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Biomimetic surface design for ultrahigh molecular weight polyethylene to improve the tribological properties

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Abstract

Tribological problem is a major obstacle that limits the using of ultrahigh molecular weight polyethylene (UHMWPE) in industrial applications and orthopedic surgeries. Many efforts have been made to improve the tribological properties of UHMWPE, such as promoting the structure, morphology, and mechanical properties of the polymer. Inspired by the features of articular surface, micro-scaled texture is introduced to improve the tribological properties of UHMWPE using micro-imprint lithography. Friction and wear experiments are conducted on textured and untextured specimens using ring-on-disc test apparatus under water lubrication. The experimental results demonstrate that the micro-scaled surface texture can remarkably improve the tribological properties of UHMWPE. Friction force can be effectively reduced by selecting suitable dimple parameters. Compared with an untextured UHMWPE, the textured one with optimum parameters shows a reduction in the friction coefficient as much as 66.7–85.7% on different load–speed conditions. The optimized area density of surface textured UHMWPE ranges from 22.9% to 29.9%, which is obviously higher than that of stiff materials such as metals and ceramics. The textured UHMWPE with area density 29.9%, diameter 50 μm, and depth 15 μm presents a significant effect of wear resistance. The average wear depth of textured UHMWPE is 35.5% of that of untextured one.

Keywords

Ultrahigh molecular weight polyethylene, biomimetic surface design, surface texture, friction, wear

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Introduction

Ultrahigh molecular weight polyethylene (UHMWPE), because of its low cost, high wear resistance, self-lubrication ability, and excellent chemical inertness,[1] has been widely used as mechanical parts in industrial applications, including gear, cam, roller, bearing, seal, etc.[2] From 1960s, UHMWPE has also been used as the material of concave component for Charnley's low frictional torque joint that is famous and widely used in orthopedic surgeries.

However, there are still some tribological problems limiting the using of UHMWPE. First, compared with other materials, although the friction coefficient of UHMWPE is low, it is still higher than the requirement in some cases of applications. For example, in orthopedic surgeries, the friction coefficient of UHMWPE is still higher than that of natural joint, which ranges from 0.005 to 0.023.[3] Second, the wear of UHMWPE can cause working faults of mechanical parts. In particular, the wear and wear debris of UHMWPE may cause periprosthetic biological reaction (osteolysis) and then lead to aseptic loosening when UHMWPE is used in orthopedic surgeries.[4]

Attempts have been made to improve the tribological properties of UHMWPE include gamma-crosslinking,[5,6] fiber reinforcement,[7,8] the chain length or molecular weight increasing,[9] and ion implantation.[10–12] Meanwhile, more attentions have been paid on the lubrication designs of UHMWPE, including surface roughness design,[13] contact face design,[14] etc. However, in some cases, the modified

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UHMWPE and lubrication design cannot meet the requirements of applications.

Through millions years of life evolution, biological surfaces have special properties to accommodate different environment. For example, the longitudinal ribs on shark skin can reduce drag and friction force. Tiny wax-coated protuberances on lotus leaves can form a self-cleaning surface to avoid fluid-dynamic deterioration caused by the agglomeration of dirt. Therefore, a smooth surface is not always the best one in all scenarios.

In 1971, Clarke observed human articular surface using a scanning electron microscope, finding that the surface of natural joint was not smooth but has distributed depressions with an average diameter from 20 to 40 μm.[15] Although some researchers think that this feature of articular surface is formed by lacunae collapse which is caused by the cartilage drying out, it is interesting to verify if the depression is the main reason of the excellent tribological properties of natural joint. The microstructure of articular surface inspires the thought of using micro-scaled surface texture to improve the tribological properties of UHMWPE.

Surface texture, such as micro-groove, micro-dimples, and micro-convex fabricated on the contact surfaces, has emerged as a viable method to improve the tribological properties of mechanical components in the last decade. The most familiar texturing application is the surface of cylinder liner through honing process since the 1940s. Nowadays, texturing technology is applied on micro-electromechanical systems devices, magnetic storage devices, and even golf ball.

