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LUBRICATION EFFECT OF METAL-ON-METAL IN HIP JOINT REPLACEMENT

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ABSTRACT

The consumption of hard-on-hard material is one of alternative methods to replace the soft-on-soft or soft-on-hard material which has long been used in hip joint replacement. The famous the type of hard-on-hard material in hip joint replacement is metal-on-metal. It is the best method which is selected by surgeon to replace the original hip joint. However, the metal-on-metal hip implants can be producing the smallest wear particle as a result of attrition of contact surface between femoral head and acetabulum cup. Therefore, the lubricant must be located between the surface of femoral head and acetabulum cup to reduce wear particle. Hence, an analysis is carried out to examine the effect of lubrication on metal-on-metal hip joint replacement upon the occurrence of contact surface between femoral head and acetabulum cup. It includes two types of analysis namely dry and lubrication contact analysis. Based on analysis in dry contact, the maximum contact pressure occurs at the surface of acetabulum cup, namely 32.887 MPa. For lubrication contact, the maximum contact pressure also occurs at the surface of acetabulum cup but its value was lower compared to another case. It was occurs because at the region between surface of femoral head and acetabulum cup have full fluid film lubrication. So, the wear that produced by metal-on-metal hip joint implants can be reduced. In addition, this project was more focuses to the effect of design parameters on the maximum contact pressure. It was involves two condition contact namely dry and lubrication contact. Based on the result of the effect of the radial clearance on contact pressure, it was found that the maximum contact pressure is increases when the radial clearance also increases. According to the result of the effect of the femoral head size, it was found that the maximum contact pressure is decrease when the femoral head size is increase.

Keywords : *metal-on-metal, wear, contact surface, hip joint replacement, lubrication, dry contact*

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1.0 INTRODUCTION

Nowadays, the total replacement of hip joint is commonly used in treatment for many cases such as osteolysis and similar disable conditions. It can improve the life-quality of millions of patients. But the hip joint replacement can produce the wear and corrosion performance by material configurations and human movement or activity such as walking, running, jumping and others. Therefore, the design parameters and development of hip joint is very important things in improvement of wear and corrosion performance.

The hip joint replacement material configurations that are commonly used are metal-on-Polyethylene (UHMWPE), metal-on-metal, and ceramic-on-ceramic. But, the metal-on-metal is the best material configuration compared with metal-on-polyethylene because the metal-on-metal configuration exhibits much lower volumetric wear than metal-on-polyethylene.

In order to produce the best and good quality of hip joint implants, the concept of tribology must be studied in detail. Tribology means the study of friction, wear, lubrication and bearings design in relative motion. It have related to the subject of engineering such as solid mechanics, fluid mechanics, material science, heat transfer and others. The aspect of tribology that related to the biological system called biotribology. Biotribology is the concept of tribology science applied to functional biological systems, especially the synovial joints and their artificial replacement. The main of tribology aspect such as friction, wear and lubrication is very important parameter to increase the hip implants performance in the long-term usage.

2.0 BIOTRIBOLOGY

Tribology deals with lubrication, friction and wear, which is can related with the basic engineering subjects such as solid mechanics, fluid mechanics, lubricant chemistry, material science, heat transfer and others. So, biotribology is the concept of tribology science aspect applied in the biological system. The principles of engineering tribology are surface metrology, contact mechanics, friction, lubrication and wear. This aspect is important to review the design characteristics of the bearing material replacement for used in the organ surgery. Besides that, it is important to eliminate and minimize the wear particles in artificial joint replacements.

2.1 Lubrication

Lubrication refers to the replenishment of the lubricant between two bearing surfaces with the purpose to control the friction and wear. The lubricant of the bearing can operate in one of three modes namely boundary lubrication, mixed lubrication or full fluid-film lubrication. Among these three modes of lubrication, the ideal lubrication regimen is full fluid-film lubrication. Boundary lubrication occurs when the entire load is carried by the asperity contacts despite the presence of a lubricant such that the extent of contact is similar to that which would have occurred in a dry regime. In the mixed lubrication, the load is carried and shared between contacts and the pressure generated within the lubricant. The full fluid-film lubrication occurs when the load is supported fully by pressure within the lubricant [1].

The theoretical method of the mode of lubrication can be analysed by calculating the ratio of effective lubricating film thickness in hip implants to composite surface roughness of the femoral head and acetabulum cup. This is known as the λ ratio. λ ratio is defined as,

$$\lambda = \frac{h_{\min}}{R_a} = \frac{h_{\min}}{\left[\left(R_{a\_Head}\right)^2 + \left(R_{a\_Cup}\right)^2\right]^{1/2}} \qquad (1)$$

Based on Equations 1, a λ value greater than three (λ>3) show that the full fluid-film lubrication is likely to common in the joint [2]. Mixed lubrication is indicated when the λ is between one and three (1<λ<3) and boundary lubrication when λ is less than or equal to one (λ≤1). In general, when λ value increase, the wear will be decrease for hip joint implants. That's why the full fluid-film lubrication is the best lubrication modes in hip joint implant.

