Available online at www.sciencedirect.com

ScienceDirect

Procedia Engineering 68 (2013) 95 – 101

Procedia Engineering

www.elsevier.com/locate/procedia

The Malaysian International Tribology Conference 2013, MITC2013

Influence of Lubrication Performance on Wear Factor in Metal-on-Metal Hip Joint Replacement using Numerical Analysis

Muhamad Noor Harun[a,]*, Zhongmin Jin[b], Ardiyansyah Syahrom[a]

[a]*Sport Innovation and Technology Centre, Universiti Teknologi Malaysia (UTM), Skudai, Malaysia*
[b]*Institute of Advanced Manufacturing Technology , School of Mechanical Engineering, Xi"an Jiaotong University, China*

Abstract

The common problem of artificial hip joint replacement is the excessive generation of wear due to contacted bearing coupled. Computational simulation is becoming popular to predict wear generation. However, wear factor computed from experimental data was found to be varied due to the improvement of conformity leading to increase of lubrication performance especially for metal-on-metal hip joint replacement. The objective of this study was to develop the predicted wear factor based on the lubrication performance. The predicted linear wear taken from computational wear simulation was validated with theoretical wear model to predict the lubrication performance after 1 million cycles. Wear factors from experimental data were calculated and then plotted in the running-in and steady state. It shows that wear factor was a function of lambda ratio which was correlated with femoral head size and diametral clearance.

Selection and peer-review under responsibility of The Malaysian Tribology Society (MYTRIBOS), Department of Mechanical Engineering, Universiti Malaya, 50603 Kuala Lumpur, Malaysia

Keywords: Wear, wear factor, hip joint replacement, metal-on-metal.

Nomenclature

c_d	Diametral clearance
D_1	Diameter of femoral head
D_2	Inner diameter of acetabular cup
E	Elastic modulus
E'	Equivalent elastic modulus
h_{min}	Minimum film thickness
R	Inner radius of acetabular cup
R_a	Composite average surface roughness
R_{a1}, R_{a2}	Average surface roughness of femoral head and acetabular cup, respectively
R_x	Equivalent radius for ball-on-plane model
δ_Φ	Local linear wear

* Corresponding author. Tel.: +607-5558450; fax: +607-5558535.
E-mail address: mnoor@fkm.utm.my

Selection and peer-review under responsibility of The Malaysian Tribology Society (MYTRIBOS), Department of Mechanical Engineering, Universiti Malaya, 50603 Kuala Lumpur, Malaysia
doi:10.1016/j.proeng.2013.12.153

1. Introduction

The most important reason that metal-on-metal (MoM) hip joint replacement becoming favourable is the advantage of tribology of the bearing surfaces, particularly regarding surface finish and lubrication. Since the adverse effect of increasing sliding distance can be cancelled out due to enhanced lubrication performance, large femoral head size is proposed to provide a wide range of motion and to reduce the risk of dislocation. Prediction of wear generation using computational method is a crucial in the early stage of design. However, wear factor is a challenging element in the equation used especially for MoM bearing couple. In polyethylene-on-metal (PoM) hip joint replacement, the effect of lubrication on the wear generation is much lesser compared to MoM. Many studies on wear prediction using computational method using same single value of wear factor for all sizes of femoral head and diametral clearance [1,2]. In the MoM hip joint replacement, wear factor is likely to vary over time as a result of wear and improved conformity and lubrication. Lubrication regime influences the wear performance of metal-on-metal hip joint replacement. Femoral head size and diametral clearance are two primary design parameters which affect the performance of the resultant lubrication. Therefore, wear factor will be correlated with the lambda ratio for different femoral head sizes and diametral clearances.
The objective of this study is to predict the wear factor of the MoM hip joint replacement based on theoretical lubrication performance.