Surface texture is introduced to tribological applications by adopting various texturing techniques, including reactive ion etching,[16] machining,[17] abrasive jet machining,[18] LIGA,[19] and laser surface texturing.[20–22] It makes significant improvements in load-carrying capacity, anti-seizure ability, wear resistance, and frictional performance of mechanical components.

The mechanisms of tribological properties improved by surface texture can be explained mainly from the following three aspects.

1. Dimples of surface texture, serving as micro-hydrodynamic bearings, can generate additional hydrodynamic pressure to provide additional lift.[23–25]
2. Surface texture can work as lubricant micro-reservoirs which are the secondary source of lubricant for enhancing lubricant retention.[26]
3. Surface texture captures wear debris to minimize the third body abrasion.[27]

Previous studies on surface texture mainly focus on stiff materials such as ceramics and metals. Only few research studies are carried out on low elastic modulus materials such as UHMWPE. Young et al.[17] fabricated a surface texture that consists of 2732 holes of 0.16 mm diameter and 0.32 mm deep on the surface of UHMWPE using a computerized, numerical-controlled milling machine. They found that compared with untextured UHMWPE, the surface texture produced a significant reduction (42%) in the friction coefficient under bovine serum lubrication. Kustandi et al.[28] utilized nanoimprint lithography to produce textured UHMWPE using nano-scaled grooves. The result indicates that, under a dry-sliding condition with loads ranging from 60 to 200 mN, textured UHMWPE performs a friction reduction of 8% to 35%, and wear depth and width are also lower than those of untextured UHMWPE. It could be found that the millimeter- and nano-scaled textures fabricated on UHMWPE present obvious friction reduction.

However, micro-scaled texture, which is more approximate to the feature of nature joint surface,[15] is known little on low elastic modulus materials. The design principles of surface texture on low elastic modulus materials, such as UHMWPE, are rarely been reported.

In this research, inspired by the feature of articular surface, micro-scaled surface texture is introduced to obtain low frictional and wear-resistant UHMWPE using micro-imprint lithography. The tribological behavior and the surface design principles of micro-scaled texture on UHMWPE surface are preliminarily investigated in different load–speed conditions.

Methods

Specimens and surface texture

The ring and disc are made of stainless steel (316) and UHMWPE, respectively, as tribo-pair shown in Figure 1. The outer diameter of the ring is 28 mm and the inner diameter is 14 mm. The contact face of ring is ground and lapped to the average roughness of $R_a = 0.02–0.03\ \mu m$. The pattern of evenly distributed dimples is fabricated on the surface of disc using micro-imprint lithography. The detailed procedure of surface texture fabrication is as follows (shown in Figure 1).

1. A copper substrate ($ø50 \times 0.8$ mm), which is used as the base of opposite mold, is finished and cleaned according to the standard procedure.
2. A negative photoresist layer is coated on the surface of the copper substrate using a spin-coater and then patterned by standard lithography processes to fabricate a photoresist mask.

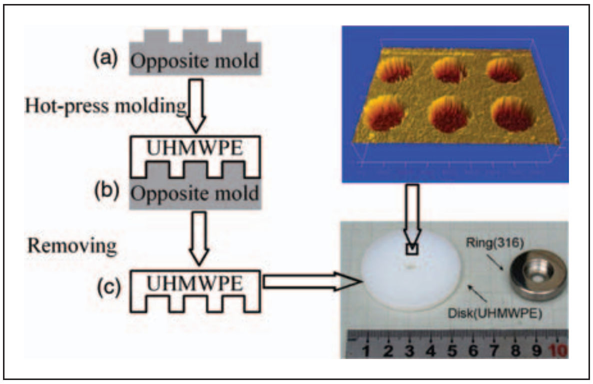

Figure 1. Specimen and the procedure of surface texture fabrication.

Table 1. Geometrical parameters of the patterns.

