 10.1002/ls

3. Willis E. Surface finish in relation to cylinder liners. *Wear* 1986; **109**(1–4):351–366.
4. Hamilton DB, Walowit JA, Allen CM. A theory of lubrication by micro-irregularities. *Journal of Basic Engineering* 1966; **88**(1):177–185.
5. Etsion I, Burstein L. A model for mechanical seals with regular microsurface structure. *Tribology Transactions* 1996; **39**(3):677–683.
6. Etsion I. State of the art in laser surface texturing. *Journal of Tribology-Transactions of the ASME* 2005; **127**:248–253.
7. Fowell M, Olver AV, Gosman AD *et al*. Entrainment and inlet suction: two mechanisms of hydrodynamic lubrication in textured bearings. *Journal of Tribology* 2007; **129**:336–347.
8. Han J, Fang LA, Sun JP *et al*. Hydrodynamic lubrication of microdimple textured surface using three-dimensional CFD. *Tribology Transactions* 2010; **53**(6):860–870.
9. Etsion I, Kligerman Y, Halperin G. Analytical and experimental investigation of laser-textured mechanical seal faces. *Tribology Transactions* 1999; **42**(3):511–516.
10. Wang XL, Kato K, Adachi K *et al*. Loads carrying capacity map for the surface texture design of SiC thrust bearing sliding in water. *Tribology International* 2003; **36**(3):189–197.
11. Brajdic-Mitidieri P, Gosman AD, Ioannides E *et al*. CFD analysis of a low friction pocketed pad bearing. *Journal of Tribology -Transactions of the ASME* 2005; **127**(4):803–812.
12. Wang XL, Kato K, Adachi K *et al*. The effect of laser texturing of SiC surface on the critical load for transition of water lubrication mode from hydrodynamic to mixed. *Tribology International* 2001; **34**(10):703–711.
13. Zum Gahr KH, Mathieu M, Brylka B. Friction control by surface engineering of ceramic sliding pairs in water. *Wear* 2007; **263**(7–12):920–929.
14. Suh NP, Mosleh M, Howard PS. Control of friction. *Wear* 1994; **175**(1–2):151–158.
15. Ranjan R, Lambeth DN, Tromel M *et al*. Laser texturing for low-flying-height media. *Journal of Applied Physics* 1991; **69**(8):5745–5747.
16. Shinkarenko A, Kligerman Y, Etsion I. The effect of surface texturing in soft elasto-hydrodynamic lubrication. *Tribology International* 2009; **42**(2):284–292.
17. Brizmer V, Kligerman Y, Etsion I. A laser surface textured parallel thrust bearing. *Tribology Transactions* 2003; **46**(3):397–403.
18. Yan DS, Qu NS, Li HS *et al*. Significance of dimple parameters on the friction of sliding surfaces investigated by orthogonal experiments. *Tribology Transactions* 2010; **53**(5):703–712.
19. Kligerman Y, Etsion I. Analysis of the hydrodynamic effects in a surface textured circumferential gas seal. *Tribology Transactions* 2001; **44**(3):472–478.
20. Murthy AN, Etsion I, Talke FE. Analysis of surface textured air bearing sliders with rarefaction effects. *Tribology Letters* 2007; **28**:251–261.
21. Galda L, Pawlus P, Sep J. Dimples shape and distribution effect on characteristics of Stribeck curve. *Tribology International* 2009; **42**(10):1505–1512.
22. Kovalchenko A, Ajayi O, Erdemir A *et al*. The effect of laser surface texturing on transitions in lubrication regimes during unidirectional sliding contact. *Tribology International* 2005; **38**(3):219–225.
23. Yuan S, Huang W, Wang XL. Orientation effects of micro-grooves on sliding surfaces. *Tribology International*; DOI: 10.1016/j.triboint.2011.04.007.
24. Wang XL, Kato K, Adachi K. The lubrication effect of micro-pits on parallel sliding faces of SiC in water. *Tribology Transactions* 2002; **45**(3):294–301.
25. Halperin G, Greenberg Y, Etsion I. Increasing mechanical seals life with laser-textured seal faces. *15th International Conference on Fluid Sealing*, BHR, Maastricht 1997: 3–11.
26. Wang XL, Kato K. Improving the anti-seizure ability of SiC seal in water with RIE texturing. *Tribology Letters* 2003; **14**(4):275–280.
27. Costa HL, Hutchings IM. Hydrodynamic lubrication of textured steel surfaces under reciprocating sliding conditions. *Tribology International* 2007; **40**(8):1227–1238.
28. Wang XL,Wei L, Fei Z *et al*. Preliminary investigation of the effect of dimple size on friction in line contacts. *Tribology International* 2009; **42**(7):1118–1123.
29. Yu HW, Wang XL, Zhou F. Geometric shape effects of surface texture on the generation of hydrodynamic pressure between conformal contacting surfaces. *Tribology Letters* 2010; **37**(2):123–130.
30. Zum Gahr KH, Wahl R, Wauthier K. Experimental study of the effect of microtexturing on oil lubricated ceramic/steel friction pairs. *Wear* 2009; **267**(5–8):1241–1251.

31. Ren N, Nanbu T, Yasuda Y *et al*. Micro textures in concentrated-conformal-contact lubrication: effect of distribution patterns. *Tribology Letters* 2007; **28**(3):275–285.
32. Wang XL, 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, CA 2007.
33. Krupka I, Hartl M. The effect of surface texturing on thin EHD lubrication films. *Tribology International* 2007; **40**(7):1100–1110.
34. Pettersson U, Jacobson S. Friction and wear properties of micro textured DLC coated surfaces in boundary lubricated sliding. *Tribology Letters* 2004; **17**(3):553–559.
35. Wang XL, Adachi K, Otsuka K *et al*. Optimization of the surface texture for silicon carbide sliding in water. *Applied Surface Science* 2006; **253**(3):1282–1286.
36. Shen C, Huang W, Ma GL *et al*. A novel surface texture for magnetic fluid lubrication. *Surface & Coatings Technology* 2009; **204**(4):433–439.

DOI: 10.1002/ls