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The Design and Fabrication of Dimples Pattern on the Surface of UHMWPE

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Abstract. Tribological problems are the major obstacle that limits the long-term using of ultra high molecular weight polyethylene (UHMWPE) in artificial joints. Many efforts have been made to improve the tribological properties of UHMWPE mainly by promoting the structure, morphology and mechanical properties of UHMWPE. In this paper, inspired from the natural joint, the micro-scale texture has been introduced to improve the tribological properties of UHMWPE. The micro-imprint lithography technology has been adopted to fabricate the textured UHMWPE. The profile of textured UHMWPE shows that the quality of textured UHMWPE is good. The result of tribological tests shows that the micro-scaled surface texture can remarkably reduce friction on UHMWPE.

Introduction

Ultra-high molecular weight polyethylene (UHMWPE) has been chosen as the material of concave components of Charnley's low frictional torque joint which is famous and widely used in orthopaedic surgeries for nearly 50 years. However, there are still two problems limiting the long-term clinical use of artificial joints: 1) the friction coefficient of artificial joint is higher than that of natural joint [1]. 2) the wear debris of UHMWPE would cause periprosthetic biological reaction (osteolysis) and then lead to the aseptic loosening [2]. Many attempts were made to improve the tribological properties of UHMWPE, including gamma-crosslinking [3], fiber reinforcement [4], the chain length or molecular weight increasing [5] and ion implantation [6]. However, the friction coefficient of the modifying UHMWPE is still higher than that of natural joint which ranges from 0.005 to 0.023 [1]. The biocompatibility of modifying UHMWPE also needs to be further validated.

In 1971, Clarke utilized scanning electron microscope to observe human articular surface, finding that the surface of natural joint was not smooth but with distribute depressions with an average diameter from 20 to 40μm [7]. It implies that excellent tribological properties of natural joint may attribute to the microstructure of the articular surface. It also inspires the possibilities of using 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 MEMS devices, magnetic storage devices, and even golf ball. Surface texture have been carried out in tribological applications by employing various texturing techniques, including reactive ion etching (RIE) [8], abrasive jet machining [9], LIGA [10], and laser surface texturing [11]. It is demonstrated that surface texture makes significant improvements in load-carrying capacity, anti-seizeure ability, wear resistance, frictional performance of mechanical components. The numerical analysis of texture performance is complicated. The main research of textural numerical analysis is force on the hydrodynamic lubrication to research the texture ability on improving load-carrying capacity by generating additional hydrodynamic pressure [12,13].

However, up to date, only a few researches have focused on the surface design of UHMWPE. Young et al. [14] fabricated surface texture which consists of 2732 0.16mm diameter and 0.32mm deep holes on the surface of UHMWPE by a computerized numerically controlled milling machine.

They found that compared with the untextured UHMWPE, surface texture produced significant reduction (42%) in the friction coefficient under bovine serum lubrication. Kustandi T. S. et al. [15] utilized nanoimprint lithography (NIL) to produce textured UHMWPE with nano-scale grooves. The result indicated that under a dry-sliding condition with loads ranging from 60 to 200 mN, the textured UHMWPE performed a friction reduction of 8% to 35%, and wear depth and width were also lower than the untextured UHMWPE.

However, due to the difficulty on fabrication, micro-scaled texture, which is more approximate to the feature of nature joint surface [7], is known little on the surface of UHMWPE.

In this research, micro-imprint lithography technique is developed to fabricate the micro-scaled texture on the surface of UHMWPE. The procedure of surface texture fabrication is introduced in this paper. The tribological tests were performed to show the effect of textured UHMWPE.

The fabrication of textured UHMWPE

The detailed procedure of surface texture fabrication is shown as Fig.1.

