ABSTRACT

The research presented in this article is a wear volume analysis of the effects of silver nanoparticles in a polyethylene-glycol lubricant (PEG). The ball-on-disk method was used to perform the tests and a surface profilometer was used to analyze the amount of wear produced by this nanolubricant. The results showed that with the addition of silver nanoparticles, the wear was reduced significantly in comparison to a control sample without any nanoparticles. This is in contrast to some of the nanoparticles which can actually increase the wear when added to a lubricant.

INTRODUCTION

What is a nanolubricant? A nanolubricant is comprised of three basic components: base oil, surfactant, and the nanoparticle. Nanoparticles are less than 100 nm and can come in a variety of shapes and materials. So why are nanolubricants important? Studies have shown that in a combustion engine, 33% of fuel energy is lost due to friction and that lubrication can improve the friction significantly1. Previous literature suggests that the nanoparticles as additives can induce marked effects on the lubricant properties2. Different combinations of nanoparticles and lubricants can result in numerous nanolubricants for different applications. Recent research has shown that nanolubricants can reduce the coefficient of friction and affect wear. This reduction of the coefficient of friction could be translated into higher fuel efficiency. However, some nanoparticles can also increase the wear. For this research, a nanolubricant containing different concentrations of silver nanoparticles was used to perform ball-on-disk friction tests to determine how nanoparticles affect wear in the mixed lubrication region of the Stribeck curve.
MATERIALS AND METHODS

The nanolubricant studied was comprised of polyethylene glycol 600 (PEG), polyvinyl pyrollidone (PVP), and concentrations of 0.15 % wt, 0.3 % wt and 0.45 % wt silver nanoparticles with average diameters of seven nanometers. In order to determine the effects of the silver nanoparticles only, the base and surfactant (PEG and PVP) was used as a control. In order to create the wear grooves, a ball-on-disk test was performed using an CETR-UMT friction testing machine with constant loads of 10 N, 30 N, and 50 N, a rotational speed of 0.5 m/s, and a total sliding distance of 2500 m, according to the ASTM standard3. Each test was performed three times to insure repeatability. The nanolubricant completely filled the testing reservoir and submerged the sample to insure an even distribution of lubricant during testing. After the ball-on-disk tests were complete, the resulting wear grooves were analyzed by using a stylus profilometer with a vertical resolution of less than one nanometer. Using a numerical scheme, the surface scans were stitched together to produce a 3D surface image of the wear groove, as seen in Figure 1.

\[
Wear\ Volume = 2\pi R \left[ r^2 \sin^{-1} \frac{d}{2r} - \frac{d}{4} \left( 4r^2 - d^2 \right)^{\frac{1}{2}} \right] 
\]

\(R = \) wear track radius
\(d = \) wear track width
\(r = \) sphere radius

RESULTS AND DISCUSSION

The effects of the nanoparticle concentration on wear volume can be seen in Figure 2. The results indicate that the addition of silver nanoparticles reduces the amount of wear when compared to that of the control lubricant. The coefficient of friction (COF) was also monitored throughout the ball-on-disk tests, and it was discovered that the COF is reduced by approximately 20% at the nanoparticle concentration of 45 mM and normal load of 30 N in comparison to the control sample. Previous research has suggested that the mechanism present to reduce friction between two surfaces is by reducing the real area of contact as the particles prevent the surfaces asperities from coming into contact as frequently4,5. However, other mechanisms may also be at work.
CONCLUSION
When the wear volume of each nanolubricant concentration was compared to the base lubricant, the results show that there is a definite reduction of wear. This may be due to the relatively soft silver particles protecting the tested surfaces like a cushion, or they could be improving the load-carrying capacity of the lubricant itself. Further research looking at the wear reduction mechanisms needs to be pursued.

