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The Analysis of Dimple Geometry on Artificial Hip Joint to the Performance of Lubrication

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Abstract. This research analyzed the effect of applied surface texturing on bearing component of the artificial hip joint due to lubrication performance. The main contribution of the paper was explaining the significant role of adding dimples in artificial hip joint surface bearing who can probably decrease friction interaction on the acetabular liner and femoral head that impact on improving wear resistance. This is achieved by analyzing the geometric variation (shape and diameter) of the dimple to the performance of lubricating metal-on-metal artificial hip joint bearings under normal walking conditions. The research method focused on numerical analysis using the Fluid-Structure Interaction (FSI) simulation method which reviewed the solid and fluid structure. From the simulation results, it can be seen that the variation of ellipse dimple with a diameter of 80 μm has the best lubrication performance, which is indicated by the largest hydrodynamic fluid pressure of 0.915 Pa, the smallest solid pressure is 0.433 Pa, and the largest lubricant thickness is 22.672 μm.

Keywords: hip replacement, bearing, surface texturing, lubrication performance, fluid-structure interaction

Introduction

Metal-on-Metal (MoM) artificial hip joint is one of the most common used in Total Hip Replacement (THR) surgery because some of its advantages such as high hardness, not easy to wear, not produce squeaking sound, low dislocation rate and long life tool [1][2]. That was widely used for clinical applications of young patients with high activity levels for 10-15 years [3][4]. MoM is controversial in many cases of the hip joint replacement operations due to biological risk to metal wear particles on-the MoM bearing of cobalt ions, and nanometer-sized chromium is very easy to absorb by body tissue, which can spread to the organs of the body [5][6][7][8]. Particles and metal ions can spread to the organs through the blood, potentially causing harmful effects on the immune system, reproduction, kidneys and nervous system [9][10]. Reducing friction, wear, and optimum lubrication are important in the application of artificial hip joints [11][12][13].

Many research of key findings from the previous time has been developed to decrease metal wear debris on the artificial hip joint with applied various types of surface texturing (dimple) [14][15]. By creating a dimple on the surface bearing on the artificial hip joint, it can also increase the load-carrying capacity of the material, long life, wear resistance and tribological performance [16][17][18][19]. Otherwise, it can also decrease friction, direct contact between the bearing surfaces [20][21]. Act as reservoir lubricant, adding dimple on a surface bearing of the artificial hip joint will optimize the fluid film thickness [22]. Proven as theoretical and experimental, surface texturing application produces some positive effect on improving tribological performance on bearing components [23].

The effect of surface texturing on the tribological analysis of the hip joint has been reported in previous works. Roy *et al*. found 22% friction and 53% wear reduction for textured compared to non-textured surface on Ceramic-on-Ceramic (CoC) artificial hip joint [24]. Chyr *et al*. from numerical and experimental results explained that adding dimple reduces friction and increases hydrodynamic pressure and fluid film thickness [22]. Compare to micro and nano dimple against a polydimethylsiloxane half-ball on dry and wet condition, on wet condition it was found that using nano dimple decreases the coefficient of friction (COF) by 93.4% [25]. Galda *et al*. found that positive effect of the dimple has more significant at lower load condition in sliding surface experiment [26]. Borjali *et al*. knowing that adding dimple will reduce wear significantly compared to without dimple in pin on disk experiment [27]. Zhang *et al*. were investigated tribological performance by adding petaloid dimple from experimental work on CoCrMo artificial hip joint to improve tribological performance. By creating additional hydrodynamic pressure effect and entrapping worn particles into the dimples, the friction and wear between the underlying surfaces are significantly reduced [28].

However, many previous studies conducted research on the application of textured surfaces, especially on the components of the artificial hip joint. Research conducted to optimize tribological performance by using dimples on the bearing surface of artificial components of the hip joint was rarely done by many researchers. Research to analyze solid to solid through Computational Solid Mechanic (CSM) and solid to the fluid through Fluid-Structure Interface (FSI) on the artificial hip joint component whose surface is given dimple also not fully understood. Simulated research using finite element method with a simplified model in the 2D form by CSM and FSI is still needed to be further investigated.

