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SURFACE TEXTURE DESIGN FOR DIFFERENT CIRCUMSTANCES[1]

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Abstract

The appealing and enigmatic properties of biological surfaces inspire people that a smooth surface is not always the best. As an artificial surface texture, the cross hatch by honing process has been successfully used for cylinder liner since the 1940s. Currently, the patterns with micro-dimples are attracting more attentions since such closed texture cells are supposed to generate hydrodynamic pressure easier than micro-grooves. The advanced manufacturing techniques provide precision and freedom for the fabrication of surface texture, which makes it possible to obtain better tribological performances by the optimization of dimple geometry and distribution. Over the past decade, experiments were carried out to investigate the effects of micro-dimples 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. And numerical and analytical models based on Reynolds equation were used to evaluate the hydrodynamic effect generated between contacting surfaces in our group. As a summary, the results suggest 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 that designed based on hydrodynamic pressure generation.

Key words: Surface texture; Sliding; Friction.

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1 INTRODUCTION

Through eons of life evaluation, biological surfaces exhibit appealing and enigmatic properties for specific purposes. The longitudinal ribs on shark skin reduce drag and friction force dramatically. The micro- and nano-structures 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 micro-dimples 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 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 micro-hydrodynamic effect is regarded as the most dominant effect of surface texture at the conditions of high-speed and low-load. At this condition, the texture design concept is mainly according to fluid dynamics.(5-8)

At the ‘‘dry’’ contact condition, it is known the surface texture could trap wear debris to prevent further abrasive wear,(9) and decreases the contact area to reduce the adhesive force between the disk and the slider of magnetic storage devices.(10)

The surface 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 part 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 is that we should know what is the principle of surface texture design for different circumstances?

Over the past decade, experiments were carried out to investigate the effects of micro-dimples 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. And numerical and analytical models based on Reynolds equation were used to evaluate the hydrodynamic effect generated between contacting surfaces in our group. Therefore, this paper will summarize several approaches to enhance the effects of surface texture for different circumstances. The data comes from our previous published papers (about ceramics and metals), our current work on polymer, and contribution by other researches.

2 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 micro-step 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.

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2.1 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 in 1999, Etsion suggested the depth over diameter ratio is the most important parameter for micro-dimples.(5) Nowadays, people also agree that the area ratio of micro-dimples is another important factor for the pattern of micro-dimples.(11) Orthogonal studies indicated that area ratio is more significant for the tribological performance than the depth and diameter of dimples.(12)

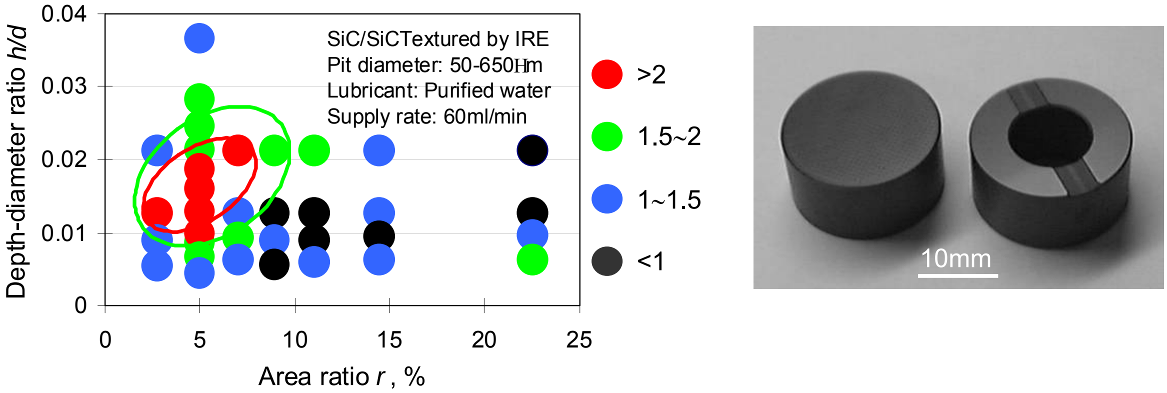

Figure 1. The effect of dimple parameters on the increment of load carrying capacity of SiC sliding in water.(6)