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REFERENCES
ABSTRACT
Approximately 285,000 total hip replacement (THR) surgeries are performed in the U.S. each year. Most prosthetic hip joints consist of a cobalt-chromium (CoCr) femoral head that articulates against a polyethylene liner (usually ultra-high molecular weight polyethylene (UHMWPE)), lubricated by joint fluid. The statistical survivorship of these metal-on-polyethylene prosthetic hip joints declines significantly after 15 years of use, primarily due to wear and wear debris incited disease. The current engineering paradigm aims to increase the longevity of prosthetic hip joints by manufacturing ultra-smooth articulating surfaces. In contrast, we aim to increase the longevity of prosthetic hip joints by adding a patterned microtexture to the ultra-smooth CoCr femoral head. The patterned microtexture increases the lubricant film thickness between the articulating surfaces, thereby reducing friction and wear. We have numerically optimized the microtexture geometry to maximize the lubricant film thickness between the articulating surfaces of the prosthetic joint, and experimentally demonstrate reduced friction for the microtextured compared to the smooth articulating surfaces lubricated with joint fluid.

INTRODUCTION
More than 285,000 total hip replacement (THR) surgeries are performed in the U.S. each year. The statistical survivorship of these prosthetic hip joints declines significantly after 15 years of use, primarily because adverse biological reaction to indigestible wear debris leads to osteolysis, instability and loosening of the implant. This lack of durability has unacceptable effects such as riskier revision surgery and surgery postponement with its attendant pain and disability. This research focuses on metal-on-polyethylene (MOP) prosthetic hip joints, which are the most common in the U.S. The current engineering paradigm for combating implant wear is to manufacture smoother sliding surfaces. In contrast, we attempt to reduce friction and wear by adding a patterned microtexture to the ultra-smooth femoral head, as illustrated in Figure 1.

A few researchers have attempted to improve the durability of MOP prosthetic hip joints by applying a surface texture...
or increasing the surface roughness of the femoral head in order to trap wear debris or store and dispense joint fluid. Ito et al. observed a 17% reduction in friction and a 36% reduction in polyethylene wear after creating circular texture features into the smooth femoral head. Sawano et al. observed a modest reduction in wear after manufacturing channels into the smooth femoral head running perpendicular to the direction of articulation. Zhou et al. observed that surface microtexturing did not improve lubrication after adding concave texture features via a diamond spherical indenter into the smooth femoral head. Tall ridges were observed around the contour of the texture features, which may have resulted in increased friction.

In contrast to the current engineering paradigm and earlier research, the objective of this work is to increase the durability of MOP prosthetic hip joints by creating a patterned microtexture that reduces friction in the prosthetic hip joint by increasing the lubricant film thickness. We have used a lubrication model to optimize the microtexture geometry in terms of maximizing the load-carrying capacity of the lubricant film between the CoCr specimen and the UHMWPE specimen. The microtexture geometry is determined by the texture density $S_p$, defined as the area covered by the texture divided by total bearing area, and the texture aspect ratio $\rho$, defined as the ratio of the depth and diameter of a texture feature. Four different microtexture designs are selected, based on load-carrying capacity, from the modeling results. These microtexture patterns are manufactured on polished CoCr (ASTM F1537-08) cylinders of diameter 50 mm and average surface roughness $R_s < 50$ nm using laser surface texturing (LST) with a solid-state laser. The characteristic radius of the spherical texture

**EXPERIMENT APPARATUS**

Figure 2 shows the friction apparatus that we have built and used. It is more realistic than a pin-on-disk (POD) apparatus but less complex than a hip simulator, and it creates the axial loading and flexion/extension rotation experienced during hip gait between the articulating CoCr and UHMWPE specimens. Figure 2(a) depicts the mechanical assembly of the apparatus. A cylindrical CoCr cylinder specimen is mounted on the shaft in the lubricant reservoir (Figure 2(b)) and a concave UHMWPE specimen is loaded against the convex CoCr specimen (Figure 2(c)) using a power screw mechanism. The loading mechanism is designed to self-align the UHMWPE specimen with the CoCr specimen. A geared stepper motor creates a reciprocal motion between the CoCr and UHMWPE specimens, while the torque and normal load between both specimens are continuously measured. This allows the friction coefficient to be computed as a function of time. The articulating surfaces are submerged in bovine serum with a protein concentration of 20 mg/ml.