2. Materials and methods

2.1 Wear

The linear wear and wear area for the 5 million cycles were obtained from computational wear simulation in the literature using 28mm femoral head with diametral clearance of 60 um [3]. It used two experimental wear factors, steady and running in state. Wear factor (*k)* was depending on volumetric wear (*V*), load (*w*), sliding distance (*s*) and number of cycle (*n*) as formulated in Eq. (1).

$$k = \frac{V}{n\sum w_i s_i} \tag{1}$$

The volumetric wear was obtained from experimental study [4]. Fig. 1 shows an overview of the wear, model, assuming that the wear area was spherical in shape. This worn area was defined by the maximum linear wear (δ_0) and total angle of worn area (2ξ)

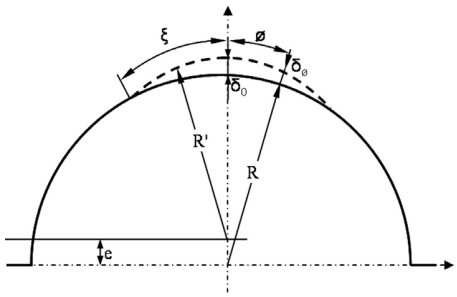

Fig. 1. General schematic diagram of theoretical wear model.

The effective radius (R'), local linear wear ($\delta_\emptyset$) and distance between the two centres (e) could be expressed as [5]:

$$\delta_\phi = e\cos(\phi) - \left(R - R^{'}\right) \tag{2}$$

$$R^{'} = \frac{R^2 \sin^2(\xi) + \left[R\left(1-\cos(\xi)\right) + \delta_0\right]}{2\left[R\left(1-\cos(\xi)\right) + \delta_0\right]} \tag{3}$$

$$e = R - R' + \delta_0 \tag{4}$$

where $\varnothing$ is the angle of local linear wear from the vertical line.

Effective radius is a corresponding radius due to the wear effect on the bearing surfaces either for the head or cup. The approach of wear prediction using computational simulation was based on previous work [3].

2.2 Lubrication parameters

Lubrication performance is determined by theoretical prediction based on the value of lambda, the ratio of minimum film thickness (h_{min}) and composite average surface roughness (R_a) as shown in Eq. (5).

$$\lambda = \frac{h_{\min}}{R_a} \tag{5}$$

$$R_a = \sqrt{\left(R_{a1}^2 + R_{a2}^2\right)} \tag{6}$$

where $R_{a1,}$ and R_{a2} is average surface roughness of femoral head and acetabular cup, respectively

To predict the lubricant film thickness in metal-on-metal hip implants, the minimum film thickness formulated by Hamrock and Dowson [6] was used:

$$\frac{h_{\min}}{R_x} = 2.8\left(\frac{\eta u}{E' R_x}\right)^{0.65}\left(\frac{w}{E' R_x^{\,2}}\right)^{-0.21} \tag{7}$$

The equivalent radius (R_x), the equivalent elastic modulus (E'), and entraining velocity (u) were calculated from:

$$R_x = \frac{D_1}{2}\left(1 + \frac{D_1}{c_d}\right) \tag{8}$$

$$E' = \frac{E}{\left(1 - v^2\right)} \tag{9}$$

$$u = \frac{\omega D_1}{4} \tag{10}$$

where D_1 is femoral head diameter and C_d is diametral clearance.

The operating parameters used for the lubrication analyses in Eq. (7) are tabulated in Table 1.

Table 1: Operating condition for lubrication analysis [7]

Parameter	Value
Load, w	1375 N
Viscosity, η	0.0009 Pa s
Angular velocity, ω	1.5 rad/s
Head surface roughness, R_{a1}	7 nm
Cup surface roughness, R_{a2}	5 nm