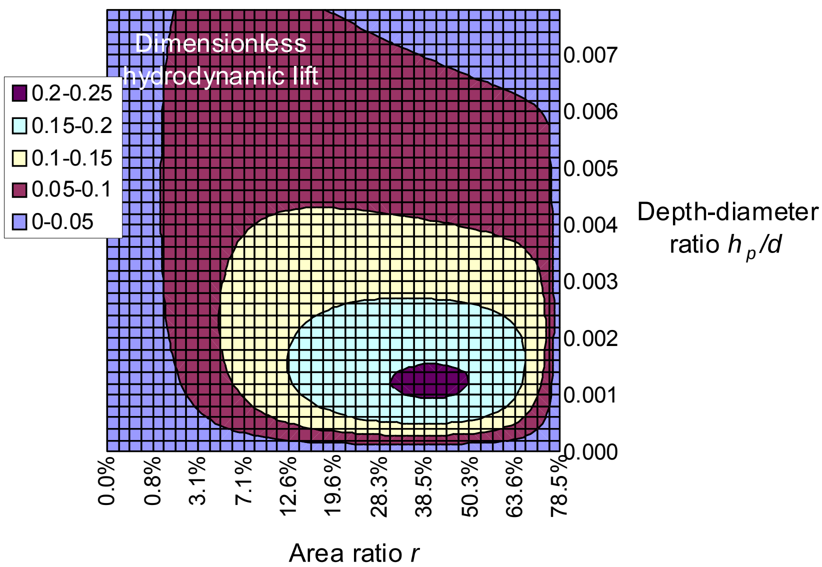

Figure 2. Dimensionless hydrodynamic lift as a function of the area ratio and depth over diameter ratio of the dimples.(6)

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

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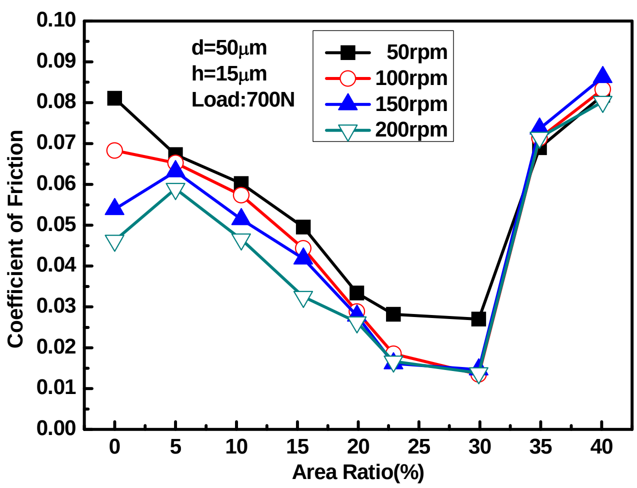
pressure is maximized within this range. However, the optimal values of area ratio obtained by experiments were usually not as high as the theoretical results. Figure 1 is an example, which shows the load carrying capacity map of the textured surface of silicon carbide sliding in water. With the optimized 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.(6)

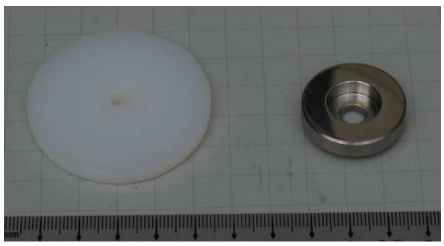
For the sliding surfaces of metals, the optimal area ratio is slightly higher than that for silicon carbide. Several studies support that 5-15% is the preferable value.(12) For example, the pattern of dimples (diameter 80μm, depth 5.5μm, 12%) is beneficial for expending the range of the hydrodynamic lubrication regime.(13)

If the material has relative lower Young's modulus, the optimal value of area ratio would be higher. As shown in Figure 3, the experiments show that area ratio as high as 29% is preferable for the contact between a soft material UHMWPE 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. 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 by theoretical analysis, 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.(14) 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 (φ90μm, depth 2–20μm, 25%) could increase the maximum PV value of the mechanical seal obviously.(15) And the dimple pattern with the area ratio of 15% shows an obvious increase of the critical load for SiC sliding in water.(16)





Lower and Upper specimens

Figure 3. The effect of area ratio on the friction coefficient between UHMWPE and stainless steel.