Dimples depth, *h* (μm)	5, 10, 15
Dimples diameter, *d* (μm)	50, 100, 200
Dimples area density, *r* (%)	5, 10.4, 15.5, 19.9, 22.9, 29.9, 34.9, 40.1

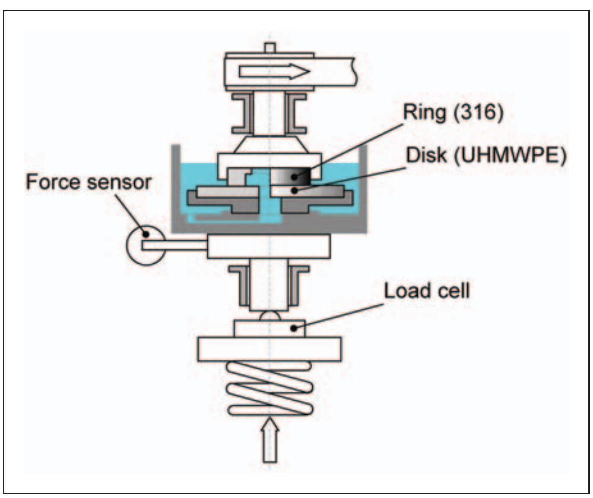

Figure 2. Schematic of the test apparatus.

3. The copper substrate covered by photoresist mask is electroplated to produce an opposite mold.
4. UHMWPE powder (3×10^6 molecular weight) is placed on the opposite mold and pressed at a temperature of 200°C and a pressure of 48 MPa for 90 min.
5. After cooled to room temperature, the opposite mold is moved. The textured UHMWPE is generated.

Figure 1 shows the image and profile of the dimple pattern observed by non-contact optical interferometer ADE MicroXAM. The dimples with flat bottom are cylinders. The area density of the dimple pattern is controlled by the lithography mask. Table 1 lists the geometric parameters of the patterns used in this research. There are 72 kinds of patterns carried out in experiments. The patterns have dimples with a diameter ranging from 50 to 200 μm, a depth ranging from 5 to 15 μm, and an area density ranging from 5% to 40.1%. The untextured UHMWPE disc has been prepared by a same procedure but using a smooth copper mold.

Tribological tests

Tribological tests are performed under distilled water lubrication at the room temperature using a ring-on-disc test apparatus that is shown in Figure 2. Tests are conducted at loads of 100 and 700 N, corresponding to the contact pressures 0.239 and 1.67 MPa. The rotational speeds are 50, 100, 150, and 200 r/min corresponding to the sliding speeds of 0.054, 0.107, 0.162, and 0.215 m/s. Before the test, the ring is ultrasonic-cleaned using acetone first and then alcohol, and the disc using isopropanol first and then de-ionized water. Tests are performed for 15 min at each load–speed condition. The stable friction coefficient data in the last minute is averaged and used as the result of test. In order to check the reproducibility of the results, every test is carried out two times.

Four tiny areas without dimple on the friction track of the disc are selected to determine wear profile using non-contact optical interferometer ADE MicroXAM after the friction tests for each specimen. The average wear depth is computed from the worn profile, which is averaged by the four measurements, divided by the wear width.

Results

Frictional properties of textured UHMWPE under water lubrication

Figure 3 illustrates the relationship between friction coefficient and area density at the loads of 100 and 700 N. The dimples have the same diameter of 50 μm and same depth of 15 μm. The area density is varied from 0% to 40.1%. Figure 3(a) shows that at the load of 100 N, when the area density is between 5% and 29.9%, textured UHMWPE shows a significant effect of friction reduction. When the area density is over 29.9%, an effect of friction increase is shown. In this group of experiments, the dimple pattern with an area density of 29.9% has lower friction coefficient than other patterns at all the rotational speeds, which decreases a maximum of 75.6% friction at the condition of 200 r/min compared with that of untextured specimen.

As shown in Figure 3(b), when the load is increased to 700 N, the pattern with the same area density of 29.9% also presents an excellent effect of friction reduction at all the rotational speeds. When the dimple area density ranges from 5% to 29.9%, the friction coefficient is reduced by the micro-scaled surface texture compared with that of untextured specimen. The friction coefficient will increase when the dimple area density is over 29.9%. The dimple pattern with an area density of 29.9% shows an obvious decrease in friction coefficient. The maximum decreasing value is about 80.3% at the condition of 100 r/min compared with untextured specimen.