3. Results and discussion

3.1 Influence of wear on diametral clearance based on experimental wear factor

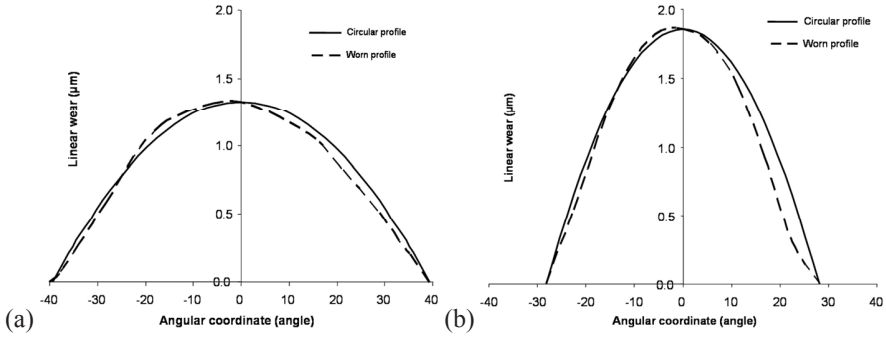

Fig.2: Comparison of linear wear (µm) profile between worn and circular profile on (a) head, and (b) cup surface, at 1 million cycles (D_l=28mm, c_d=60µm).

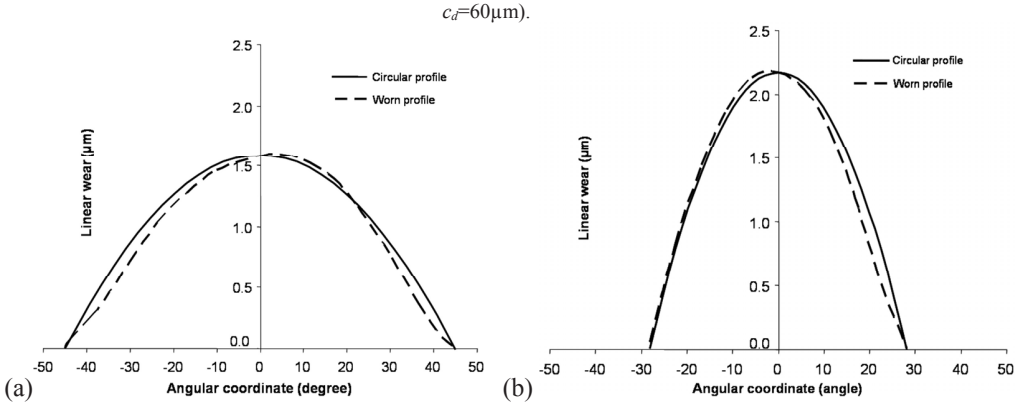

Fig.3: Comparison of linear wear profile between worn and circular profile on (a) head, and (b) cup surface, at 2 million cycles (D_l=28mm, c_d=60µm).

Fig. 2 and Fig. 3 compare the linear wear profile along the centre line of the worn area with a single circular geometry by matching the maximum wear depth and the angle of the worn area on the head (a) and cup (b) at 1 and 2 million cycles, respectively.

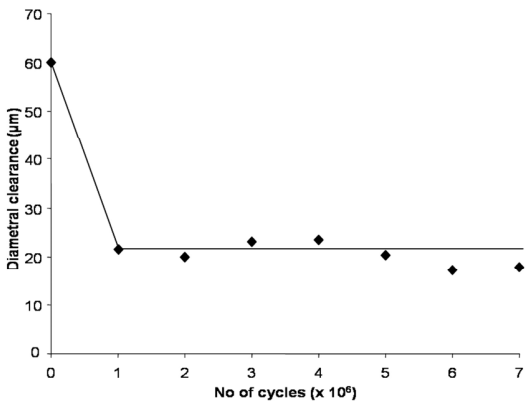

Fig.4: Change of effective diametral clearance over number of cycles (D_l=28mm, c_d=60µm).

The effective radius of the worn area was subsequently determined for both the head and the cup. This enabled the effective clearance to be calculated as a function of wear over the number of cycles. Fig. 4 shows the change of effective clearance as a function of number of cycles. Relatively good agreement was observed between the simplified circular and the actual worn profile. This justified the use of Eq. (2) to determine the effective radius and the effective clearance. Diametral clearance between the femoral head and acetabular cup decreased from its initial value of 60 to 23 µm after 1 million cycles due to wear and remained constant for the rest of cycles.