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Diameter and depth of the dimple doesn't seem to be as important as the area ratio at high-speed and low-load condition. Analytical model suggests that 100-300μm 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 the preferable value of it is in the range 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.(5) This is confirmed by experiments of SiC lubricated by water as shown in Figure 1.

2.2 Dimple Shape

Although circular dimples are low cost and easy for fabrication, modern micro-manufacturing techniques are able to fabricate the dimples with other shapes. This enables the optimization of dimple geometry to obtain better tribological performance of sliding surfaces. Table 1 lists a group of specimens which have dimples with same depth, individual area and area ratio, but different shapes.

Table 1. Geometry parameters of the patterns of dimples(17)

	Depth (μm)	Radius (μm)	Area of a dimple (μm^2)	Pitch (μm)	Area ratio (%)
Circle	8	75	17671	500	7
Ellipse	8	150/37.5	17671	500	7
Triangle	8	188 (Side length)	17671	500	7

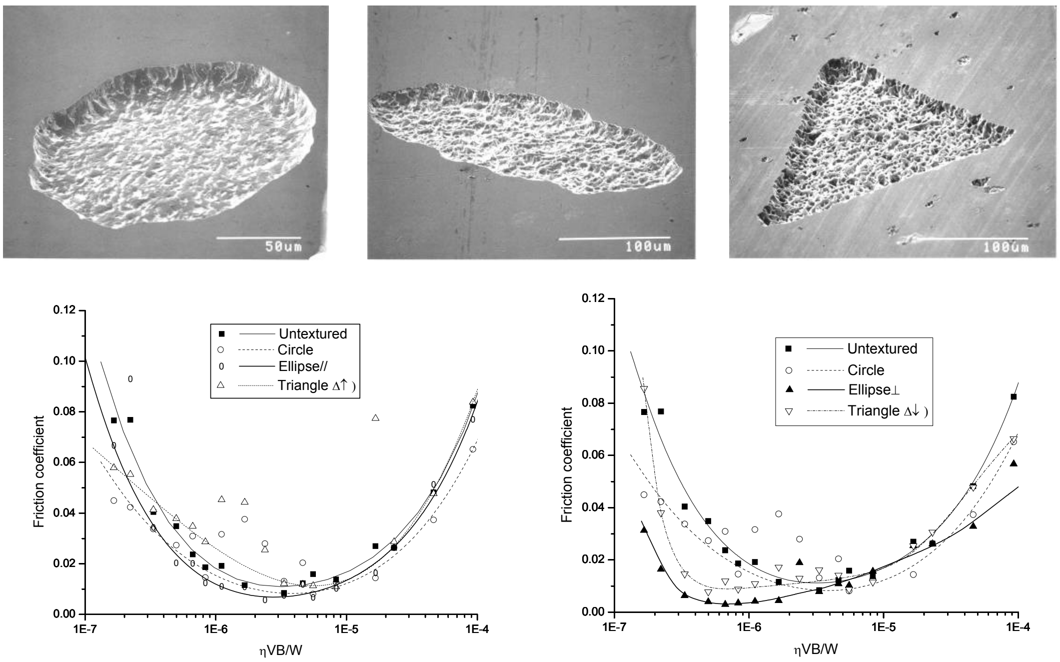

Figure 4. Stribeck curves of the surface textures parallel (left) and perpendicular (right) to the direction of sliding (η is the viscosity of the lubricant, V is the sliding speed, B is the contact width, and W is the normal load).(17)

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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 found, 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. 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.(17) Similar results were also obtained by other researchers.(18)

