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Finite Element Study of the Effect of UHMWPE Liner Thickness on the Contact Area and Stress Distribution in a Bipolar Hip Joint

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Abstract. Contact area and stress distribution of the polyethylene liner (PE liner) have a major influence on the wear process. The main factor that affects the contact area and stress on the PE liner is thickness. The International Standards Organization (ISO) recommends a minimum PE liner thickness of 6 mm. However, the thickness of PE liner in a bipolar hip prosthesis has a limited range of motion compared to the unipolar one due to the addition of the outer liner component. Therefore, the study of the effect of PE liner thickness on the contact area and stress distribution in the bipolar model is interesting. Theaim of this research is to investigate the effect of the PE liner thickness to the contact area and stress distribution on the surface of contact between head and PE liner and the contact between outer liner and cup in the bipolar model. This research was carried out by finite element analysis. The results showed that the highest contact stress on the liner occurred at the lowest liner thickness. The maximum contact radius on the liner surface took place at the highest liner thickness. The bipolar model with the liner thickness of 4.5 mm in this research provided the lowest contact stress.

Keywords: Finite element, UHMWPE, Bipolar Hip Joint

1. Introduction

Islam is the largest religion in Indonesia based on the central bureau of statistics in Indonesia [1]. In Islam, its adherent is called as a Muslim. One of the religious activities for Muslim is *Salat* activity. Salat activity consists of standing, bowing (*ruku'*), straightening up (*i'tidal*), the transition of standing towards prostration, prostration (*sujud*), sitting between the two prostrations, and sitting [2]. Salat is an essential activity for Muslim, including for Muslim patients who use hip prostheses. In another word, Salat activity and the general activities will affect the motion of hip prosthesis [3-5]. One of the differences between Salat activity and daily activities is the range of motion (RoM) in the hip prosthesis movement. Based on the RoM data of hip prosthesis from Soeharso Orthopedic Hospital,

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Solo, some movement with a large angle of the range of motion was found. The effects of the large angle would accelerate the process of impingement which is potential to dislocation. Therefore, the design of hip prosthesis for Muslim patients must be tailored to accommodate the movement of Salat. Especially for Indonesian people, the dimension of the hip prosthesis must also be adapted to the diameter of the average hip size of Indonesian people.

In general, there are two types of the hip prosthesis in total hip replacement, i.e. unipolar model, and bipolar model. The unipolar model consists of a cup, liner, head and stem, whereas the bipolar model consists of the cup, outer liner, inner liner, head, and stem. A calculation of the RoM of Salat for the unipolar and bipolar models had been performed [6]. Based on this study, it was found that the bipolar model can accommodate Salat movement better than the unipolar model with the same head diameter. The consequence of using the bipolar model to PE liner is that the liner thickness becomes definite. By assuming the outer diameters of the cup and head of both models are the same, the liner thickness of the unipolar model is thicker than that of the bipolar model. Based on the International Organization for Standardization (ISO), the recommendation of liner thickness is equal to 6 mm [7]. This recommendation can be applied in the unipolar model. However, it is difficult to be applied in the bipolar model. It is due to the limitation of cup dimension and the addition of outer liner. In fact, the liner thickness will affect the contact stress distribution and contact area due to the contact interaction between the head and liner. The contact stress and contact area on the liner will affect the wear of the liner surface.

Several researchers investigated the effect of the liner thickness to the contact stress. In 1985, Bartel *et al*. [8] reported the effect of conformity and plastic thickness on the contact stresses in Metal-Backed plastic implants. They found that the contact stresses on the liner were very sensitive to clearance with a minimum thickness of 4-6 mm. Furthermore, in 1986, Bartel *et al*. [9] continued their research concerning the effect of conformity, thickness and material on stresses in the ultra-high molecular weight polyethylene (UHMWPE) components for total hip replacement. Their results found that the liner thickness should be maximized to reduce the contact stress that led to surface damage. In 2010, Shen *et al*. [10] investigated wear versus the thickness and other features of 5-Mrad cross-linked UHMWPE liners. They found that the reduction of the liner thickness from 6 mm to 3 mm increased the contact stress by 46%.However, the wear rate decreased by 19%. Recently, Jamari *et al*. [11] investigated the effect of the wall thickness on the wear of PE liner. Their results showed that higher contact stress wouldbe achievedby decreasing the liner thickness. The general conclusion from literature related to the liner thickness is that the liner thickness which is less than 6 mm causes a high contact stress on the liner surface that will also increase the wear process. Unfortunately, most of the contact stress investigations were only performed for the unipolar model. Therefore, the investigation of the contact stress distribution and contact radius in the bipolar model was performed.