An important factor that can to be as the key of the potential for full fluid-film lubrication is the roughness of the bearing surface and accurate prediction of a representative film thickness for the bearing (h_{min}). Both of these factors can be determined by using the Hamrock-Dawson formula [3] as shown in Equations 2:

$$\frac{h_{\min}}{R} = 2.8\left(\frac{\eta u}{E'R}\right)^{0.65}\left(\frac{W}{E'R^2}\right)^{-0.21} \qquad (2)$$

The value of equivalent radius (R) depends on the diameter of femoral head (d) and the diametral clearance between the femoral head and the acetabulum cup (c_d). The equivalent radius (R) can be determined using the Equations 3:

$$R = \frac{d\left(d + c_d\right)}{2c_d} \qquad (3)$$

Based on the Equations 2, the determination of the entraining velocity (u) can be calculated from the angular velocity of the femoral head like Equations 4:

$$u = \frac{\omega d}{4} \qquad (4)$$

The formula of equivalent elastic modulus (E') is given by Equations 5,

$$E' = \frac{2}{\left[\frac{1-\nu^2{}_{Head}}{E_{Head}} + \frac{1-\nu^2{}_{Cup}}{E_{Cup}}\right]} \qquad (5)$$

where E represent as elastic modulus and ν represent as Poisson's ratio.

Based on equation of equivalent radius (R), diametral clearance (c_d) and femoral head diameter (d) has important effect of the lubrication. To get the higher value of equivalent radius, the diametral clearance must be reduced and the diameter of femoral head must be increased. The increasing of femoral head depends on the increasing of the entraining velocity (u). This will affect the lubricant film thickness due to elastohydrodynamic action. It also can reduce the volumetric wear and friction if the equivalent radius is increase especially metal on metal bearings.

2.2 Wear

Wear can be defined as the progressive damage, which occurs on the surface of the component as a result of relative motion. The effect of the wear in artificial joints can cause the adverse tissue reaction, osteolysis and loosening. Besides that, the wear particles can also have an injurious effect on the quality of magnetic recording systems.

The wear coefficient (K) can be calculated using the laws of wear as shown in Equations 6. The unit of wear coefficient (K) is mm^3/Nm.

$$K = \frac{V}{Ws} \tag{6}$$

From the Equations 6, it can be determining the depth of wear (δ). The wear depth depends on the applied load. If the applied load is increase, the wear depth is also increase. The effects of this situation can cause to corrosive the acetabulum cup and the femoral head little by little. Finally, the hip joint is loosening and should to be replaced quickly. Therefore, the wear can be reduced by optimization of the bearing design in terms of clearance and head diameter.

2.3 Wear Problem in Metal-on-Metal Hip Joint

In metal-on-metal hip implants, the femoral metal and acetabulum metal are slide against each other during the human activity such as walking and running. Its affect will cause the metal from hip implants released and can cause the wear and corrosion at the connection of the femoral head and acetabulum. Metal ions that released from metal such as cobalt and chromium ions will be entering the blood vessels and may lead to side effects to the body human because the characteristics of metal ions is very high toxicity. Figure 1 shows that the metal ions are released from metal hip implants and entering the joint space and surrounding tissues of bone. Figure 2 shows that metal ions are interrupt the joint capsule and surrounding tissues and finally lead to the inflammation.

Figure 1: Metal Ion Are Released and Entering the Joint Space and Surrounding Tissues

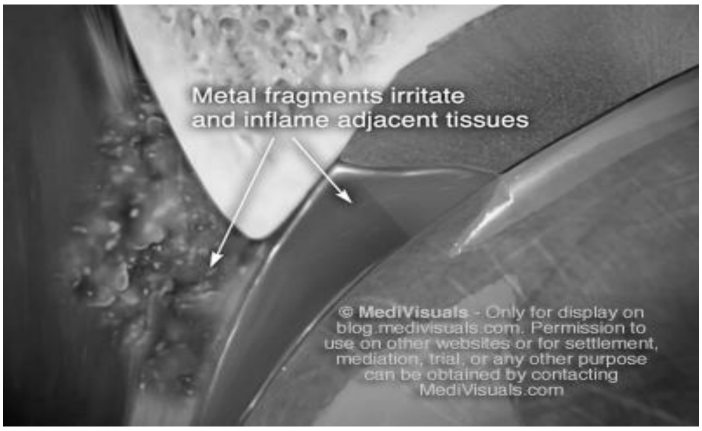

Figure 2: Metal Ions Are Interrupting the Joint Capsule and Surrounding Tissue

Many adverse effect that encountered by the system in human body when metal ions released. One of them is DNA damage. DNA damage can be lead to the development of cancer types such as leukaemia and lymphoma because this damage takes the form of chromosome translocations and aberrations. Besides that, the emission of metal ions can cause the sensitivity of metal. This problem occurs when the metal ions which are produced from wear or corrosion can start to reaction of [2]. It can be result in T-cell mediated periprosthetic osteolysis.