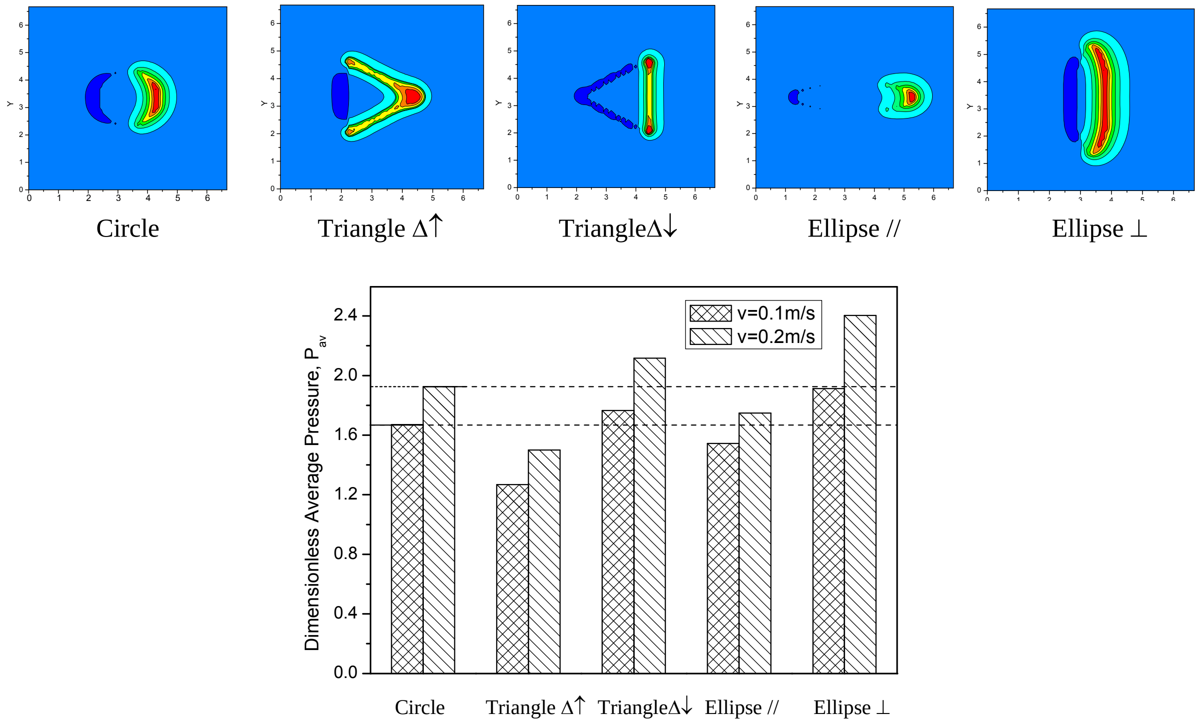

Figure 5. Average pressure P_{av} of different textural shapes and orientations at the speed of 0.1m/s and 0.2m/s.(17)

2.3 Dimple Distribution

Dimples evenly distributed as a square or hexagon array are the normal ways people design the surface texture. As shown in Figure 5, the 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, optimization 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 left 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

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shift 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 keep identical. A model based on 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 17% just by the optimizing the angle α, which is around 70 degree in this case.

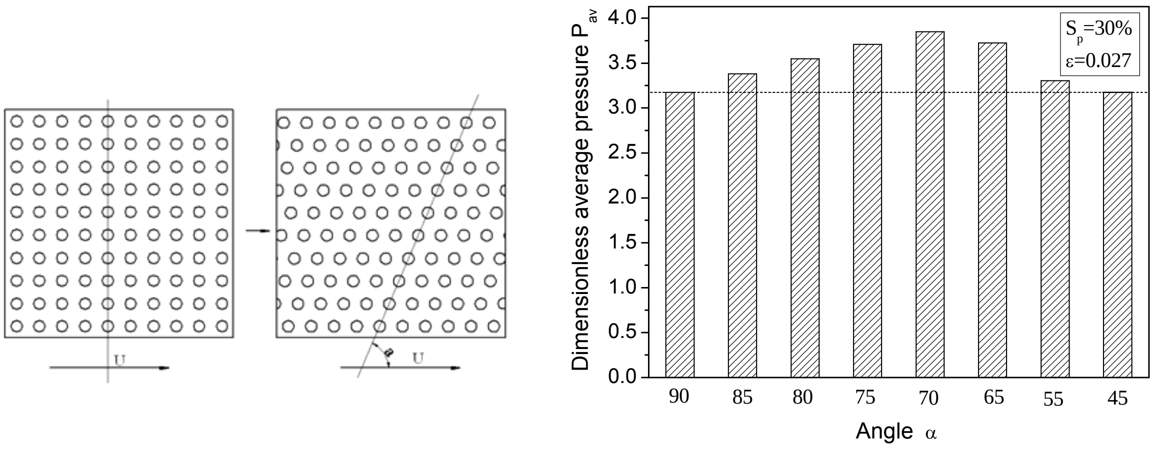

Figure 6. Average dimensionless hydrodynamic pressure as a function of the angle α between line and column of dimples (The area ratio S_p=30%, the depth over diameter ratio ε=0.027).

