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Investigation of the Influence of Shapes-Texture on Surface Deformation of UHMWPE as a Bearing Material in Static Normal Load and Rolling Contact

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Abstract. Surface texture is a common method for improving wear properties of a tribo-pair of soft and hard bearing material. The reduction of wear rates on the contacting surface material is becoming important issues. In the present study, analysis of the contact pressure on the flat surface of UHMWPE (Ultra High Molecular Weight Polyethylene) under the static- and rolling motion with the surface of steel ball used the 3D finite element method (FEM) (the ABAQUS software version 6.12). Five shaped-texture models (square, circle, ellipse, triangle, and chevron) were presented on the flat surface for analysis. The normal load of 17, 30 and 50 N was deliberately set-up for static and rolling contact analysis. The contact pressure was determined to predict the wear behavior of the shaped-texture on the flat surface of UHMWPE. The results have shown that the static normal load yielded the lowest von-Mises stress distribution on the shaped-texture of the ellipse for all values applied a load, while the square shape experienced the highest stress distribution. Under rolling contact, however, the increasing load yielded the increasing von Mises stress distribution for the texture with a triangle shape. Moreover, the texture shapes for circle, ellipse, and chevron respectively, may undergo the lowest stress distribution for all load. The wear calculation provided that the circle and square shape may undergo the highest wear rates. Obviously, the surface texture of circle, ellipse, and chevron may experience the lowest wear rates and is potential for use in the surface engineering of bearing materials.

Keyword: Surface texturing, texture shapes, wear, contact pressure, rolling contact, finite element method.

1. Introduction

Ultra-high molecular weight polyethylene (UHMWPE) has emerged as a common bearing material for biomedical application because of having excellent properties such as self-lubrication ability, and chemical inertness. It has been widely found in many joint replacement devices in medical applications, including artificial joints and face surgery. However, wear and plastic deformation are two critical mechanisms that may lead to failure of this material during contacting to harder material both in sliding and rolling contacts. The implementation of the surface technology has become a great concern in the development of wear-resistant materials. In this case, the performance and lifetime of the bearing material rely on the changes in the surface engineering level. Recently, the surface texture developed on the soft material, namely UHMWPE has become a promising method to improve
tribological property [1]. Surface texture can be considered as an artificial micro-geometry which can be made by micro-groove, micro-dimples, or micro-convex scale on the surface contact.

Surface texturing can be made as an array of cavities fabricated on a surface, with specified geometry (size, shape, and distribution) and has achieved an important part of surface engineering in the critical surface area of tribological applications such as mechanical seals, bushings, and cylinder liners [2-5]. Creating surfaces with controlled microgeometry may be adopted as an approach to achieve the best performance of tribological interfaces. A textured surface with various depth, diameter, and distribution of cavities may operate as a lubricant reservoir that causes the load carrying-pressure to diminish on the surfaces of the counterparts and hence reducing the surface friction. Surface texturing in the range of hydrodynamic and elastohydrodynamic lubrication regimes may perform according to a Stribeck curve [6-9].

The great interest of the surface texturing reflected by the previous paper is for the surface technology of bearing materials. The most of the research was mainly focus on the surface texture of hard material as ceramics and metals. The researchers have conducted study intensively on the development of surface texture for soft polymeric materials (UHMWPE). Zang B et al. [10], proposed the micro-imprint lithography technology to construct micro-sized dimples on the UHMWPE surface. The result indicated that the surface textured on UHMWPE has an outstanding effect on the friction reduction compared to the tough materials such as metals and ceramics. Zang B et al. [11] manufactured dimple patterns on the surface of the 316 stainless steel and UHMWPE in order to compare the effect of surface texture on different materials. The texture was generated using the micro-imprint lithography and the combination of photolithography and electrolytic etching. The textured design on the UHMWPE surface provided a better wear resistance than the designed texture of the steel surface.

Further, Young et al. [12] developed a surface texture of UHMWPE by a CNC (computerized numerical controlled) milling machine. The surface texture generated yielding a substantial reduction (42%) in the friction coefficient using the bovine serum lubrication. Kustandi et al. [13] created nanoscale grooves on the surface of UHMWPE using nanoimprint lithography. The result showed that under a dry sliding condition for loads ranging from 60 to 200 mN, the surface texture of UHMWPE presented a friction reduction, whereas wear depth and width generated were lower than those of non-textured surfaces. Lopez-Cervantes et al. [14] studied the effect of texturing cavities on the stress distribution of the UHMWPE surface by numerical analysis using 2D and 3D finite element method. The numerical simulation was focused on the static contact under dry and wet condition. It was shown that under dry conditions, the textured surface with empty cavities has the highest von Mises stress. However, the contact pressure decreased as the liquid filled cavities. The subsequent research by Lopez-Cervantes et al. [15] reported the experimental design that resulted from tribological tests worked on UHMWPE flat disks, plain and textured, applying for a ball on disk construction to evaluate the performance of UHMWPE textured versus plain surface, under the different combinations of sliding and rolling motion. It was proposed that a lower traction coefficient will develop the performance of UHMWPE as a plastic spacer in prosthesis applications where a combination of sliding/rolling motion takes place.