3.0 MATERIAL AND METHOD

3.1 The Hip Design

The typical material configuration in hip joint implants is metal-on-metal (CoCrMo) in which the acetabulum cup and femoral head manufactured from metal. This model is constructed in two-dimensional (2D). In this project, the model was simulated without fluid (dry contact) and with fluid as lubricant. The physics condition that used in these modelling are solid mechanics (dry contact) and fluid-structure interactions (lubrication contact). For the solid mechanics physics, it consists of a 28mm diameter femoral head and the nominal radial clearance between the femoral head and the acetabulum cup was assumed to be 30μm. The thickness of the acetabulum cup is 5mm. A whole structure of hip joint implant model was shown in Figure 3.

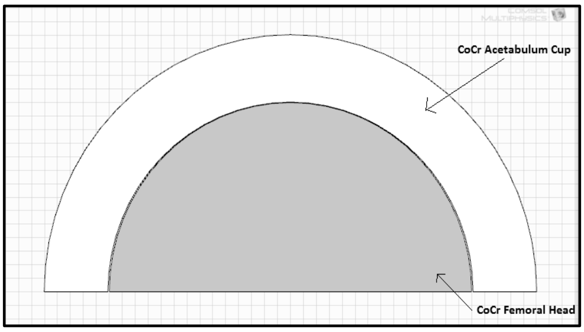

Figure 3: The Whole Structure of Hip Joint Implant Model

All the materials were assumed linearly elastic. The material properties which are used on the hip joint implants are 210GPa and 0.25 for Elastic Modulus and Poisson's Ratio respectively. The density of this material is 7000kg/m^3.

For the fluid-structure interaction physics, it consists the hip implant and the fluid at the surface between the femoral head and acetabulum cup. The diameter of the femoral head was 28mm and the nominal radial clearance was assumed to be 0.03mm. The thickness of the acetabulum cup is same with the model without fluid, namely 5mm. The fluid or lubricant was constructed between the acetabulum cup and femoral head. The structure was shown in Figure 4.

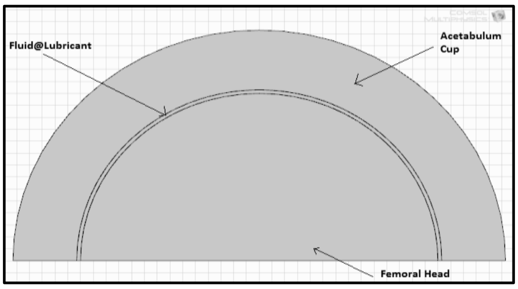

Figure 4: The Structure Modelling of Hip Joint Implants (Lubrication Contact)

The material properties of the femoral head and acetabulum cup is same with the 2D modelling hip joint implants without fluid, namely Elastic's Modulus is 210GPa, Poisson's Ratio is 0.25 and the density is 7000kg/m^3. Besides that, this modelling have one more material properties, namely for fluid or lubricant. The properties of lubricant that used in the analysis are density is 1600kg/m^3 and the dynamic viscosity is assumed 0.0025Pa.s [4].

Besides that, the design parameters such as femoral head size and radial clearance was constructed to identify the effect of them on the two different contact conditions, namely dry and lubrication contact. The parameter of femoral head size which involved are 14mm, 16mm, 18mm, 21mm and 27mm and radial clearance parameters that involved in this analysis are 30µm, 60µm, 80µm, 120µm and 200µm.

3.2 Finite Element Model

The finite element model for metal-on-metal hip joint implant was developed using COMSOL Multiphysics software. This software is used to simulate and analyse the contact pressure between the two bearing surfaces under applied loading. Based on the diagram of hip implants modelling, it looks like a semi-circle because this modelling was assumed as axisymmetric modelling.

The outside of the acetabulum cup was varied from partially, to fully constrained boundary conditions, representing fixation conditions. Contact pair between the surface of acetabulum cup and femoral head was set. A coefficient of friction at the contact pair was assumed as 0.1. This contact is very important to get the result of contact pressure at the acetabulum cup and femoral head when applied the load. A fixed load of up to 3000 N was applied through the centre of the femoral head.

For meshing process, it consists five meshes namely finer, fine, normal, coarse and coarser. A uniform mapped of mesh was applied on the acetabulum cup, while the femoral head was modelled with a uniform mesh of free triangular. Figure 5 show that the mesh shape of the hip implants model.