In this study, we modify the contact area on the acetabular liner by adding dimple and analyzing the effect of variations in the dimple geometry on the performance of lubricating on the artificial hip joint by the Computational Solid Mechanics (CSM) method and the Fluid-Structure Interaction (FSI) method using COMSOL Multiphysics 4.3b software. Surfaces textured result in lower wear rates than non-textured surfaces, due to the reduced surface contact area, reduced friction coefficient, and can trap lubricating fluid to form a thicker lubricant layer and reduce surface wear [27].

This study aims to analyze the geometry variations (shape and diameter) dimple to the performance of lubrication on the bearing MoM artificial hip joint in normal running conditions. The research method focused on the numerical analysis of the 2D Finite Element Method (FEM) using Computational Solid Mechanic (CSM) which reviewed the solid and solid structure and Fluid-Structure Interaction (FSI) simulation method which reviewed the solid and fluid structure.

Materials and Method

1. Material and dimensions

The dimensions of the bearing hip joint in the form of cup and ball are taken from a previous study [8], the diameter of the femoral head, the clearance, and the cup thickness is 28 mm, 30 μm and 9.5 mm respectively. The bearing material will be used in CSM simulation and FSI is the metal-on-metal type, with 210 GPa elasticity modulus, Poisson ratio 0.3, and material density of 8300 kg/m3. The type of lubricant used in the simulation of this study is synovial fluid characteristic the same as blood plasma in the human body, that is dynamic viscosity equal to 0.0025 Pa.s, and density equal to 1012 kg/m3 [3][29].

2. Loading to bearing artificial hip joint

As the standard daily activities conducted after THR surgery, problems and limits of this research taken normal movement patterns, then used as a reference the imposition on the normal movement patterns. In most transient lubrication simulation at normal conditions only vertical load and movement review flexion-extension. A variation of the load is obtained based on the standard ISO 14242-1, as shown in Figure 1.

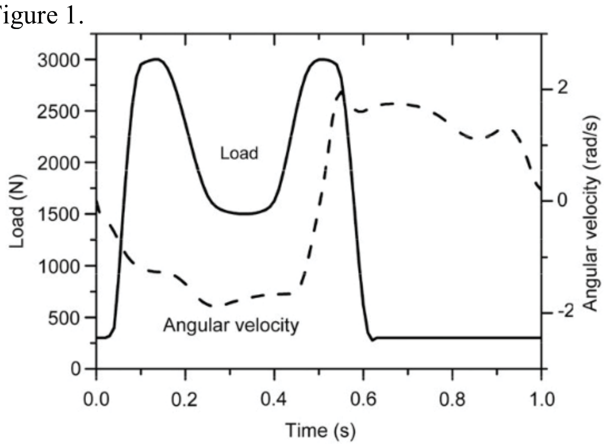

Figure 1. Vertical loading (Wy) and angular velocity flexion-extension (Wx), for BW = 750 N.

3. Modeling

The model resolution used in COMSOL Multiphysics 4.3b in the form of a 2D model of the ball in the socket that has a dimple and without dimple in conditions without lubrication by using the method in Computational Solid Mechanics (CSM), and modeled sample in the form of two pieces of plate 1 mm x 0.1 mm which one of its plate was given a dimple with a variation of diameter size and a predetermined shape by using the method of Fluid-Structure Interaction (FSI).

3.1. Modeling of the 2D ball in the socket without lubricant

The design of the 2D ball in the socket is created based on the data obtained from the reference [8]. The model is made in the form of one-fourth of the circle because the model assumed wheelbase symmetrical. This modeling uses the settlement method in Computational Solid Mechanics (CSM), so there is only the domain of the solid. The 2D modeling of the ball in the socket without a dimple is created in the software Multiphysics 4.3 b shown in Figure 2. The design of the 2D ball in the socket for a surface with dimple have the same dimensions with the design of the ball in the socket without the dimple. Modeling with a dimple made on the software Multiphysics 4.3 b shown in Figure 3.