The objective of this research is to study the contact stress distribution and contact area on the liner surface due to the contact interaction. Moreover, the contact stress distribution on the cup surface due to interaction contact between outer liner and the cup is also studied. The finite element analysis is employed for calculating the contact area and stress distribution.

2. Experimental Method

2.1. Material Model

In general, hip prostheses are made from metal and plastic materials. In this research, the femoral head, the outer liner, and the cup components were made from the SS316L material, while the liner and the inner liner are made from UHMWPE material. For validation process, the cobalt chromium molybdenum (CoCrMo) was employed. These materials are considered as elastic materials, following Archard's wear equation [12]. The properties of UHMWPE, CoCrMo, and SS316L materials can be seen in Table 1.

Table 1. Material properties of UHMWPE and SS316L

Material	Modulus Elasticity [GPa]	Poisson's ratio
UHMWPE [13]	0.5-1	0.4
CoCrMo [13]	230	0.3
SS316L [14]	193	0.3

Table 2. Variation of thickness of the inner liner and cup

Thickness	Inner liner	Cup
Thickness 1	3 mm	1.9 mm
Thickness 2	3.5 mm	1.65 mm
Thickness 3	4 mm	1.4 mm
Thickness 4	4.5 mm	1.15 mm

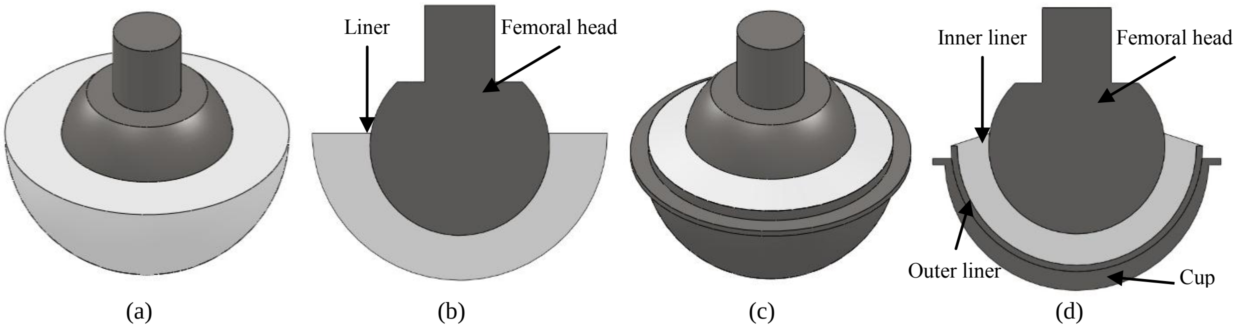


Figure 1. Unipolar model (UM) and bipolar model (BM) of the hip prostheses [6]: (a) UM isometric view, b) UM cross-section view, c) BM isometric view and d) BM cross-section view. (Note: dark gray color represents metal material, and light gray color represents plastic material)