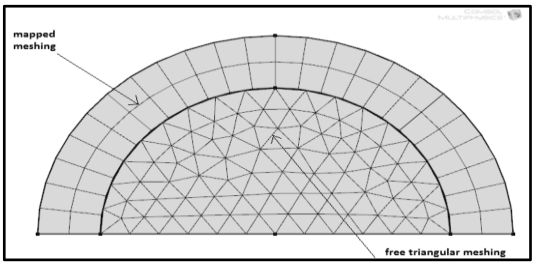

Figure 5: Mesh Shape of the Hip Implants Model

In fluid-structure interaction, it consists boundary condition and initial condition. The structure of hip joint implants was applied boundary condition and the lubricant was applied initial condition. For hip joint implants, the outside of acetabulum cup was fully constrained, representing fixed conditions and load of 3000N was applied at the bottom through the centre of femoral head. Contact area was set at the surface on the femoral head and acetabulum cup. A coefficient of friction was assumed as 0.1 at the contact area surface.

For meshing process, a uniform mesh, namely normal element size was set at the acetabulum cup, femoral head and lubricant. The mesh shape of the whole structure for with fluid cases was shown in Figure 6.

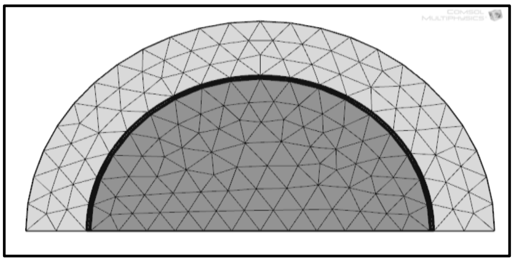

Figure 6: The Shape of Mesh of the Whole Structure (lubrication contact)

4.0 RESULT AND DISCUSSION

4.1 Convergent Study (Mesh Sensitivity)

The result of the hip joint implants in dry contact was distributed to five meshes types, namely finer, fine, normal, coarse and coarser. The maximum contact pressure which are determined according to these conditions are:

a) finer (782 element) : 32.887 MPa
b) fine (418 element) : 33.390 MPa
c) normal (278 element) : 35.508 MPa
d) coarse (158 element) : 37.332 MPa
e) coarser (120 element) : 41.353 MPa

These analyses were performed to select the suitable result of the maximum contact pressure. The suitable result can be selected based on the compromise time and accuracy. It can be concluded that, when the analysing process of the finite element analysis take a relatively long time, the accuracy of the result is increases and accurate. Therefore, the suitable meshes that be selected is finer meshes. The finer mesh is suitable because it is more accurate result. The graph of maximum contact pressure (MPa) versus angular position (degree) for five types of meshes was shown in Figure 7.

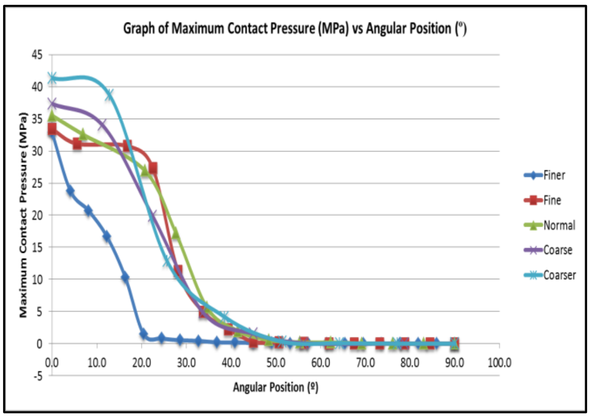

Figure 7: Graph of Maximum Contact Pressure (MPa) vs Angular Position (º)

The number of element in the five meshes types actually to identify the effect of meshing sensitivity. The identification of meshing sensitivity intended to predicted contact parameters at the surface of femoral head and acetabulum cup. For the finer type, it was found that 782 elements while for the fine type, it was found namely 418 elements.

The elements of normal meshes type was being found that 278 elements. For the coarse and coarser types, it was found that 158 and 120 elements respectively. The meshing sensitivity can be found by the graph form. Figure 8 indicates graph of maximum contact pressure (MPa) against the number of element. According to the graph, it was found that the graph will be linear when the lines of graph are located at point of fine types (418 elements) and normal types (278 elements).