3 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.

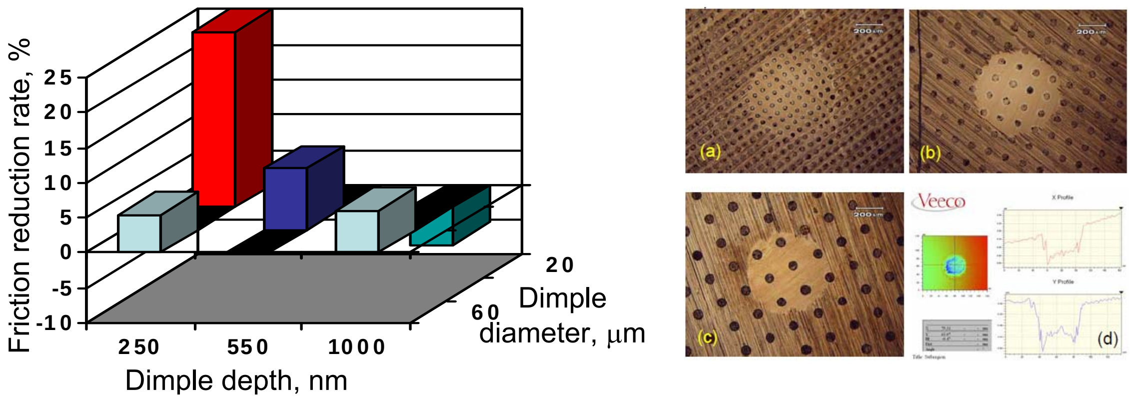

Figure 7. Friction reduction rates of different patterns.[19]

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 (0.2m/s) and high-load (203MPa). It shows that the small and shallow dimple would have an obvious effect of

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friction reduction compared with other specimens which has the same area ratio and nearly the same depth over diameter ratio.(19) The reason has been well explained with EHL experiments by Krupka, which showed that a significant increase in lubricant film thickness is induced by a shallow micro-cavity in the elastohydrodynamic lubrication regime.(20)

Figure 8 shows the experimental data obtained from the friction tests between soft materials. A PDMS disk 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 resulted decrease of friction while the larger dimples caused high friction. Clearly, lubricant retaining effect is more important than the hydrodynamic effect in this case.

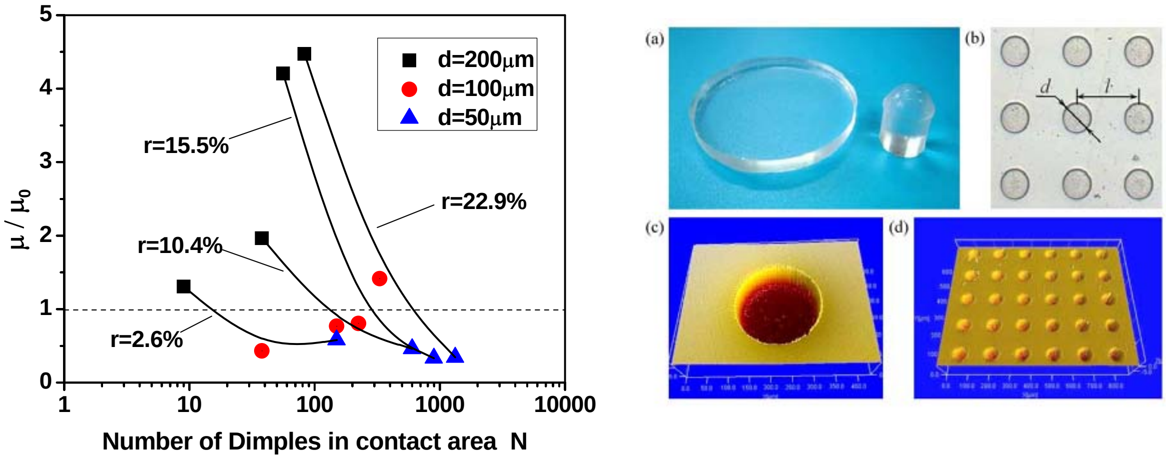

Figure 8. The μ/μ_0 as a function of number of dimples in the contact area. (μ-friction coefficient, μ_0-friction coefficient of the untextured specimen).