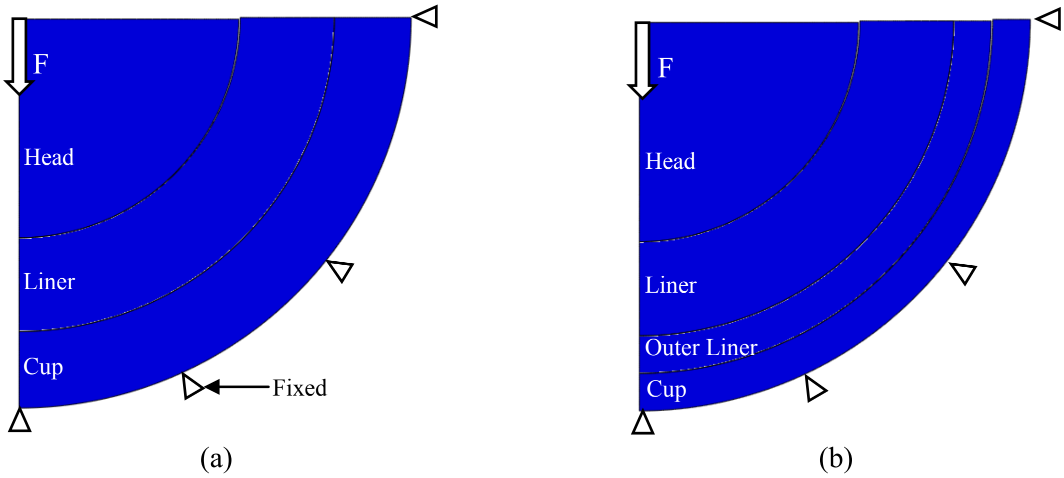


Figure 2. (a) Unipolar model and (b) bipolar model

2.2. Geometrical Model

There were two models employed in this research, i.e. unipolar and bipolar models (see Figure 1a-d for more detail). The unipolar model was used for validation process, whereas the bipolar model was used for analyzing the contact stress distribution and contact area on the liner and cup surfaces (Figure 2). The dimension of the unipolar model was adopted from the model of Puccio and Mattei [13]. The dimension of the bipolar model was designed based on the femoral head dimension average of Indonesian people. The data from the Indonesian orthopedic hospital show that the average diameter of Indonesian femoral head is 42 mm. The data were then used as a parameter to determine the dimension of outer liner and inner liner of the bipolar model. The head diameter of the bipolar model was 28 mm. To investigate the effects of the inner liner thickness on the contact stress and contact area on the inner liner, the thickness of inner liner was varied. The variations of the inner liner thickness are 3 mm, 3.5 mm, 4 mm and 4.5 mm. Further, the different thickness of the head and the inner liner was divided into two thicknesses to get the thicknesses of the outer liner and cup. Therefore, when the thickness of the inner liner increased, the thickness of cup was decreased. See Table 2 for more details. The clearances between the head-inner liner and outer liner-cup were 0.1 mm.

2.3. Finite Element Simulation
The commercial finite element of ABAQUS software was employed for analysis. The axisymmetric contact model was consideredto simplify and minimize the cost of simulation. The element type of axisymmetric quadrilateral of 4-node bilinear with reduced integration andhourglass control (CAX4R) was employed, while the average number of the element was approximately 5000. The load of 3000 N was appliedat the center point of the femoral head for all models. The outer surface of the inner liner followedthe Hertzian model, and the cups in both unipolar and bipolar modelswere fixed for all directions. In order to obtain the detailed information, the area around the contact interaction was partitionedathigher mesh.