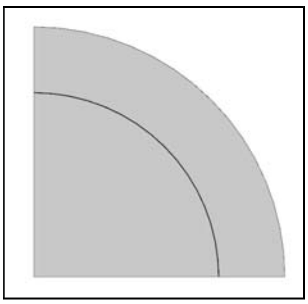

Figure 2. Model of the 2D ball in the socket without a dimple

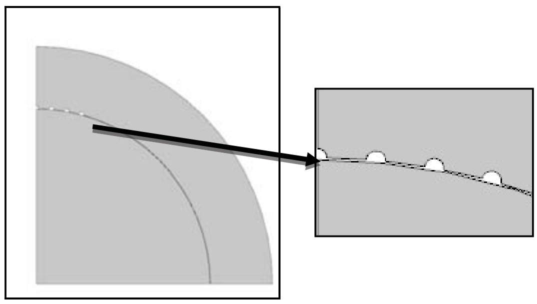

Figure 3. Model of the 2D ball in the socket with a dimple

3.2. Modeling of the 2D two plates with lubricant

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In this model, the 2D design in two parallel plates with an area of 1 mm x 0.1 mm, then inserted into the lubricants in the form of synovial fluid with dimensions of 1.5 mm x 0.7 mm, as shown in Figure 4.

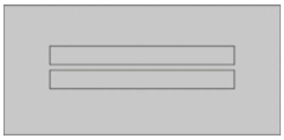
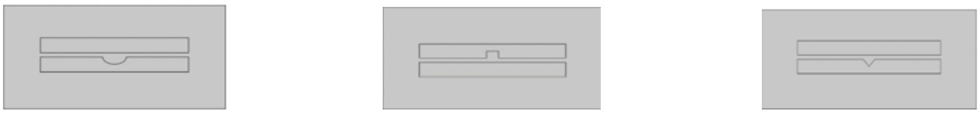


Figure 4. A sample of two plates without the given lubricant dimple.

The next modeling was done by designing two plates of which one of the plates was dimple with a depth of 50µm and variations in the shape of Ellipse, Rectangle, and Triangle dimple as in Figure 5 with dimple diameter 80µm, 100µm, and 120µm. This dimple shape variation is taken from the side view of a 3D sample.



(a) **(b)** **(c)**

Figure 5. Sample two plates with variations of the dimple (a) Ellipse, (b) Rectangle, (c) Triangle.

3.3. Boundary conditions

3.3.1. The 2D model of the boundary condition of the ball in the socket without lubricant

The outer portion of the cup is fixed, the elastic linear material, the surface between the cup and the ball is given a contact pair. A coefficient of friction on the contact pair is assumed to be 0.1, this contact is useful for obtaining contact pressure between ball and cup. Given a fixed load of 3000 N which is the maximum load on the hip bone joint when walking normally. For modeling, without a dimple, the theory of Hertz is applied.

3.3.2. The boundary conditions model of the 2D two plates with lubricant

Modeling the 2D two plates with dimples and without dimple on the FSI method has the same boundary condition. The plates at the bottom are variations of shape and diameter dimple as in Figure 5, and then in fixation. Both plates are inserted into the lubricant given the wall and the lubricant is given a force volume. Then the top plate is loaded with body load with the value as in Figure 1.

4. Meshing the model

Process simulation of meshing is done as shown in Figure 6. This study was conducted in the two-meshing process, namely on the 2D modeling ball in the socket and modeling of the 2D two plates with lubricant. In the process of meshing convergence, the study needs to be done in order to determine the appropriate type of meshing.