Figure 4 shows the relationship between friction coefficient and dimples depth. At the load of 100 N, the minimum value of the friction coefficient is obtained when the dimple depth is 10 μm. At the depth of 10 μm, all patterns perform an excellent effect of friction reduction. At the depth of 15 μm, the patterns with area density ranging from 5% to 34.9% show an effect of friction reduction. At the depth of 5 μm, the patterns with area density ranging from 15.5% to 34.9% can reduce the friction coefficient. At the load of 700 N, the specimens with the depth of 15 μm show more obvious reduction in friction coefficient than the specimens with other depths. At the depth of 15 μm, the patterns with area density ranging from 15.5% to 29.9% can effectively reduce the friction coefficient. At the depth of 10 μm, the patterns with area density ranging from 19.9% to 22.9% present an effect of friction reduction. Moreover, at the depth of 5 μm, only the pattern with an area density of 19.9% reduces the friction reduction. The research shows that, in general, the heavier the load is, the deeper the optimal depth is.

Summarized with the experimental data of the patterns with an area density ranging from 19.9% to 29.9%, Figure 5 shows the relationship between friction coefficient and dimples diameter. In most cases, dimple patterns with dimples diameter of 50 μm show a greater effect of friction reduction. Instead, large dimples

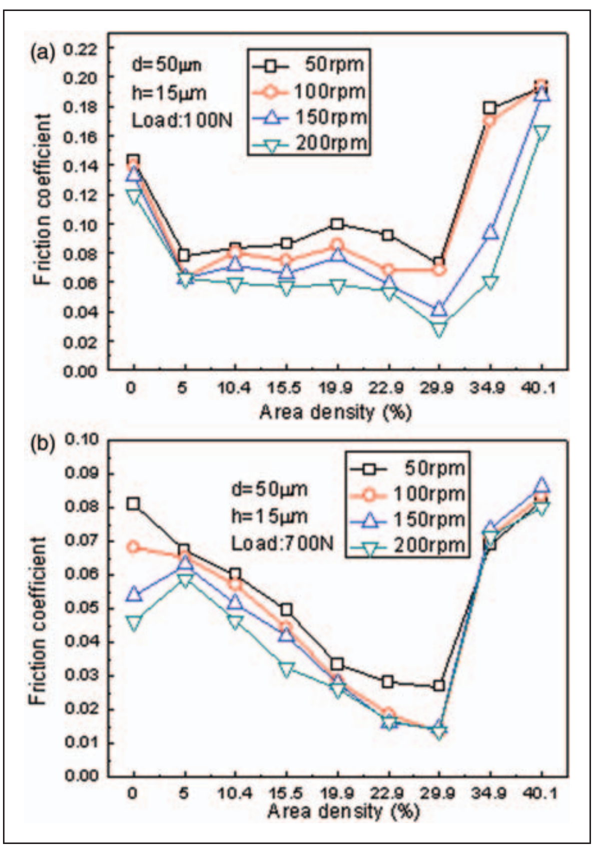

Figure 3. Dimple area density effect on friction coefficient for surface texture at the different rotational speed and load conditions.

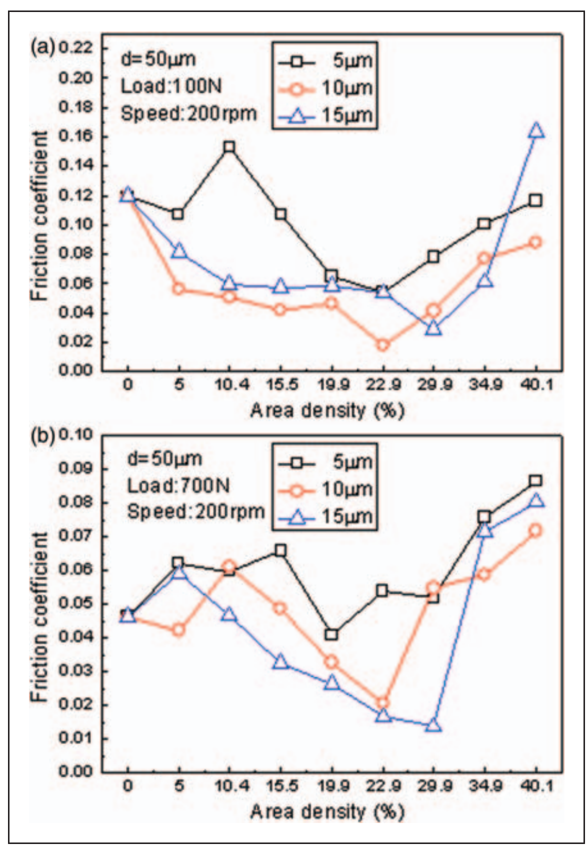

Figure 4. Dimple depth effect on friction coefficient for surface texture at rotational speed 200 r/min and different loads.

diameter (200 µm) does not present a significant effect of friction reduction, and even performs an effect of friction increase at the load of 700 N.