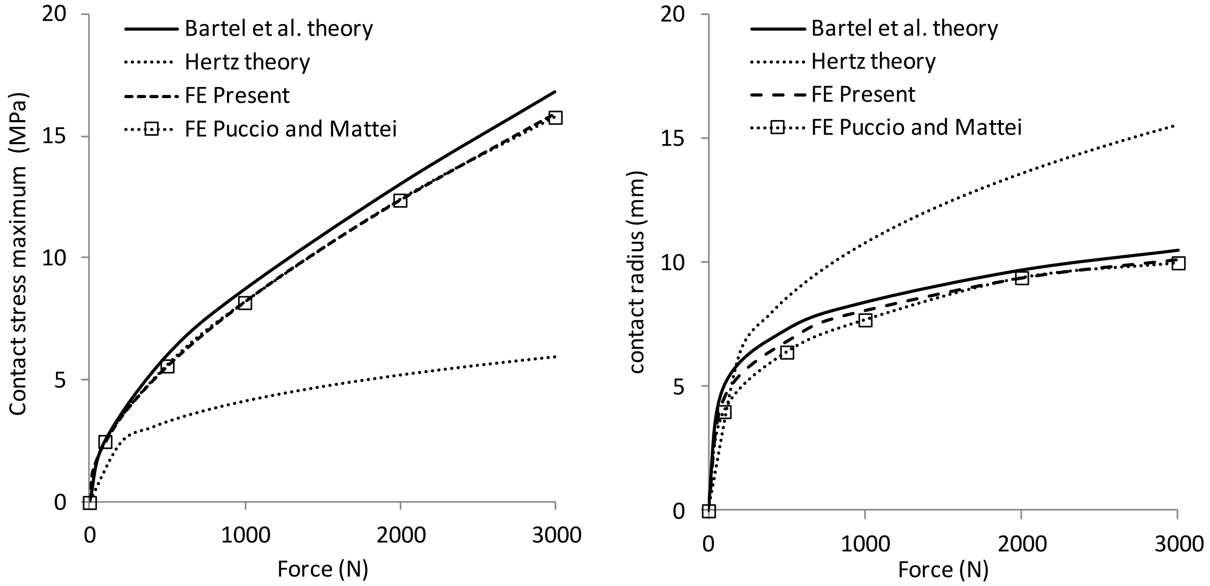
3. Results and Discussion

3.1. Validation
In the previous research [6], the applied load was 5 N which was relatively small. Thiswas because the result was compared with Hertzian contact theory. Bartel *et al*. [8] showed that the Hertzian contact theory was not recommended for the conformal contact case. The Hertzian contact theory cannot calculate accurately for the high contact load. Therefore, this research was validated by the theory of Bartel *et al*. Bartel *et al*. theory is a set ofreferences, and all results were compared based on them. The head diameter and liner thicknesses were 28 mm and 6 mm, respectively. The material of head and liner are cobalt chrome and UHMWPE material, respectively.

Figure 3a presents the maximum contact stress on the liner surface as a function of load. The value of contact stress was takenfrom the center point of the contact surface. Figure 3a shows the results of Bartel *et al*., Hertz, FE Puccio and Mattei, and FE present theories. Based on Figure 3a, the FE present showed a good agreement with Bartel *et al*. theory and FE Puccio and Mattei theory with an error amounted to 5 % and 0.5 %, respectively. However, the Hertz theory showedsignificantlydifferent results compared to the others.

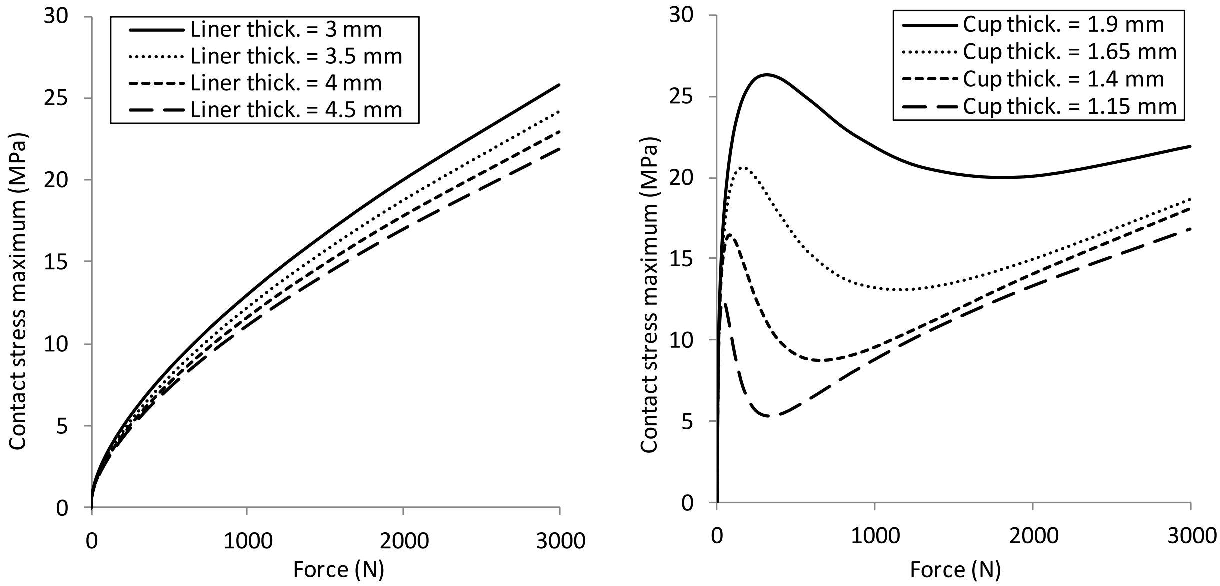
Figure 3b shows the progress of the contact radius as a function of the load. Based on Figure 3b, the FE present also showed a good agreement with Bartel *et al*. theory and FE Puccio and Mattei with the error of 5 % and 1 %, respectively. However, the Hertz theory was significantlydifferent with Bartel *et al*., FE Puccio and Mattei and FE present theories.