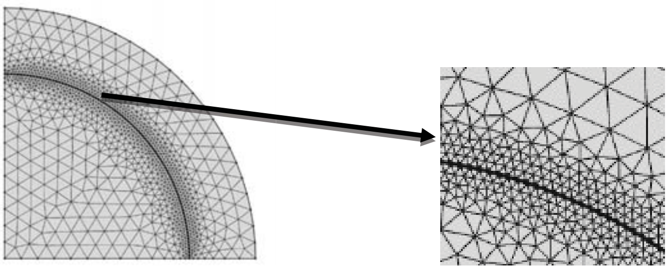


Figure 6. Example of meshing on the 2D modeling ball in the socket.

5. Mesh Sensitivity Study

A mesh sensitivity study was conducted by running a preliminary tribological analysis of the hip joint. This study was conducted on the convergence on modeling of the 2D, meshing ball in the socket without lubricant, and modeling of the 2D two plates with lubricant. The mesh convergence study aims to determine the optimum number of elements that will be used later in numerical simulation.

5.1. Convergence Study for modeling the 2D ball in the socket without lubricant

Sensitivity analysis of mesh on this modeling uses parameters contact pressure that occurs in the area of contact between the ball in the socket as shown in Figure 7. Type of meshing used, namely the fine meshing has 5784 elements.

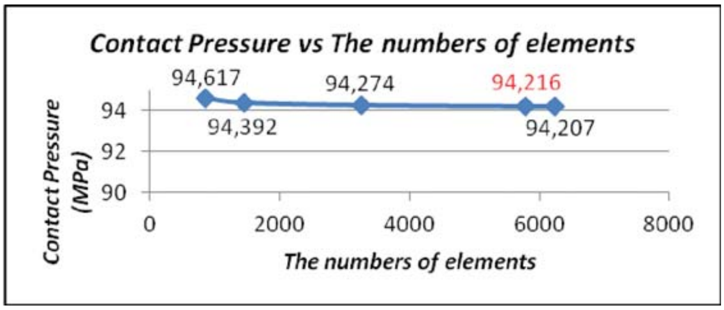


Figure 7. The Convergence study of the model 2D ball in the socket without lubricant

5.2. Convergence Study for modeling of the 2D two plates with lubricant

Sensitivity analysis of mesh on this modeling uses the parameters of the speed of fluid that occurs in the area of contact between two plates. Type of meshing used, namely the meshing of the finer points that have 28192 elements, as shown in Figure 8.

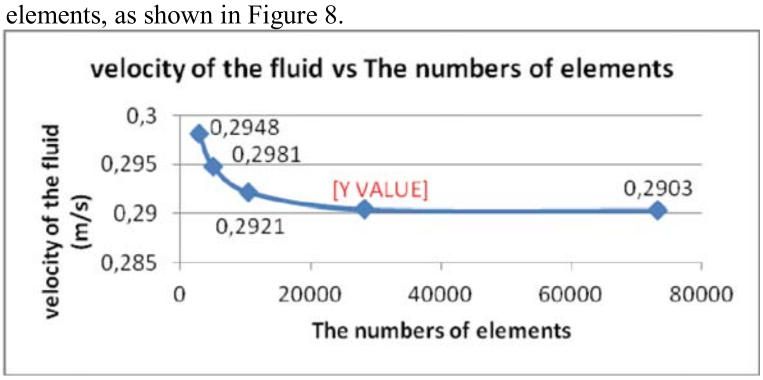


Figure 8. The Convergence study of the model 2D ball in the socket with lubricant

Results and Discussion

1. Modeling of the 2D ball in the socket

Based on Figure 9, it can be seen the value of contact pressure against angle coordinates where the contact pressure between the surfaces without dimple with the theory of Hertz is approaching the same value. This is evidenced by the maximum value of the pressure contact surface without dimple with the simulation of the CSM of 94.216 MPa, while the maximum value of the contact pressure of the theory of Hertz is equal to 89.6 MPa. Contact pressure obtained from the theory of Hertz is also assumed without a dimple, therefore the results of the simulation of the CSM and the results of calculations of the theory of Hertz are approaching the same value.

