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Numerical study of surface texturing for improving tribological properties of ultra-high molecular weight polyethylene

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Abstract

Ultra-high molecular weight polyethylene (UHMWPE) has been used in total joint arthroplasty for over 50 years. Conventionally, smooth UHMWPE surfaces are used for total joint replacements; however, smooth surface contacts have been shown to be inadequate in friction reduction and/or anti-wear. More recently, micro-textured surfaces have been investigated for reduction of the friction and wear of two contact interfaces. Unfortunately, the tribological behavior of textured UHMWPE surfaces requires further research to understand its tribological behavior. A numerical model is presented to understand the potential use of specially textured surfaces to improve the tribological properties of UHMWPE. A two dimensional, transient form of Reynolds equation was used to model the lubrication condition of the textured surfaces. The effects of area densities and pore depths over varying diameters were examined for several textured geometries including circle, rectangle, square and triangle. The simulation results show that the surface texturing can effectively be used to enhance hydrodynamic effects. More specifically, it was shown that the rectangular surface texture displayed superior characteristics over the other geometries investigated. The results provide a theoretical reference for the tribological design of surface texture on UHMWPE.

Keywords: Surface texturing; Hydrodynamic lubrication; Friction; UHMWPE

1. Introduction

Owing to its low cost, self-lubrication ability, excellent biocompatibility and high wear and impact resistance, UHMWPE has been widely used for the artificial joint prosthetics as well as other industrial applications since the 1960s [1]. However, tribological problems associated with micron and submicron sized wear particles of the material are a major obstacle that limits its service life in industrial and orthopedic applications [2–4].

Various methods, including inorganic filling (such as hydroxyapatite [5,6], zirconium oxide [7,8] and carbon black [9–11]), cross-linking [12,13] and surface texturing [14–16] have been employed to enhance the tribological properties of UHMWPE. Among these, surface texturing has recently gained the research interest of triobologists. Designing special function orientated surface textures, such as micro-groove, micro-dimple and micro-convex geometries fabricated on contact surfaces, has been considered as a viable method to improve the tribological properties of mechanical components [17–19]. Surface texturing plays an increasingly important role as it can directly influence the friction and wear behaviors of contact surfaces in many ways. Firstly, micro-textures can improve the load-carrying capacity of the lubricant film through the enhanced hydrodynamic effect generated by the lubricants stored in the micro-textures [20–22]. Secondly, the lubricants stored in the micro-textures can provide increased space for extra lubricants which also improve the lubrication

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condition [23]. Thirdly, wear debris can be captured by the micro-textures, which reduces abrasive wear between contact surfaces [16].

As the lubrication condition shifts to hydrodynamic lubrication, the roles of lubricant pressure and load-carrying capacity of lubricant film formed by surface texturing become important [24]. Many researchers have investigated the effects of geometric parameters of textures, such as area densities and pore depths and diameters, on the lubricant pressure and loading capacity [25–28]. Ronen et al. [29] developed a simulation model to investigate influences of the aforementioned variables on friction forces and found that a change in the area densities, in the range between 5% and 20%, affected the friction forces by less than 7%. An optimum value of the pore depth over diameter ratio was found, which varied between 0.1 and 0.18. A one-dimensional numerical model was used by Tomandik [30] to simulate effects of surface textures which considered both the full and partial texturing. The results indicated that micro-dimples were able to generate a significant hydrodynamic effect which improved its performance characteristics. In particular, partial laser surface texturing improved the friction and wear of hydrodynamic support near top dead center and at middle stroke by 50% and 90% respectively. However, existing simulations have not considered the effects of pore patterns, such as circle, square, rectangle and triangle on the tribological properties.

Experimental researches also confirm that tribological properties of contact surfaces can be improved by selecting a propriety surface texturing. Kustandi et al. [31] fabricated nano-textures on the surface of UHMWPE by nano-imprint lithography whereby friction and wear tests were conducted in a sliding condition. They found that the textured UHMWPE surface had a reduction of friction coefficient between 8% and 35% compared with the non-textured surface. Reciprocating wear tests were carried out and the results showed that the textured UHMWPE surface resulted in a lower wear depth and width in comparison to the non-textured surface. Zhang et al. [14,32] adopted the micro-imprint lithography technology to fabricate the UHMWPE surfaces. The tests were performed under a lubricated condition using distilled water at room temperature. The optimized area density of the textured UHMWPE surfaces was found range from 22.9% to 29.9%. The textured UHMWPE also presented a significant improvement to the total wear resistance. The average wear depth of the textured UHMWPE showed a 35.5% improvement than that of the non-textured system. All the results mentioned above demonstrate that texturing on the UHMWPE surface can significantly improve its tribological properties. However, similar to the current numerical simulations, the existing experimental studies have only investigated circle geometry dimples on the surface. There is a lack of data on effects of UHMWPE surfaces with other texture patterns. Therefore, numerical simulations have been introduced to further understand the overall improvement of tribological properties over a various range of contact geometries and texture patterns.

In this paper, a simulation model is presented to study the potential use of micro structures with different patterns to improve the tribological properties of UHMWPE. The work was intended to investigate effects of UHMWPE surfaces with circle, square, rectangle and triangle patterns on film thickness and friction force. The effects of dimple parameters such as area density and depth are also investigated to obtain an optimal outcome in terms of a maximal film thickness and minimal friction force.

2. Analytical method

A two-dimensional lubrication model illustrated in Fig. 1 was developed to study the lubrication and friction performance of contact surfaces with consideration of effects of surface textures on the UHMWPE surfaces. The objective of the model is to predict the friction force obtained using different textured shapes of the UHMWPE surfaces to optimize their performances.

2.1. Textured shape and geometry

Fig. 1 shows a schematic of the model where the micro-textures were presented on the UHMWPE surface.

Four different shape including a circle, square, rectangle and triangle were chosen to study the optimum geometries for the maximum hydrodynamic effect and minimal friction force under the specific operation conditions. The geometrical parameters of the textured surfaces are presented in Fig. 2 and Table 1. The dimples were uniformly distributed with a base depth h_d. Each dimple is located in the center of an imaginary square area of $l \times l$. The dimple area density and dimple depth over diameter ratio are the two key parameters

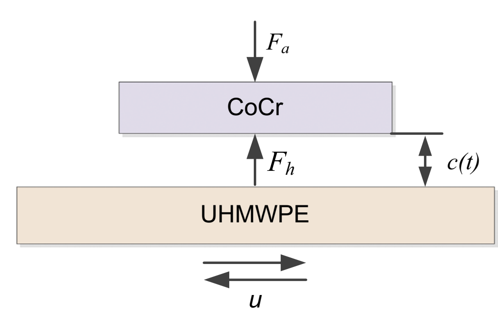

Fig. 1. Simple model of CoCr pin and UHMWPE slider.

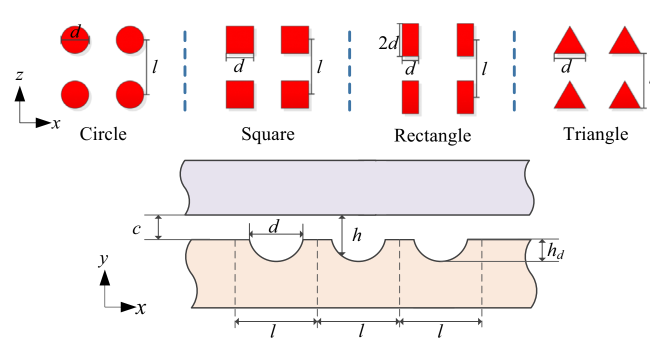

Fig. 2. Geometrical model of textured surface with different shapes.