In general, at the load of 100 N, specimen with dimples diameter 50 µm, area density 22.9%, and depth 10 µm presents an excellent effect of friction reduction, which decreases 72.8–85.7% comparing with untextured UHMWPE under different speeds. At the load of 700 N, the maximum reduction of friction is 66.7–80.3% than an untextured one, which is obtained for the specimen with dimples diameter 50 µm, area density 29.9%, and depth 15 µm.

Wear properties of textured surface under water lubrication

Figure 6 shows the effect of the geometric parameters of textured UHMWPE on average wear depth (Avg. WD) measured after the friction tests. The average wear depth of each specimen is accumulated over testing. The bar chart shows the relationship between average wear depth and geometric parameters. The point-line chart shows the relationship between friction coefficient and geometric parameters at the load of 700 N. The dimple pattern with diameter 50 µm, area density 29.9%, and depth 15 µm presents a better effect of wear resistance than other dimple patterns in this experiment. The average wear depth of the dimple pattern is 35.5% of that of untextured UHMWPE. In general, the average wear depth and friction coefficient show a good correlation, which indicates that effective friction reduction can availably decrease average wear depth.

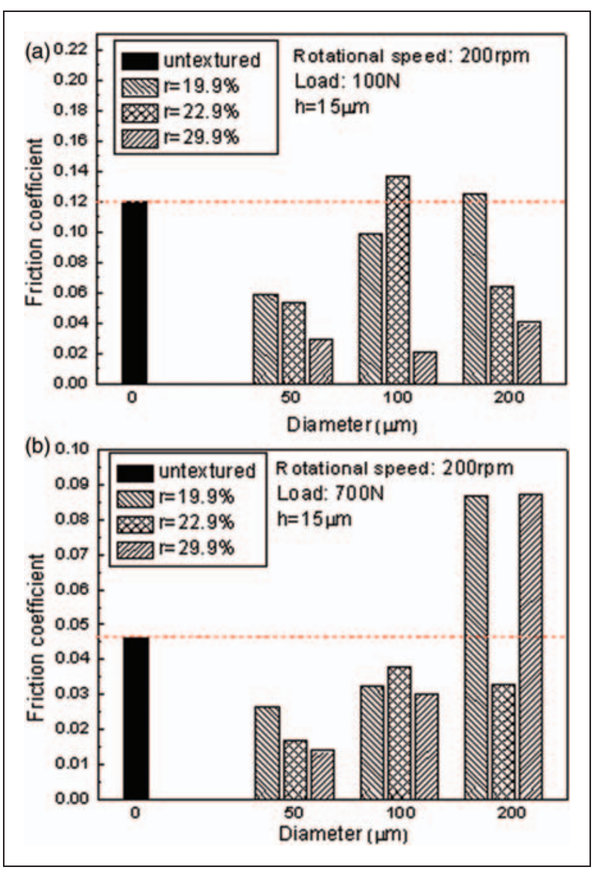

Figure 5. Dimple diameter effect on friction coefficient for surface texture at rotational speed 200 r/min and different loads.