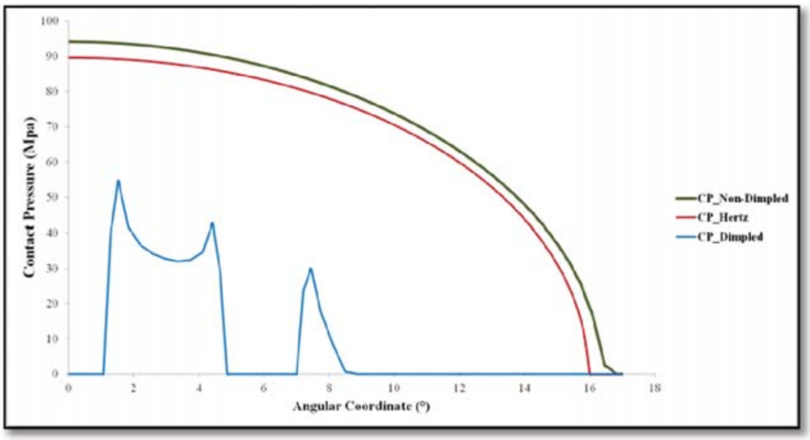


Figure 9. Comparison of contact pressure between Hertzian theory and CSM with dimple and without a dimple

The results of the simulation of the 2D ball in the socket with the addition of the surface of the dimple, seen that the contact pressure decreases where the maximum value of the pressure of the contacts only amounted to 54.84 MPa. This shows that the contact pressure becomes smaller with the addition of the dimple so that it can reduce the wear and tear. The addition of the dimple is the basis for further research using the methods of FSI to analyze the influence of the dimple that is lubricated.

2. Modeling of the 2D two plates

Hydrodynamic Pressure

The relationship of variations in the shape and diameter of the dimple against the pressure of the hydrodynamics on the maximum load can be seen in Figure 10.

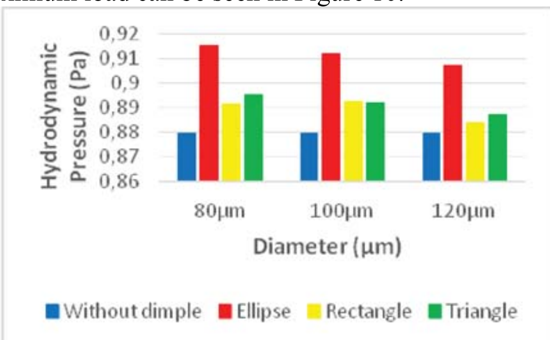


Figure 10. Effect of the geometries of the dimple on the hydrodynamic pressure of artificial hip joint

From Figure 10 it is seen that the hydrodynamic pressure of the plate with a dimple is greater than that of the plate without dimple for all diameters and the ellipse-shaped dimple has the greatest hydrodynamic pressure compared to the other forms. Therefore, the hydrodynamic pressure of hip joint, decreased as the dimples diameter increased, which indicated that the presence of the dimple diameter significantly enhances the hydrodynamic pressure of the artificial hip joint. From the simulation results, surface texturing can increase the hydrodynamic pressure by providing numerous converging gaps in the path of fluid flow and enhancing the elastohydrodynamic lubricant (EHL) film formation in a heavily-loaded contact such as artificial hip joint. Dimples act as reservoirs to simultaneously increase and entrap wear debris [30].

Solid Pressure
The relationship of variations in the shape and diameter of the dimple against the solid pressure on the maximum load can be seen in Figure 11.