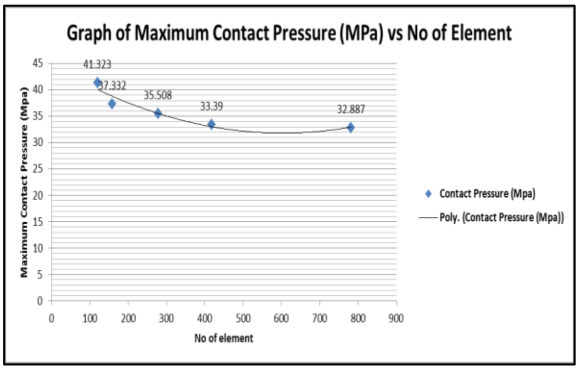

Figure 8: Graph of Maximum Contact Pressure (Mpa) against No of Element.

4.3 Validation of Dry Contact Case

The validation of dry contact case was made because to know outcome of the analysis either right or wrong result. This validation was made by comparing the results of this project analysis to the results that obtained from previous studies. In this project, the result of the maximum contact pressure at contact surface is 32.887 MPa while the result of maximum contact pressure that obtained from previous study is 32 MPa. The previous study result can be proved via the curve on the left. The curve on the left is symmetrical about the 0º axis, corresponding to the axisymmetric model, and the predicted maximum contact pressure is 32 MPa [5].

4.4 Effect of Radial Clearance on Contact Pressure

The values of radial clearance that was involved are 30µm, 60µm, 80µm, 120µm and 200µm. For metal-on-metal hip joint implants in dry contact, the graph of maximum contact pressure (MPa) versus angular position (º) was shown in Figure 9. According to this graph, it was found that the value of maximum contact pressure at the contact surface is increases when the radial clearance is also increases. At the smallest value of radial clearance, the maximum contact pressure at the contact surface is 32.887 MPa while the maximum contact pressure at the contact surface in biggest value of radial clearance is 43.811MPa.

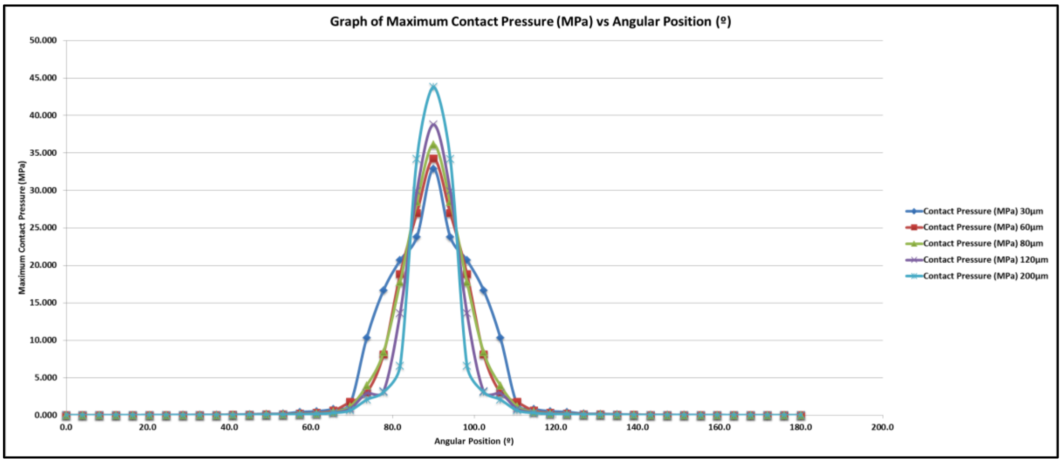

Figure 9: Graph of Maximum Contact Pressure (MPa) versus Angular Position (º) (Dry Contact) – Constant Femoral Head Size

For another case, namely metal-on-metal hip implant in lubrication contact, the data was plotted in Figure 10. Based on the graph, it was found that the value of maximum contact pressure at the contact surface is also increase when the radial clearance is increases. The value of maximum contact pressure at the contact surface in smallest radial clearance is 13.367 MPa. For the biggest radial clearance, it was provide the value of maximum contact pressure is 32.358 MPa. This matter proves that the value pattern of maximum contact pressure at the surface contact for both condition is similar, namely maximum contact pressure value is increase when the radial clearance increases.