The purpose of this analysis was to observe the change of the effective clearance between the femoral head and acetabular cup of metal-on-metal bearing surfaces due to wear. The effective clearance changed over time, particularly during the running-in phase, where the effective radii of head and cup became larger and smaller, respectively. For instance, at the first million cycles for a maximum wear depth of 1.3µm and 1.8µm, with the total wear angle of 80º and 60º on the head and cup, respectively, the diameter of the worn area became 28.009mm and 28.032mm, and thus the effective diametral clearance was decreased to 23µm. This supports the discussion in literature [3] that contact pressure was decreased, accompanied with the increase of contact area as a result of improved conformity after wear, particularly after the first million cycles.

3.2 Influence on diametral clearance on lambda ratio

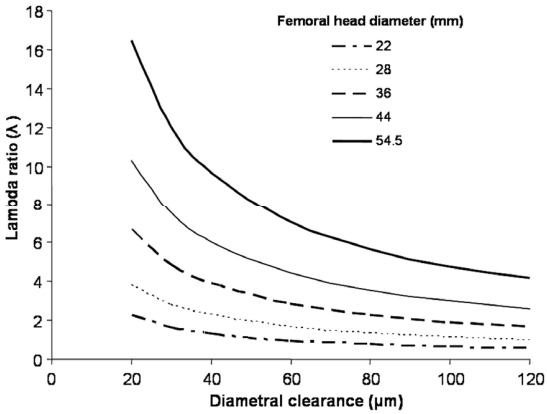

Fig.5: Effect of femoral head size and diametral clearance on lambda ratio (w = 1375 N, ω = 1.5 rad/s, η = 0.0009 Pa s, R_a = 8.6 nm).

The influence of diametral clearance with different femoral head sizes on lambda ratio is shown Fig. 5 for the condition considered. The diametral clearance depicted was in the range 20 and 120 µm. Five different sizes of femoral head were considered in this analysis. In general, the lambda ratio increased with the decrease of diametral clearance and the increase of femoral head size. For a given diametral clearance, the larger femoral head size had a higher lambda ratio. For example, if the femoral head diameters of 54.5mm and 36mm have the same diametral clearance of 80 µm, the lambda ratios are about 5.7 and 2.3, respectively.

Theoretically, if the lambda (λ) ratio is greater than 3, the bearing is operating in fluid film lubrication, in which the bearing surfaces are mainly separated by the fluid film. For the largest diameter femoral head of 54.5mm, even though the decrease of the lambda ratio is due to increase of diametral clearance, the bearing is still operating in the fluid film lubrication regime. For example, for the diameter of 54.5mm, the increase of diametral clearance from 40µm to 120µm decrease the lambda ratio from 9.7 to 4.2, which is still in fluid film lubrication; however, for the 28mm, the lambda ratio is decreasing from 2.2 to 1, which shifts the operating condition from mixed to boundary lubrication.