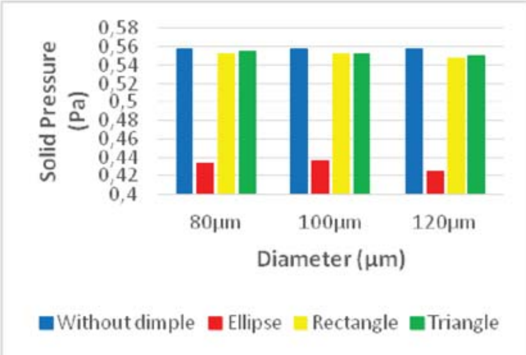


Figure 11. Effect of the geometries of the dimple on the solid pressure of artificial hip joint

It is seen from Figure 11 that the solid pressure to the plate with a rectangle and triangle-shaped dimple and without dimple have more or less the same value of 0.55 Pa and are greater than that of the plate with the ellipse-shaped dimple of the order of 0.43 Pa for all diameters. The larger the dimple diameter, the smaller the solid pressure.

Lubrication Film Thickness
The film thickness of lubrication contact of the artificial hip joint is one of the most important aspect to reduce contact area and effort to minimize friction already taken form pair of the component that increases its wear resistance. Surface texturing known may trap lubricant film and increase its thickness make lubricant improved tribological performance [31]. The relationship of variations in the shape and diameter of the dimple against the lubrication film thickness on the maximum load can be seen in Figure 12.

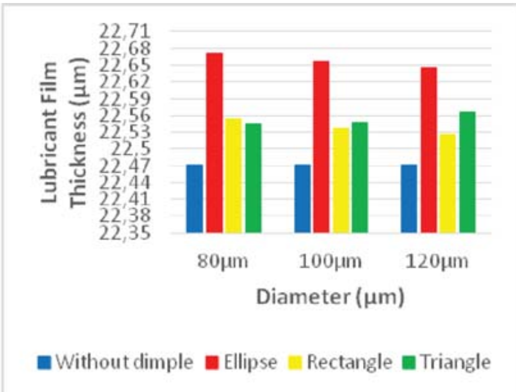


Figure 12. Effect of the geometries of the dimple on lubrication film thickness of artificial hip joint

It is seen from Figure 12 that the lubrication film thickness of the plate with a dimple is greater than that of the plate without dimple for all diameters and the ellipse-shaped dimple has the greatest lubricant film thickness compared to the other forms. The larger the dimple diameter, the smaller the lubrication film thickness.

Conclusions

This paper presents a study of dimples variation for the improvement of hydrodynamic lubrication performance of the artificial hip joint. Using an FSI modeling approach implemented via the finite element method, a parametric study was performed to investigate the effect of various dimple geometries on the hydrodynamic pressure and lubricant film thickness, followed by a search for optimum design of the new texture shape. The following are the key conclusions drawn from the study.

1. In the 2D ball in socket modeling with Computational Solid Mechanics (CSM) simulation method in the condition without lubrication, it can be concluded that the addition of dimple can reduce the pressure of contact so as to reduce wear. It is proved that the maximum contact pressure on the surface of the dimple is 54.84 MPa compared with the surface without dimple of 94,22 MPa.
2. From the variation of the shape of the dimple in the form of an ellipse, rectangle, and triangle for the dimple diameter of 80 μm, the plates of the ellipse-shaped have the best film thickness among other dimple forms, which is 22.67 μm.
3. In the 2D modeling of two lubricated plates using the Fluid-Structure Interaction (FSI) simulation method, the ellipse-shaped dumple with 80 μm diameter is the most optimum geometry compared to the plate with other geometries in this study, since the ellipse plate of 80 μm diameter has hydrodynamic pressure the largest of 0.915 Pa and a small solid pressure of 0.433 Pa so as to increase the thickness of the lubricant film of 22.67 μm which is an important parameter in the performance of lubrication.