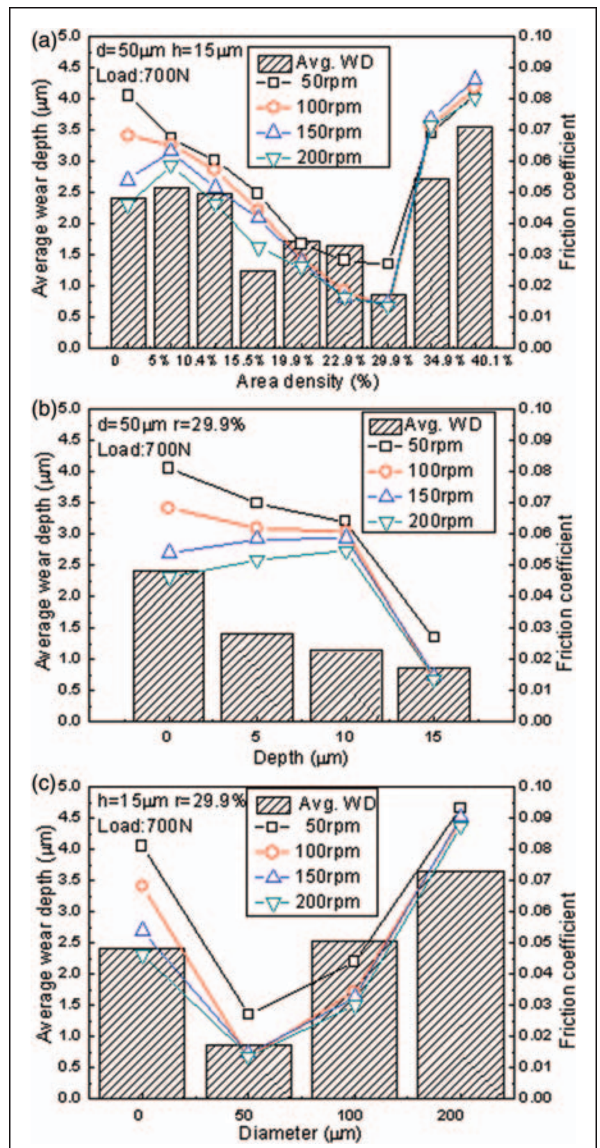

Figure 6. Geometric parameters effect of textured UHMWPE on average wear depth (Avg. WD) measured after the friction tests.

Discussion

In this research, at the load of 100 or 700 N, the pattern with an area density of 29.9% always presents an excellent effect of friction reduction when textured on the surface of UHMWPE which is a kind of low elastic modulus materials. It is different from the results experimented on stiff materials such as ceramics and metals. These results show that the area density ranging from 5% to 15% presents a significant effect of friction reduction, and when the area density is over 20%, the effect of friction reduction is indistinctive or may lead to an effect of friction increase in some cases.[16,18,29]

For the surfaces sliding in mixed lubrication regime, there is always a portion of the area keeping in solid contact. Yuan et al.[30] suggest that the edge of groove perpendicular to sliding direction will lead to a high stress at the edge of groove which will result in the increase of friction in solid contact. In this article, in order to investigate the influence of edge effect of dimple, the FEM software ANSYS is used to analyze the contact situation of dimple's (50 μm diameter) edge during sliding.

The contact problem is simplified as a block with a dimple sliding against a plane with contact. Both contacting surfaces are smooth, ignoring surface roughness. SiC is selected as an example of stiff materials.

The calculation conditions are set as follows:

Contact pressure $P = 1.67$ MPa
Young's modulus of stiff material (SiC) $E_1 = 450$ GPa
Young's modulus of UHMWPE $E_2 = 0.69$ GPa
Poisson's ratio of stiff material (SiC) $\varepsilon_1 = 0.14$
Poisson's ratio of UHMWPE $\varepsilon_2 = 0.49$
Friction coefficient $\mu = 0.10$
Area density $r = 20\%$

Figure 7 presents a stress distribution around a single dimple (50 μm diameter). For stiff materials (SiC), the stress at the edge of dimple while contacting and sliding is relatively higher than that of low elastic modulus materials (UHMWPE) during sliding. This stress will induce extra deformation at specific location such as the edge of dimple, which results in the increase of overall friction force.

Therefore, although the results of numerical analysis for the hydrodynamic effects on surface texture suggest that the pattern with high area density usually as 20–40% perform the best additional hydrodynamic effect which can reduce the frictional force during the sliding,[31,32] that hydrodynamic lubrication model did not consider the contact between two solid bodies. For the surfaces sliding in mixed lubrication regime, a portion of the surface is in solid contact and another portion of the contact area is in hydrodynamic lubrication; so, considering the solid contact, the existence of stress will increase friction eventually for the patterns with high area density, in particular, for stiff materials such as ceramics and metals in mixed lubrication regime.