Fang et al. [16-18] applied surface texturing techniques to practice attentively distributed UHMWPE particles with measured sizes and shapes. The basis of surface texture design has been established to accomplish wear particle morphology controlling in water. This accomplishment allows the bioactivity estimation of different sizes and shapes of UHMWPE wear particles. Furthermore, Fang et al. [19] examined the influences of biological lubricants on the morphology of UHMWPE wear particles produced with microfabricated surface textures. The result showed that a restricted circulation of the particles has been achieved by employing microfabrication of the surface textures. It was also shown the ability to restrain the particle size and shape by the dimensions of the surface textures. The length of the particle produced in serum is smaller than in water. Zhang et al. [20] utilized the numerical study to explore the ability usage of microstructures with different patterns to advance the tribological properties of UHMWPE. The simulation results demonstrated that the
rectangular surface texture displayed interesting features over the other geometries and the result that investigated can be excellent work to enhance hydrodynamic effects.

Jamari et al. [21] examined the effect of surface texturing on the stress distribution of UHMWPE under rolling contact. As a result, the maximum von Mises stress was concentrated in the direction of rolling. Our previous study [22], the research has investigated the influence of normal load under static contact by 3D finite element method. Different diameter and separation of the dimple were introduced in this numerical study. The increasing diameter cavities and separation resulted in the reduction von Mises stress distribution. Because of the importance of surface technology for the development of wear resistant material, a numerical model of surface texture should be developed on a smaller scale or more precisely to the level of surface micro-geometry. As a result, the level of surface technology change may relate to wearing rate of the material.

In the present study, a tribo pair of hard material and soft material, that are steel and UHMWPE, was examined. Surface texture with the different geometry was created on the surface of UHMWPE. A numerical contact model using FEM was developed. The effect of different texture shape on the contacting surface was investigated at different load conditions for normal load and rolling motion. This model of the elastic and elastic-plastic behavior of the textured surfaces was subsequently run using FEM software. Deformations and elastic-plastic sub-surface stresses were determined using the data that obtained from FEM analysis. Wear prediction of the different textured-shapes on the plate surface of UHMWPE was also investigated in this study using contact pressure value that was resulted from the simulation.

2. Eksperimental Method

This present work was to continue our previous research [21], which was mainly focused on analyzing the surface of the circle shaped-texture under static normal load. In the present study, contact simulations by FEM performed on the various shapes of texture under a normal load and rolling motion. In order to understand the effect of surface texture during contact, the FEM software ABAQUS version 6.12 was used to analyze the contact condition on the dimple region during static and rolling motion. Figure 1 shows the geometric contact of two bodies observed during the study. In this research, the flat surface body was a presumable elastic body which has a very low modulus of elasticity compared to the high modulus elasticity of the sphere with radius R. Eventually a normal load F subjected to the flat surface yielded a contact pressure.

![Figure 1](image.png)

Figure 1. The geometric contact between spherical steel ball and flat UHMWPE.

Five different shaped-texture was generated on the surface material of UHMWPE (circle, ellipse, triangle, square, and chevron), which was represented as a flat bottom profile. The geometry of each texture pattern is depicted in Figure 2.
Material properties of steel and UHMWPE were selected to simulate the surface contact of between hard and soft material. Detail properties of contact surface are presented as follows:

Friction coefficient $\mu = 0.1$

Young’s modulus of steel $E_1 = 210.000$ MPa

Young’s modulus of UHMWPE $E_2 = 945$ MPa

Poisson’s ratio of steel ($\nu_1$) = 0.29

Poisson’s ratio of UHMWPE ($\nu_2$) = 0.46

The steel ball as the indenter has a diameter of 10 mm, while the flat UHMWPE as the slave surface has the square dimensions of 6 x 6 mm. All shapes have the depth of grooves and separation, and it was set to 0.5 and 1 mm, respectively. The normal load applied on the indenter varied from 17, 30, and 50 N.