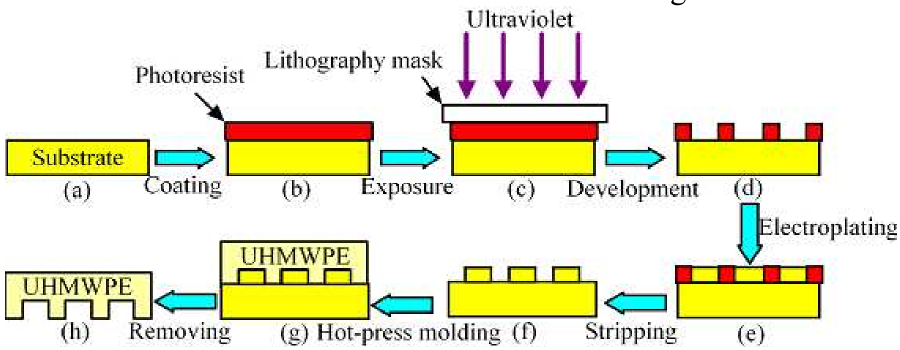
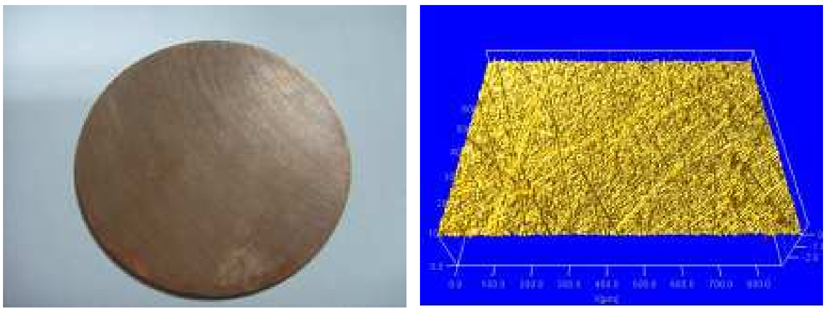


Fig.1 The detailed procedure of micro-imprint lithography.

A copper substrate (Φ50 × 0.8 mm), which is used as the substrate of opposite mold, is finished and cleaned according to the standard procedure by Beta Grinder-Polisher. The copper substrate was ground and lapped to the average roughness of Ra=0.06μm~0.07μm shown in Fig.2.



(a) (b)

Fig.2 The copper substrate and its 3D optical profile.
(a) copper substrate (b) the 3D optical profile of copper substrate

Before lithography, the copper substrate must be ultrasonic-cleaned by using acetone firstly and then alcohol. The negative photoresist (BN308-450) is adopted in this research. A negative photoresist layer is coated on the surface of the copper substrate by using a spin-coater with speed 500rpm firstly and 3000rpm secondly. The thickness of the negative photoresist layer is 5μm. The lithography mask, which can control the dimples area density and dimples diameter, is employed to exposure. The photoresist mask is developed by the negative photoresist developer and rinsed by negative photoresist rinser. A electroplate system is build to produce an opposite mold. The copper substrate should be acid pickled with dilute sulphuric acid (15% H_2SO_4) to eliminate the effect of oxide layer during the electroplating. The electroplating condition is shown in table 1.

Table 1 The electroplating condition.

$CuSO_4.5H_2O$ [g.L^{-1}]	240
H_2SO_4 [g.L^{-1}]	80
NaCL [g.L^{-1}]	30
Temperture [℃]	25±1
Current density [A.dm^{-2}]	1.5

After the electroplating, the sample should be stripped by negative photoresist stripper to produce an opposite mold. UHMWPE powder (3×106 molecular weight) is placed on the opposite mold and pressed at a temperature of 200℃ and a pressure of 48 MPa for 90 minutes. After cooled to room temperature, the opposite mold is moved. The textured UHMWPE is generated.

Effect of electroplating parameters

The electroplating thickness is depended on the electroplating time and current density. Considering the bonding strength, the current density can not too high. In this research, the current density of 1.5 A.dm-2 is chosen. So the electroplating time is the only factor to depend the electroplating thickness. Based on the Faraday's law, there's one mole of electrons of electrode reaction on either electrode when passing 96485.3C of capacity, and meanwhile the amount of substance is one mole too.