3.3 Wear factors as a lambda function

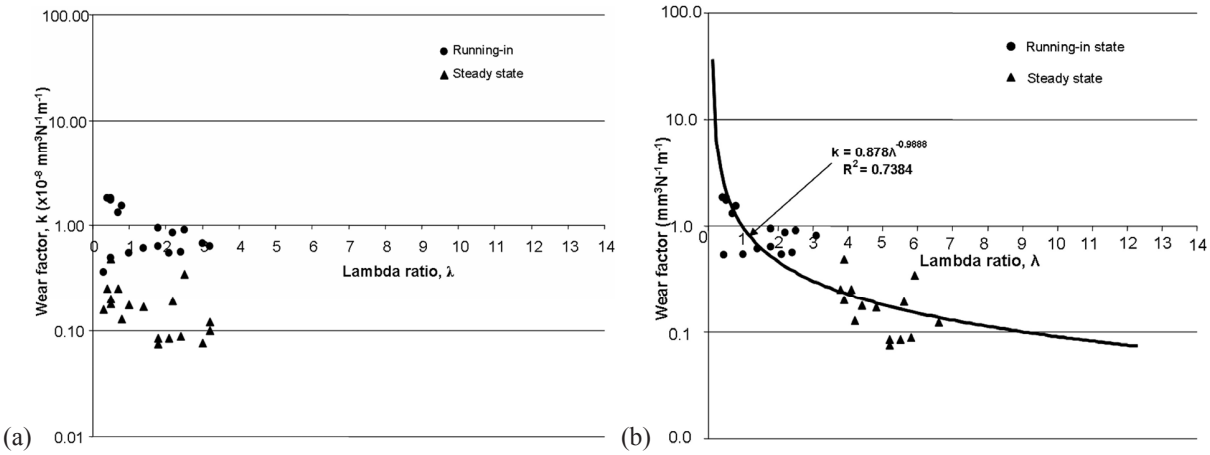

Fig.6: (a) Wear factor as function of lambda ratio based on original geometry, (b) Single function of computational wear factor versus lambda ratio (w = 1375 N, D_1 = 28mm ω = 1.5 rad/s, η = 0.0009 Pa s, R_a = 8.6nm)

Fig. 6(a) shows the wear factor [4] versus lambda ratio based on the original geometry. Fig. 6(b) shows the single function of computational wear factor, taking into account the modified geometry and improved lambda ratio.
It is clear that there is a difference of wear factor in running-in and steady state phases, as shown in Fig. 6(a), however the running-in lambda ratio need to be shifted due to the geometrical change of bearing surfaces, which enhance the lubrication performance. The computed lambda ratio in the steady state phase was based on the average initial diametral clearance of 60µm (range of 10.2–86.4µm). Since the effective diametral clearance decreased from 60µm to 23µm (Fig. 4), the lambda ratio increased from 1.64 to 3.8 in steady state phase (Fig. 5). The steady state wear factor for each bearing was shifted to the new steady state lambda ratio as shown in Fig. 6(b). Subsequently, a best fitted power relationship (R^2=0.7384) was used to correlate the computational wear factor over lambda ratio as follows:

$$k = 0.878 \times 10^{-8} \lambda^{-0.988} \ \text{mm}^3\text{N}^{-1}\text{m}^{-1} \tag{11}$$

In the single function of wear factor, if the lambda ratio is approached to zero, the wear factor becomes higher until infinite value. The lesser the lubricant thickness, the higher the asperity contact is, which could generate higher wear. In the single function of wear factor, the wear factor increased significantly when the lambda ratio decreased from 1 to zero, but it decreased gradually when the lambda ratio exceeded 1. Boundary lubrication usually occurs when the lambda ratio is under 1. If the lambda ratio is 0.9, the wear factor would be $1\text{x}10^{-8}$ $\text{mm}^3\text{N}^{-1}\text{m}^{-1}$. This value is lower compared to the pin-on-plate testing, about $1\text{x}10^{-6}$ $\text{mm}^3\text{N}^{-1}\text{m}^{-1}$ [8-9]. In the mixed lubrication, where the lambda ratio is between 1 and 3, the change of wear factor was apparent, between 0.878 and 0.297 $\text{x}10^{-8}$ $\text{mm}^3\text{N}^{-1}\text{m}^{-1}$. This indicates that the shift of operating condition for a metal-on-metal bearing from mixed to fluid film lubrication, for example from the lambda ratio 1.1 to 3.1, could decrease the wear by about 200%. It should also be pointed out that even when the lambda ratio is above 3, the extrapolated wear factor is not zero, for example at λ= 4, k = 0.223 x 10^{-8} $\text{mm}^3\text{N}^{-1}\text{m}^{-1}$. This could indicate that wear can also take place due to other mechanisms such as corrosion. Returning to the lambda ratio equation (Eq. 5), the change of lambda ratio means either variation in film thickness or composite average surface roughness. Thus, to increase lambda ratio, either the film thickness needs to be increased or the surface roughness decreased. However, in the present study, the surface roughness was assumed constant and, hence, the increase of lambda ratio was only caused by the change in lubricant film thickness.

3.4 Validation of wear

Fig. 7 presents the comparison of running-in and steady state volumetric wear rate between experimental

measurement and computational simulation using single function of lubrication-dependent wear factor (Fig. 6(b)).