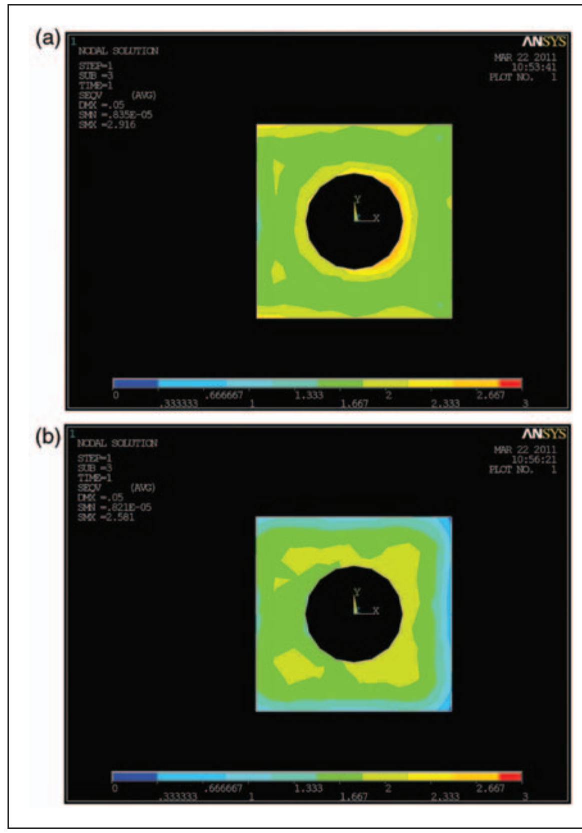

Figure 7. Single dimple's (50 μm diameter) pressure distribution chart of stiff material (a) and UHMWPE (b).

However, as to UHMWPE of which Young's modulus is 0.69 GPa much lower than that of stiff materials as ceramics and metals, the edge effect is not as significant as stiff materials as shown in Figure 7. Therefore, textured UHMWPE with a high area density like 29.9% can show an excellent effect of friction reduction.

The research also implies that the heavier the load is, the deeper the optimal depth is. At the load of 100 N, the pattern with dimples depth of 10 μm presents an obvious effect of friction reduction. This result may be explained by the hydrodynamic effects, which usually suggest the pattern with shallow dimples can maximize the additional hydrodynamic effect. At the load of 700 N, the lubricating film may be hard to form, and 'secondary lubrication' effect is probably more important than additional hydrodynamic effect to keep the lubricating film. The lubricant trapped in the dimples of surface texture can be considered as a secondary source of lubricant, which is squeezed out by the deformation

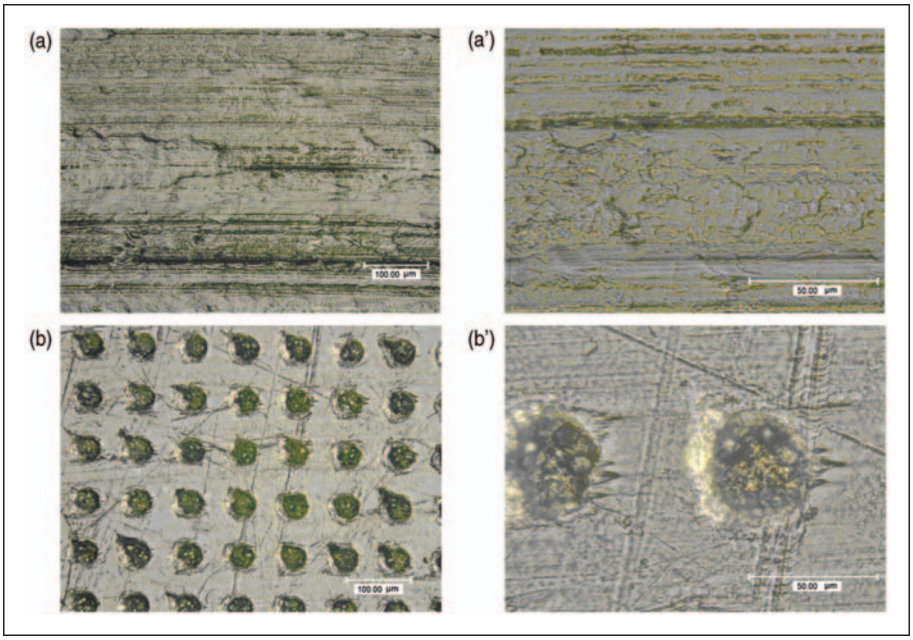

Figure 8. Optical images of untextured (a, and its enlarged detail a′) and textured (b, and its enlarged detail b′) surface with the diameter of 50 μm, area density of 29.9% and depth of 15 μm.