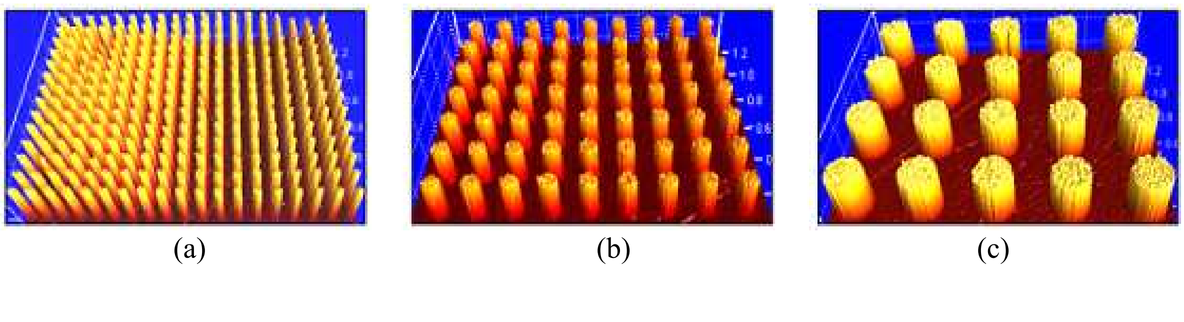
$$Q = \frac{mzF}{M} \tag{1}$$

Where Q is the total electric charge passed through the substance. m is the mass of the substance liberated at an electrode in grams. F is the Faraday constant (96485.3C/mol). z is the valency number of ions of the substance. M is the molar mass of the substance. Bringing the and into the equation 1, the relationship between the electroplating thickness and electroplating time can be learned as follows:

$$d = \frac{MJ\eta t}{\rho zF} \tag{2}$$

Where d is the electroplating thickness in μm. J is the current density in A/dm2. η is the current efficiency. t is the electroplating time in s. ρ is the density of Cu.

The 3D profile of the opposite mold is shown in Fig.3(a ~ c) following the process parameters calculated from equation 2. Fig.3(a) is the profile of opposite mold with area density 15%, diameter 50μm, high 15μm. Fig.3(b) is the profile of opposite mold with area density 15%, diameter 100μm, high 15μm. Fig.3(c) is the profile of opposite mold with area density 15%, diameter 200μm, high 15μm The optical image of copper convex can be observed by KEYENCE microscope shown in Fig.3(e). The profile and image of the opposite mold show that the verticality of copper convexes is good, and the soundness of the copper convexes is high.

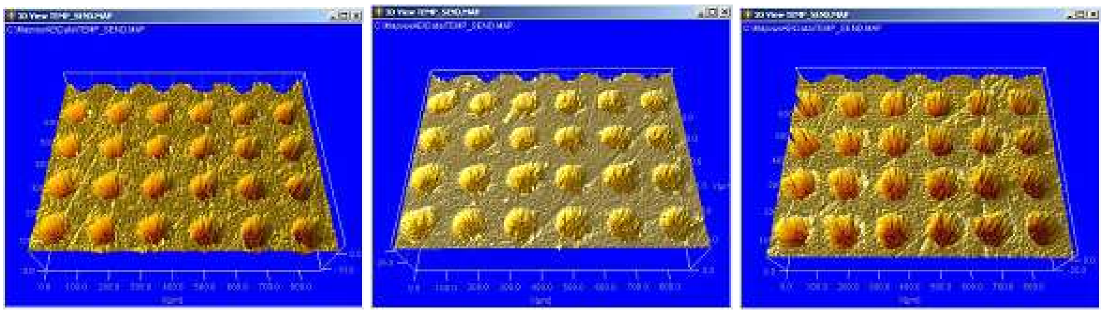


(a) (b) (c)

(d)

Fig.3 The profile and image of the opposite mold.