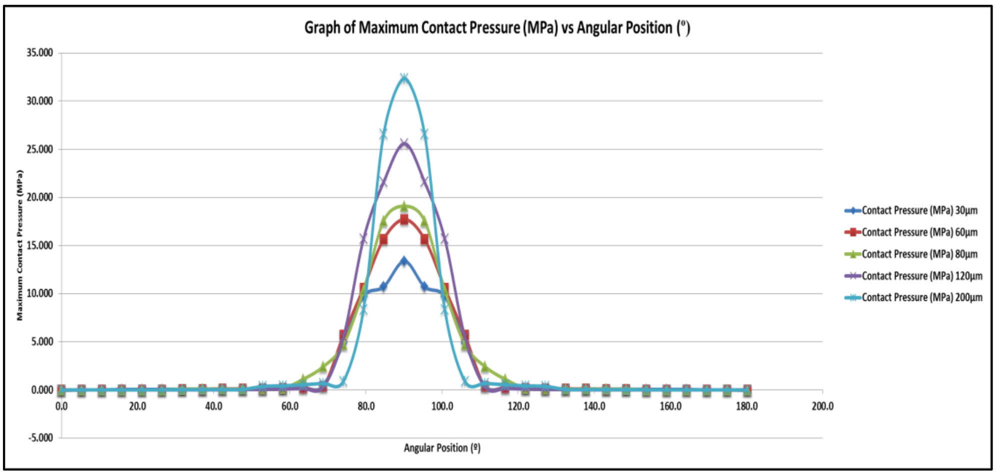

Figure 10: Graph of Maximum Contact Pressure (MPa) versus Angular Position (º) (Lubrication Contact) – Constant Femoral Head Size

According to this analysis, it was found that the pattern for both contact condition was similar, namely the value of maximum contact pressure at the contact surface is increases when the radial clearance is increases. It can cause the enhancement of the wear significantly [6]. Even though the result of lubrication contact has a similar pattern with dry contact, however, it was still having the low value of result compared to dry contact. It can be proven by previous studies, namely an effective lubricant film is able to reduce wear significantly, while severe wear may occur if the lubricant film is not thick enough to separate the bearing surface [7]. Therefore, a reduction in the radial clearance can be to reduce the wear rates [8].

This analysis was more detailed by making comparison between the values of maximum contact pressure at the surface contact for both conditions in the context of difference radial clearance values. The result of this analysis shows that the value of maximum contact pressure at the surface contact for lubrication contact is lower compared to dry contact. The graph of maximum contact pressure (MPa) versus radial clearance (μm) was shown in Figure 11.

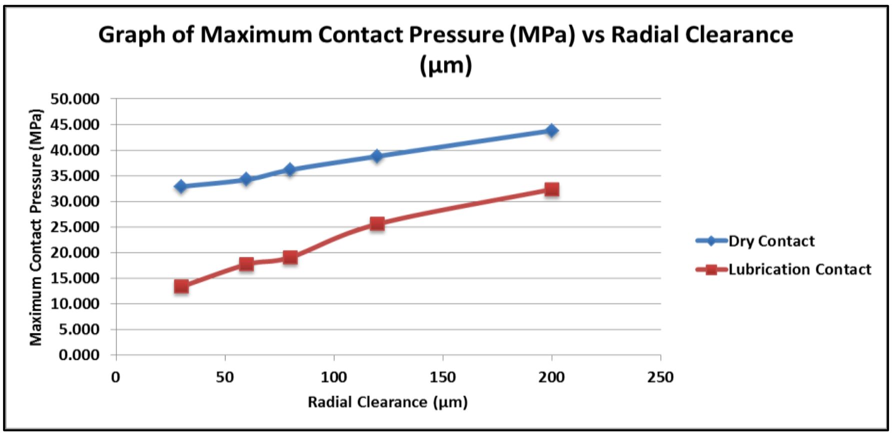

Figure 11 : Graph of Maximum Contact Pressure (MPa) versus Radial Clearance (μm)

4.5 Effect of Femoral Head Size on Contact Pressure

The value of radial clearance is 60μm, whereas the values of femoral head are 14mm, 16mm, 18mm, 21mm and 27mm. For hip implant in dry contact, the analysis was described in the graph of maximum contact pressure (MPa) against angular position (º). Based on graph, it was found that the value of maximum contact pressure at the contact surface is decreases when the size of femoral head is increases. In the smallest femoral head size, the value of maximum contact pressure at the surface contact is 34.246 MPa while the maximum contact pressure at the surface contact in the largest size is 21.864 MPa. The graph of maximum contact pressure (MPa) against angular position (º) was shown in Figure 12.