References

[1] *Hip Replacement Surgery*. Arthritis Research UK, 2013.
[2] S. G. Ghalme, A. Mankar, and Y. Bhalerao, “Biomaterials in Hip Joint Replacement,” *Int. J. Mater. Sci. Eng.*, vol. 4, no. 2, pp. 113–125, 2016.
[3] W. Z. Wang, Z. M. Jin, D. Dowson, and Y. Z. Hu, “A study of the effect of model geometry and lubricant rheology upon the elastohydrodynamic lubrication performance of metal-on-metal hip joints,” *Proc. Inst. Mech. Eng. Part J J. Eng. Tribol.*, vol. 222, no. 3, pp. 493–501, 2008.
[4] S. M. Jhurani and C. F. Higgs, “An elastohydrodynamic lubrication (EHL) model of wear particle migration in an artificial hip joint,” *Tribol. Int.*, vol. 43, no. 8, pp. 1326–1338, 2010.
[5] M. J. Nine, D. Choudhury, A. C. Hee, R. Mootanah, and N. A. A. Osman, “Wear debris characterization and corresponding biological response: Artificial hip and knee joints,” *Materials (Basel).*, vol. 7, no. 2, pp. 980–1016, 2014.
[6] M. Topolovec, A. Cör, and I. Milošev, “Metal-on-metal vs. metal-on-polyethylene total hip arthroplasty tribological evaluation of retrieved components and periprosthetic tissue,” *J. Mech. Behav. Biomed. Mater.*, vol. 34, pp. 243–252, 2014.
[7] S. Pal, *Design of Artificial Human Joints & Organs*. Springer, 2014.
[8] L. Gao, P. Yang, I. Dymond, J. Fisher, and Z. Jin, “Effect of surface texturing on the elastohydrodynamic lubrication analysis of metal-on-metal hip implants,” *Tribol. Int.*, vol. 43, no. 10, pp. 1851–1860, 2010.
[9] G. M. Keegan, I. D. Learmonth, and C. P. Case, “Orthopaedic metals and their potential toxicity in the arthroplasty patient: A review of current knowledge and future strategies.,” *J. Bone Joint Surg. Br.*, vol. 89, no. 5, pp. 567–573, 2007.
[10] M. Alvarez-Vera, J. A. Ortega-Saenz, and M. A. L. Hernandez-Rodríguez, “A study of the wear performance in a hip simulator of a metal-metal Co-Cr alloy with different boron additions,” *Wear*, vol. 301, no. 1–2, pp. 175–181, 2013.
[11] C. Brockett, S. Williams, Z. Jin, G. Isaac, and J. Fisher, “Friction of Total Hip Replacements With Different Bearings and Loading Conditions,” *J. Biomed. Mater. Res.*, vol. 81 B, no. 2, pp. 508–515, 2007.

[12] M. Niemczewska-Wójcik, "Wear mechanisms and surface topography of artificial hip joint components at the subsequent stages of tribological tests," *Meas. J. Int. Meas. Confed.*, vol. 107, pp. 89–98, 2017.

[13] S. Ghosh, D. Choudhury, and B. Pingguan-Murphy, "The lubricating ability of albumin and globulin on artificial joint implants: a tribological perspective," *Int. J. Surf. Sci. Eng.*, vol. 10, no. 2, pp. 193–206, 2016.

[14] D. Choudhury, F. Urban, M. Vrbka, M. Hartl, and I. Krupka, "A novel tribological study on DLC-coated micro-dimpled orthopedics implant interface," *J. Mech. Behav. Biomed. Mater.*, vol. 45, pp. 121–131, 2015.

[15] H. A. Ching, D. Choudhury, M. J. Nine, and N. A. Abu Osman, "Effects of surface coating on reducing friction and wear of orthopedic implants," *Sci. Technol. Adv. Mater.*, vol. 15, no. 1, pp. 1–21, 2014.

[16] J. Baena, J. Wu, and Z. Peng, "Wear Performance of UHMWPE and Reinforced UHMWPE Composites in Arthroplasty Applications: A Review," *Lubricants*, vol. 3, no. 2, pp. 413–436, 2015.

[17] S. Ghosh and S. Abanteriba, "Status of surface modification techniques for artificial hip implants," *Sci. Technol. Adv. Mater.*, vol. 17, no. 1, pp. 715–735, 2016.