The verticality and soundness of copper convexes are influence results of hot-press molding. If the verticality and soundness of copper convexes are not good, after cooled to room temperature, the opposite mold will not be moved easily even some copper convexes of the opposite mold will break. The 3D profile of the textured UHMWPE is shown in Fig.4. Fig.4(a) shows the profile of textured UHMWPE with area density 35%, diameter 100μm, depth 5μm. Fig.4(b) shows the profile of textured UHMWPE with area density 35%, diameter 100μm, depth 10μm. Fig.4(c) shows the profile of textured UHMWPE with area density 35%, diameter 100μm, depth 15μm.



(a) (b) (c)

Fig.4 The 3D profile of the textured UHMWPE.

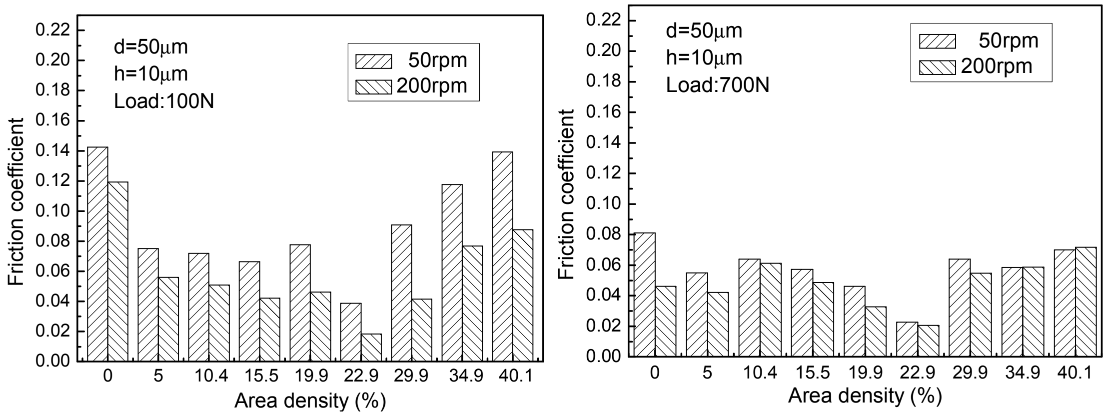
Tribological tests

Tribological tests are performed under distilled water lubrication at the room temperature by using a ring-on-disk test apparatus. The ring and disk are made of stainless steel (316) and UHMWPE respectively, as tribo-pair shown in Fig.5. 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 Ra=0.02 ~0.03 μm. The pattern of evenly distributed dimples is fabricated on the surface of disk by using micro-imprint lithography.

Fig.5 Specimen of ring and disk.

Tests are conducted at loads of 100 N and 700 N, corresponding to the contact pressures of 0.239 MPa and 1.67 MPa. The rotational speeds are 50 rpm and 200 rpm, corresponding to the sliding speeds of 0.054 m/s and 0.215 m/s. Tests are performed for 15 minutes 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.

At the load of 100N, with the same dimples diameter of 50μm, same depth 10μm, when the area density is between 5% and 29.9%, textured UHMWPE shows a significant effect of friction reduction shown in Fig.6(a). The dimple pattern with area density of 22.9% has the lowest friction coefficient in this group of experiments, which decreases 72.8% at the condition of 50rpm and 84.7% at 200rpm. When the area density exceeds 29.9%, the friction coefficient begins to increase. When increasing the load to 700N, all the textured specimens present significant effect of friction reduction though at different rotational speeds. the dimple pattern with area density of 22.9% has the lowest friction coefficient, which decreases 72.1% at the condition of 50rpm and 55.3% at 200rpm (Fig.6(b)).



(a) (b)

Fig.6 Dimple area density effect on friction coefficient

The micro-scaled surface texture can remarkably reduce friction on UHMWPE, which brings an effective approach for the improvement of the tribological properties of UHMWPE.

Summary

High friction coefficient and wear are two main problems that limit the using of UHMWPE in industrial applications and orthopaedic 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. The quality of photoresist mask can be obviously influenced by the exposure time. The process parameters of electroplating can influence the profile of textured UHMWPE. The micro-scaled surface texture can remarkably reduce friction on UHMWPE.

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