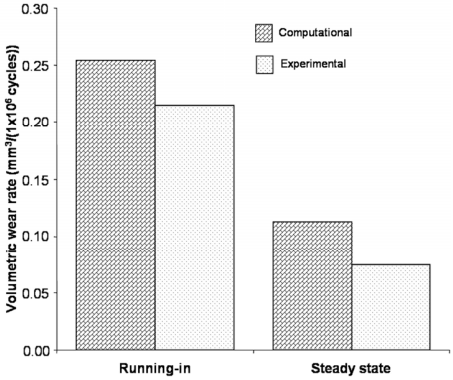

Figure 7: Comparison of volumetric wear rate between experimental measurement and computational simulation (D_1=28mm, c_d=60μm)

In computational wear simulation, different wear factor was applied in the running-in and steady state phase from the single function of wear factor. There was a difference of volumetric wear rate between experimental measurement and computational simulation in both phases. Even though the volumetric wear rate predicted based on the computational simulation in the steady state was relatively higher, it was still in the acceptable range from the previous study [4].

4. Conclusion

The present study demonstrated the relationship of wear factor with the lubrication performance in one single function. The volumetric wear rate using function of wear factor was still in the range as in vitro. As a conclusion, varied wear factor should be applied in predicting wear using computational simulation for various sizes of femoral head and diametral clearance of MoM hip joint replacement.

Acknowledgment

We would like to express our gratitude and deepest thanks to Universiti Teknologi Malaysia (UTM), Ministry of High Education (MoHE) and Public Service Department for supporting this study.

References:

[1] Maxian, T. A., Brown, T. D., Pedersen, D. R. and Callaghan, J. J. (1996a) 3-Dimensional Sliding/Contact Computational Simulation of Total Hip Wear, *Clinical Orthopaedics and Related Research*, 41-50.

[2] Teoh, S. H., Chan, W. H. and Thampuran, R. (2002) An Elasto-Plastic Finite Element Model for Polyethylene Wear in Total Hip Arthroplasty, *Journal of Biomechanics,* 35, 323-330.

[3] Harun, M.N., Wang, F. C., Jin, Z. M. and Fisher, J., 2009 Long term contact coupled wear prediction for Metal-on-Metal total hip joint replacement. *Proceeding of the Institution of Mechanical Engineers, Part J: Journal of Engineering Tribology, 223 (7), pp 993-1001*

[4] Chan, F. W., Bobyn, J. D., Medley, J. B., Krygier, J. J. and Tanzer, M. (1999) The OttoAufranc Award - Wear and Lubrication of Metal-on-Metal Hip Implants, *Clinical Orthopaedics and Related Research, 10-24*

[5] Liu, F., Jin, Z. M., Hirt, F., Rieker, C., Roberts, P. and Grigoris, P. (2005a) Effect of Wear of Bearing Surfaces on Elastohydrodynamic Lubrication of Metal-on-Metal Hip Implants, *Proceedings of the Institution of Mechanical Engineers Part H-Journal of Engineering in Medicine,* 219, 319-328.

[6] Hamrock, B. and Dowson, D. (1978a) Elastohydrodynamic Lubrication of Elliptical Contacts for Materials of Low Elastic Modulus, I:Fully Flooded Conjuction., *Trans. ASME, J. Lubrication Technology,* 100, 236-245.

[7] Dowson, D. (2006) Tribological Principles in Metal-on-Metal Hip Joint Design, *Proceedings of the Institution of Mechanical Engineers Part H-Journal of Engineering in Medicine,* 220, 161-171.

[8] Tipper, J. L., Firkins, P. J., Ingham, E., Fisher, J., Stone, M. H. and Farrar, R. (1999a) Quantitative Analysis of the Wear and Wear Debris from Low and High Carbon Content Cobalt Chrome Alloys Used in Metal on Metal Total Hip Replacements, *Journal of Materials Science-Materials in Medicine,* 10, 353-362.

[9] Scholes, S. C., Green, S. M. and Unsworth, A. (2001) The Wear of Metal-on-Metal Total Hip Prostheses Measured in a Hip Simulator, *Proceedings of the Institution of Mechanical Engineers, Part H: Journal of Engineering in Medicine,* 215, 523-530