4 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. On the other hand, the typical mechanical components such as piston rings usually work in a complicated lubrication condition. 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 both large and small dimples, namely, the ability of generating hydrodynamic pressure by large dimples, and the lubricant retaining ability by small dimples. As results, the load carrying capacity was obviously improves comparing to both the patterns with only large or small dimples.(21)

Figure 10 shows a design of "magnetic surface texture". A micro-scale dimple pattern was firstly fabricated on the surface, and then a permanent magnet material

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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.(22)

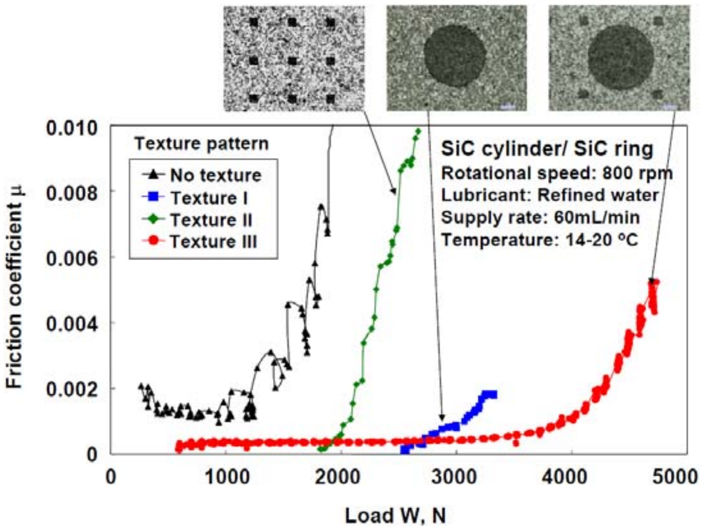

Figure 9. The friction coefficients of the patterns with only large, only small, and both large and small dimples.(21)

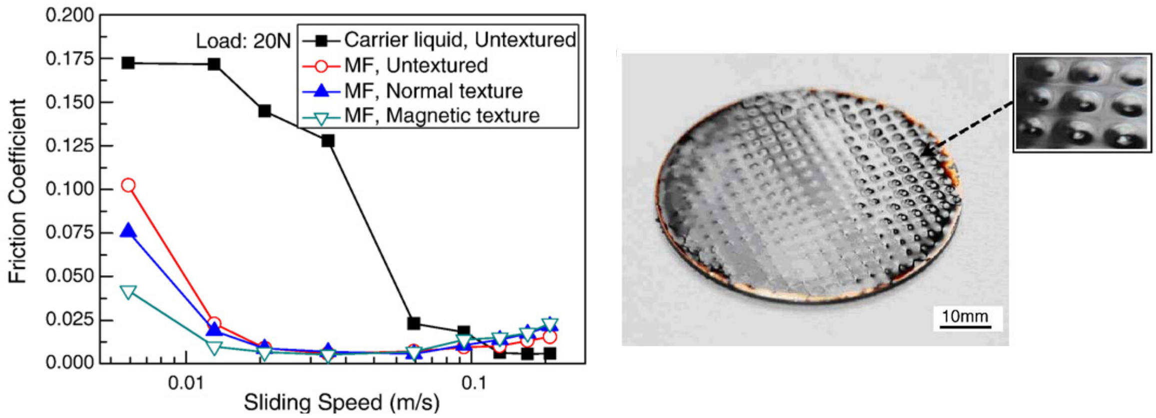

Figure 10. The magnetic surface texture and its friction properties at different speeds.(22)

4 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

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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 that 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.

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