of the surface to permeate the surface to form squeeze film and to reduce the friction. Therefore, deeper dimples have more space to provide as micro-reservoirs to enhance lubricant retention; so, the pattern with deep dimples (15 μm) shows an excellent effect of friction reduction.

Compared with the stiff materials, such as ceramics and metals, having the surface pattern with the diameter 120[18] or 250–350 μm,[16] which show an excellent effect of friction reduction, the textured UHMWPE with small dimples diameter (50 μm) presents an obvious effect of friction reduction. In some conditions, the dimple pattern with large diameter (200 μm) even increases the friction. Although the area density of the texture with small dimples diameter is the same as the texture with large dimples diameter, the former may have a better distribution than the latter, because the interval between dimples of the former is smaller than the latter. Also, the texture with large dimples diameter which has large interval may lead to partial dry friction at heavy load.

The worn surface of UHMWPE is examined using KEYENCE microscope after the friction tests to reveal the reason why surface texture can reduce the average wear depth of UHMWPE, as shown in Figure 8. The wear ploughs phenomenon is rather serious on the worn surface of untextured UHMWPE (Figure 8(a)). Many microscopic undulations (Figure 8(a′)) on untextured UHMWPE could also be observed, which is probably due to the frictional heating in the contact region. Figure 8(b) and 8(b′) shows the worn surface of textured UHMWPE with diameter 50 μm, area density 29.9%, and depth 15 μm, which shows the best effect of friction reduction. It could be found that the worn surface is smoother than that of untextured UHMWPE and exhibits slight scratches (Figure 8(b)) on both sides of the dimples, while the area covering the dimples in the middle appears to be smooth (Figure 8(b′)). It is due to the wear debris trapping effect of the texture, which can capture wear debris to minimize the third body abrasion. The second lubrication effect can improve the lubrication condition of the contact region. Therefore, the surface texture can effectively reduce the frictional heating and limit the appearance of adhesion.

Conclusions

High friction coefficient and wear are two main problems that limit the using of UHMWPE in industrial applications and orthopedic surgeries. In order to improve the tribological properties of UHMWPE, the micro-imprint lithography is successfully used to fabricate surface texture on the surface of UHMWPE. Micro-scaled dimple patterns with area density ranging from 5% to 40.1%, diameter from 50 to 200 μm, and depth from 5 to 15 μm are fabricated. The tribological behaviors of the textured and untextured UHMWPE are investigated by experiment. The design principles of surface texture on UHMWPE are discussed. The following conclusions have been drawn as the most significant.

1. The micro-scaled surface texture can remarkably reduce both friction and wear on UHMWPE, which brings an effective approach for the improvement of the tribological properties of UHMWPE.
2. The optimum friction reduction can be achieved by selecting suitable dimple parameters. In this research, textured UHMWPE with diameter 50 μm, area density 22.9%, and depth 10 μm presents an excellent effect of friction reduction at the load of 100 N. At the load of 700 N, the maximum reduction of friction is obtained for the textured UHMWPE with diameter 50 μm, area density 29.9%, and depth 15 μm. Different from the results experimenting on stiff materials such as ceramics and metals, the textured UHMWPE with a high area density of 29.9% always presents an excellent effect of friction reduction.
3. The textured UHMWPE with diameter 50 μm, area density 29.9%, and depth 15 μm presents a significant effect of wear resistance. The average wear depth of the textured UHMWPE is 35.5% of that of untextured UHMWPE.

Funding

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Appendix

Notation

d	dimples diameter (μm)
E_1	Young's modulus of stiff material (GPa)
E_2	Young's modulus of UHMWPE (GPa)
h	dimples depth (μm)
P	contact pressure (MPa)
r	area density (%)
ε_1	Poisson's ratio of stiff material
ε_2	Poisson's ratio of UHMWPE
μ	Friction coefficient