**SPECIMENS**

A traditional lubrication model is used to optimize the geometry of the microtexture in terms of maximizing the load-carrying capacity of the lubricant film between the CoCr specimen and the UHMWPE specimen. The microtexture geometry is determined by the texture density $S_p$, defined as the area covered by the texture divided by total bearing area, and the texture aspect ratio $\rho$, defined as the ratio of the depth and diameter of a texture feature. Four different microtexture designs are selected, based on load-carrying capacity, from the modeling results. These microtexture patterns are manufactured on polished CoCr (ASTM F1537-08) cylinders of diameter 50 mm and average surface roughness $R_s < 50$ nm using laser surface texturing (LST) with a solid-state laser. The characteristic radius of the spherical texture
features is \( r_p = 50 \ \mu m \). Figure 3 shows optical microscopy and white light interferometry images of each of the four microtexture patterns implemented on cylindrical CoCr specimens (ASTM F1537-08) showing the results of the LST process. The radius of the dimples, \( r_p = 50 \ \mu m \).

**RESULTS AND DISCUSSION**

Figure 5 shows two seconds of typical results extracted from a longer duration experiment performed in our experimental apparatus. Figure 5(a) shows the kinematic cycle including velocity and angular position of the CoCr specimen with respect to the UHMWPE counterface as a function of time. The kinematic cycle is designed to maximize the portion during which a constant velocity is maintained to best approach the
steady-state lubrication model used to optimize the microtexture geometry. The frequency of the kinematic cycle is 1.0 Hz [12] (ISO 14242-1), which is similar to walking gait. Figure 5(b) shows the friction coefficient as a function of time for a microtextured \((S_p = 0.05, \varepsilon = 0.005)\) and smooth CoCr specimen, articulating against the UHMWPE specimen with a contact pressure of 0.90 MPa, realistic for hip joints.

We observe that the friction coefficient is periodic with reversals between clockwise (CW) and counter-clockwise (CCW) rotations. The magnitude of the friction coefficient is maximal surrounding the starts and stops, and it is minimal throughout the middle of each cycle when the sliding velocity at the surface of the cylinder is constant (0.1 m/s). The microtextured CoCr specimen outperforms the smooth specimen in two ways. First, the friction coefficient is lower for the microtextured compared to the smooth cylinder over almost the entire kinematic cycle (for this particular texture geometry, kinematic cycle, and loading example), indicating that friction is reduced significantly. Second, the friction coefficient for the microtextured CoCr specimen experiences a sharp drop surrounding direction reversals (at \(t = 0.5, 1.0, 1.5\)). In contrast, the friction coefficient for the smooth CoCr specimen decreases slowly after direction reversals. This indicates that solid-on-solid contact between the CoCr and UHMWPE surfaces is reduced for the textured versus the smooth surfaces. This could lead to reduced wear and, correspondingly, increased longevity.

To evaluate and compare the performance of the four microtexture geometry designs, we have quantified the portion of the kinematic cycle during which each of the microtextured CoCr specimens displays a lower friction coefficient than the smooth CoCr specimen. Table 1 summarizes the results and shows the percentage of the kinematic cycle during which the microtextured CoCr specimen outperforms the smooth one. Each microtexture geometry design outperforms the traditional smooth surface design over at least part of the kinematic cycle. These results confirm the hypothesis that friction can be reduced at low sliding velocities in a surrogate MOP prosthetic hip joint by means of a patterned microtexture on the surface of the femoral head.

**CONCLUSION**

We find that the friction coefficient between the surrogate convex CoCr and the concave UHMWPE specimens is lower for textured CoCr specimens than for the benchmark smooth CoCr specimen. This demonstrates that the patterned microtexture reduces friction by reducing contact between the articulating surfaces. A reduced friction coefficient between the articulating bearing surfaces promises reduced wear and increased longevity of a prosthetic hip joint. Also, in contrast with the smooth surrogate CoCr femoral head, the friction coefficient decreases very quickly after sliding direction reversals for the microtextured surrogate femoral heads. Daily human joint activity includes frequent starts and stops, and it is during these periods of high-friction boundary lubrication that the most wear occurs. Thus, the microtexture reduces friction and wear precisely at instants where it is needed most.

**REFERENCES**


**PUBLICATIONS RESULTING FROM THIS WORK**

**Journal Publications**


**Conference Proceedings**