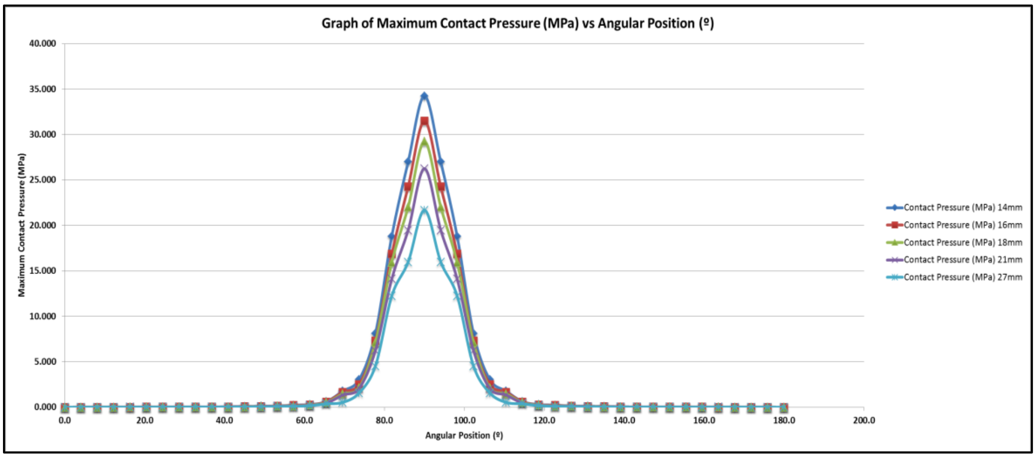

Figure 12: Graph of Maximum Contact Pressure (MPa) versus Angular Position (º) (Dry Contact) – Constant Radial Clearance

For another condition, namely metal-on-metal hip implant in lubrication contact, the data was analysed and plotted in Figure 13. According to this graph, it was found that the value of maximum contact pressure at the surface contact is also decrease when the size of femoral head increases. At the smallest size of femoral head, the result of maximum contact pressure at the surface contact is 17.707 MPa. For the biggest size of femoral head, it was provide the value of maximum contact pressure at the contact surface is 5.738 MPa. Based on the both of graph, it was found that the reduction form of the both result is similar.

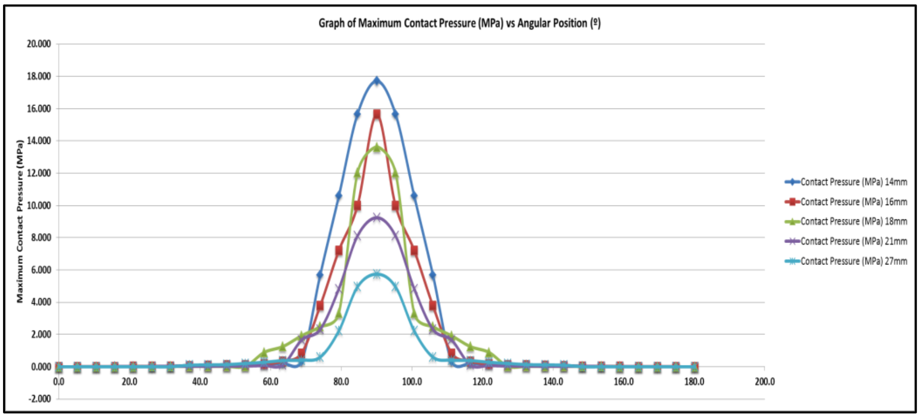

Figure 13: Graph of Maximum Contact Pressure (MPa) versus Angular Position (º) (Lubrication Contact) – Constant Radial Clearance

Based on this analysis, it was found that the pattern graph for both condition contacts is similar, namely the result of maximum contact pressure is decrease when the size of femoral head is increase. The reduction of the maximum contact pressure was provide affect to the wear, namely the wear can be reduced. It can be proven by previous study. The benefit of large femoral heads in wear reduction has been further demonstrated in a study of metal-on-metal hip resurfacing prostheses [6]. Besides that, in zirconia-on-metal total hip replacement analysis have proved that for larger diameter zirconia-on-metal joints, operating in the mixed or fluid-film lubrication regime, an increase in femoral head could be expected to reduce wear even further by promoting fluid-film lubrication [9]. For example, a modest increase in femoral head diameter of less than 6mm, can be reduce the wear of zirconia-on-metal joints by an order of magnitude [9].

The analysis can be detailed by making comparison between the result of dry and lubrication contact condition for constant radial clearance. It shows that the result of maximum contact pressure at contact surface for lubrication contact is lower than dry contact. The comparison between them can be seen in Figure 14, namely the graph of maximum contact pressure (MPa) versus radial clearance (μm).

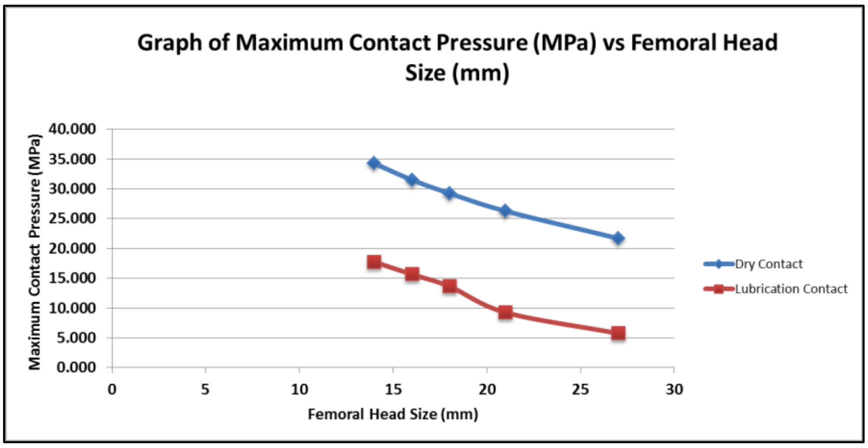

Figure 14: Graph of Maximum Contact Pressure (MPa) versus Femoral Head Size (mm)