[18] M. Qiu, A. Delic, and B. Raeymaekers, "The Effect of Texture Shape on the Load-Carrying Capacity.PDF," *Tribol Lett*, vol. 48, no. 3, pp. 315–327, 2012.

[19] H. Sawano, S. Warisawa, and S. Ishihara, "Study on the long life of artificial joints by investigating optimal sliding surface geometry for improvement in wear resistance," *Precis. Eng.*, vol. 33, no. 4, pp. 492–498, 2009.

[20] P. Lu, R. Wood, M. Gee, L. Wang, and W. Pfleging, "The Friction Reducing Effect of Square-Shaped Surface Textures under Lubricated Line-Contacts—An Experimental Study," *Lubricants*, vol. 4, no. 3, p. 26, 2016.

[21] Q. Meng, L. Gao, F. Liu, P. Yang, J. Fisher, and Z. Jin, "Contact mechanics and elastohydrodynamic lubrication in a novel metal-on-metal hip implant with an aspherical bearing surface," *J. Biomech.*, vol. 43, no. 5, pp. 849–857, 2010.

[22] A. Chyr, M. Qiu, J. W. Speltz, R. L. Jacobsen, A. P. Sanders, and B. Raeymaekers, "A patterned microtexture to reduce friction and increase the longevity of prosthetic hip joints," *Wear*, vol. 315, no. 1–2, pp. 51–57, 2014.

[23] I. Etsion, Y. Kligerman, and G. Halperin, "Analytical and Experimental Investigation of Laser-Textured Mechanical Seal Faces Analytical and Experimental Investigation of Laser-Textured Mechanical Seal," *Tribol. Trans.*, vol. 42, no. 3, pp. 511–516, 2008.

[24] T. Roy, D. Choudhury, S. Ghosh, A. Bin Mamat, and B. Pingguan-Murphy, "Improved friction and wear performance of micro dimpled ceramic-on-ceramic interface for hip joint arthroplasty," *Ceram. Int.*, vol. 41, no. 1, pp. 681–690, 2014.

[25] M. Kang, Y. M. Park, B. H. Kim, and Y. H. Seo, "Micro- and nanoscale surface texturing effects on surface friction," *Appl. Surf. Sci.*, vol. 345, pp. 344–348, 2015.

[26] L. Galda, J. Sep, and S. Prucnal, "The effect of dimples geometry in the sliding surface on the tribological properties under starved lubrication conditions," *Tribol. Int.*, vol. 99, pp. 77–84, 2016.

[27] A. Borjali, J. Langhorn, K. Monson, and B. Raeymaekers, "Using a patterned microtexture to reduce polyethylene wear in metal-on-polyethylene prosthetic bearing couples," *Wear*, vol. 392–393, no. September, pp. 77–83, 2017.

[28] H. Zhang, L. G. Qin, M. Hua, G. N. Dong, and K. S. Chin, "A tribological study of the petaloid surface texturing for Co-Cr-Mo alloy artificial joints," *Appl. Surf. Sci.*, vol. 332, pp. 557–564, 2015.

[29] Z. M. Jin, "A general axisymmetric contact mechanics model for layered surfaces, with particular reference to artificial hip joint replacements.," *Proc. Inst. Mech. Eng. H.*, vol. 214, no. 5, pp. 425–35, 2000.

[30] Gao L, Yang P, Dymond I, Fisher J, Jin Z."Effect of Surface texturing on the elastohydrodynamic lubrication analysis of metal-on-metal hip implants.," *Tribology International*., vol. 43, no. 10, pp.1851-1860,2010.
[31] N. Noroozi and D. Grecov, "Numerical simulation of three-dimensional flow-induced microstructure in a simplified prosthetic hip joint with nematic liquid crystal lubricant," *Rheol. Acta*, vol. 53, no. 5–6, pp. 457–465, 2014.