3. Results and Discussion

FEM analysis of the rolling contact between a rigid, smooth steel ball and a deformable the surface textures of UHMWPE provided the resultant stress applied on the surface. The von Mises stress distribution in the subsurface of the surface textures was determined under static and rolling contact. Plots of the resultant stress results are given in Figures 3 and 4, respectively. The texturing effect for stress analysis was made by the variation of texture shapes. In the presence of static contact under all applied load, it shows that the ellipse shape texture experienced the lowest von Mises stress distribution. However, the highest von Mises stress may be experienced by the surface texture with a square shape at the load of 30 and 50 N, triangle shape at the load of 17 N.

![Figure 2](image)

**Figure 2.** The geometrical model of textured surface with different shapes.

![Figure 3](image)

**Figure 3.** The von Mises stress distribution on the contact surface as a function of different static load
Differences in results of stress distribution occurred in the case of rolling contact was noted. The simulation procedures performed on the rolling contact of the textured surface under a normal load, shifted motion, rotation of the steel ball. The rolling contact simulation resulted in deformation and stress on the textured surface where deformation occurred in the contact area, while the stress distributed on the cavities of the texture. In the rolling contact, von Mises stress values are undergoing in the different shaped-textures (Figure 4). It shows that the surface texture of square shape experienced the highest value of von Mises stress. Moreover, for all normal load, the lowest value of von Mises stress distribution may be subject to the surface texture with the geometry of circle, chevron, and ellipse. Under rolling contact at 17 N load, the lowest von Mises stress goes to the circle shape texture, while chevron shape has the lowest von Mises stress at the load of 30 N. The increasing load to 50 N lead the texture of the ellipse to experience the lowest von Mises stress distribution.

![Figure 4. The von Mises stress distribution at the rolling contact surface as a function of different load.](image)

The plot of the 3D contour of von Mises stress for each of surface textures in the contact rolling is shown in Figure 5. It can be seen that the concentrated high-stress fields near the surface are in the middle of the flat disk and decreased in magnitude and expand along the edge. The red color on the contours indicates the stress concentration images, which show the highest value of von Mises stress distribution. Accordingly, the stress concentration occurs when the ball contacts on the texture areas.
Figure 5. The three-dimensional von Mises stress distribution of the rolling contact for chevron dimple (A), circle dimple (B), square dimple (C), ellipse dimple (D), triangle dimple (E) at the load of 17 N

The results of FEM modeling can be used to analyze the influence of contact pressure on the shaped-texture under the static normal load of 17, 30, and 50 N (Figure 6). It shows that all shapes of texture have the similar trend of the contact pressure for all applied loads. Trend charts show straight line at the time of initial penetration pressure area, which cannot be distributed to the cavities. The chart shows increasingly contact pressure for distributed load and form a wider contact area with increasing load. There are no significant differences in the contact pressure on the shape of the texture, but the loading 17 N made the texture shape of a triangle having the highest value of the contact pressure. Moreover, in the imposition of 30 and 50 N, the highest contact pressure goes to the square texture shape.

The contact pressure can be used as a prediction of premature wear, where the higher the value of contact pressure, the higher wear rates occur. The contact pressure resulting from the FEM simulation in this study are then used as input to calculate the wear. Here the average of contact pressure was obtained by adding the contact pressure on each node and then divided by the number of nodes in contact. The average value of the contact pressure obtained from simulations providing almost the same for all textures. The average value of the contact pressure at the highest loading of 17N is undergone by the circle shape (16.737 MPa), while the respective loading of 30 and 50 N in the square shaped-texture yielded the contact pressure of 19.846 and 22.989 MPa, respectively. The texture shape that has the largest contact pressure value allows for the wear is higher than in any other shape.

Based on simulation results, the different shaped-texture have insignificant values of von Mises stress and contact pressure for all operating conditions. This is due to the absence of differences in diameter and separation between cavities. The previous study [22] showed that the greater diameter and separation provided the lower von Mises stress in the texture of circle. Lopez work [14] also demonstrated that the von Mises stress and the contact pressure value are lower when the surface of the textured UHMWPE is under wet condition. Moreover, the texture of rectangular under the condition of optimum area density, radius, and depth shown capable of providing the maximum load-carrying capacity as proposed by Zhang et al. [20].
Figure 6. The contact pressure at the load (a) 17N, (b) 30N, (c) 50N

4. Conclusion
Operating conditions greatly affect the von Mises stress distribution on the surface texture of UHMWPE. In the static contact loading, the ellipse shape texture may reduce the stress distribution to a minimum value compared to the other forms. Different values of stress in the rolling contact condition are noted. The lowest value of von Mises stress distribution may reach through the texture of circle shape at the load of 17 N, chevron at the load of 30 N, and the shape of the ellipse at the load of 50N. This indicated that the surface texture of the ellipse is potential for improving wear properties. Based on the wear calculating using the average of contact pressure value with FEM, texture with shape circle and square may also be used for the surface engineering of bearing materials.

5. References
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