According to comparison between the result of dry and lubrication contact condition for two effects of design parameters, it was found that the value of maximum contact pressure at the contact surface for lubrication contact is lower compared to dry contact. It was occurs at region between surface of femoral head and acetabulum cup have a full fluid film lubrication. In full fluid-film lubrication, there is no contact between the bearing surface and the load is carried solely by pressure generated within the lubricant as a result of the contact pressure [1]. This causes the volumetric wear that produced by metal-on-metal hip joint implant can be reduced because an effective lubricant film is able to reduce wear significantly [8]. Therefore, it can be proved that the theoretical and analysis of the full fluid-film lubrication by previous studies is true, namely the wear will be reduced if there have a full fluid-film lubrication layer between the surface of femoral head and acetabulum cup.

5.0 CONCLUSION

It can be concluded that hip joint is the ball and socket joint represent femoral head and acetabulum cup respectively in the pelvis. When the human was suffering hip joint pain such as dislocation or osteolysis, the hip joint must be replaced. The hip joint replacement can be replaced using the material configurations either *soft-on-soft* nor *hard-on-hard*. But many surgeons were recommending using the *hard-on-hard* material such as metal-on-metal. Hence, this study was focuses to the metal-on-metal hip joint replacement. This study was focuses it because the metal-on-metal can be produce the wear particle of metal. Therefore, the lubrication effect was plays an important role in preventing the formation of wear particle at surrounding the metal-on-metal hip implant.

Besides that, the aspect of tribology especially lubrication and wear was also discussing in this study. Lubrication can be operating in three types of condition namely boundary lubrication, mixed lubrication and full fluid-film lubrication. Wear in metal-on-metal hip implant occurs when the femoral head and acetabulum cup are slide against each other during the human activity. The metal ions that released from metal such as cobalt and chromium ions will be entering the blood vessels and may lead to side effects to the body human because the properties of metal ions is very high toxicity.

According to analysis dry and lubrication contact of metal-on-metal hip joint replacement, the following conclusions can be drawn are:

a) The results of hip joint implant for dry contact can be distributed to five types of meshes, namely finer, fine, normal, coarse, and coarser.
b) These meshing was made because to analyse the meshing sensitivity of the contact pressure result. It was because the identification of meshing sensitivity intended to predicted contact parameters at the bearing surface. Besides that, the meshing sensitivity was made because to choose the best meshing to used it in the next analysis, namely the effect of design parameters.
c) The result of the meshing sensitivity analysis also was shows that the accuracy of the maximum contact pressure result is more accurate when the number of element is increase as well as the response time to compute the analysis is too long.
d) The effect of design parameters like the radial clearance and size of femoral head was affects the result of maximum contact pressure for dry and lubrication contact.
e) When the value of radial clearance is fixed, it was provide effect to the result and graph pattern of maximum contact pressure for both condition contacts. When the radial clearance is increases, the result of maximum contact pressure at the contact surface is also increases.
f) For the effect of femoral head size on contact pressure, the graph pattern for both condition contact is similar, namely the value of maximum contact pressure at the contact surface is decrease when the size of femoral head is increases.
g) The result of maximum contact pressure at the contact surface for dry contact case is 32.887 MPa.
h) The result of the maximum contact pressure for lubrication contact is lower compared to dry contact case because at the region between surface of femoral head and acetabulum cup have full fluid-film lubrication. It causes the wear of the metal-on-metal hip joint implant can be reduced. Thus, the maximum contact pressure at the bearing surface for lubrication contact can be reduced.

To ensure that the study can be improved in the future, there are some suggestions for this study can be used to improve the result accuracy of metal-on-metal hip joint replacement analysis in near future. Among them are :

a) The 3D modelling metal-on-metal hip joint replacement
The 3D modelling metal-on-metal hip joint implant should be constructed and analysed in further study so that provide the result of maximum contact pressure and compare it to the result of 2D modelling metal-on-metal hip joint implant. The analysis must be consists two cases condition, namely dry and lubrication contact.

b) The different material configurations of the hip implant
In the further study, the hip implant can be made of the different material configurations such as ceramic-on-ceramic, metal-on- ceramic and zirconia-on-metal. The result of the maximum contact pressure for various material configurations can be compared to the metal-on-metal hip implant result.

c) The various positions (º) for location of the femoral head
The position (º) for location of the femoral head can be diversified such as 45º and 60º to get the result of maximum contact pressure and compared to the result of maximum contact pressure for original position, namely 0º.

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