3.2. Maximum Contact Stress
Figure 4a shows the maximum contact stress on the inner liner surface with a variation of liner thickness as a function of force, whereas Figure 4b shows the maximum contact stress on the cup surface. The maximum contact stress was taken in the center of the contact interaction. Based on Figure 4a, the contact stress on the inner liner increasedappropriately with the increase of the force. The highest contact stress occurredwhen the inner liner thickness was equal to 3 mm, while the lowest contact stress took place when the inner liner was equal to 4.5 mm.



(a) (b)

Figure 3. (a) The comparison between contact pressure distribution as a function of contact radius for Hertz theory and FE, and (b) the contour plot of contact pressure distribution for Hertz contact using FE simulation.



(a) (b)

Figure 4. (a) The comparison between contact pressure distribution as a function of contact radius on the inner liner surface and (b) on the outer liner surface for Hertz, unipolar and bipolar condition.

Figure 4b shows the contact stress on the cup surfaces as a function of load. Based on figure 4b, the contact stress phenomenon on the cup surface was different with the contact stress phenomenon on the inner liner surfaces. The increasing contact stress on the cup surface was fluctuation. As in the cup thickness that was equal to 1.9 mm, the initial contact stress increaseduntil 27 MPa at the force of 400 N, then the contact stress was fluctuation until it reached the force of 3000 N. Such phenomenon occurred at all of the cup thickness.

3.3. Contact Stress Distribution and Contact Radius

Figures 5a and 5b show the contact stress distribution and contact radius on the liner and cup surfaces as a function of the contact radius. These values were takenat the force equal to 3000 N. Figure 5a presents the contact stress distribution on the liner surface. The maximum contact stress was getting started at the center point of contact then decreased to reach the last contact radius, see Figure 6a. The highest contact stress occurredwhen the liner thickness was equal to 3 mm, while the lowest contact stress took place when the liner thickness was equal to 4.5 mm. However, the contact radius showedthecontrary phenomena. The highest contact radius occurred when the liner thickness was equal to 4.5mm, whereas the lowest contact stress took place when the liner thickness was equal to 3 mm.

Figure 5b presents the contact stress distribution on the cup surface as a function of the contact radius. The location of the highest contact stress did not appear at the center point of contact. However, it shifted to the last contact radius, see Figure 6b. The highest contact stress occurred when the cup thickness was equal to 1.9 mm, while the lowest contact stress took place when the cup thickness was equal to 1.15 mm. However, the contact radius showed different phenomena. The highest contact radius occurred when the cup thickness was equal to 1.15 mm, while the lowest contact radius happened when the cup thickness was equal to 1.9 mm.

The contact stress and contact radius on the cup and liner surface showed different phenomena. The highest contact stress on the liner surface to the liner variation occurred at the lowest liner thickness, while the highest contact stress on the cup surface to the cup variation occurred at the highest liner thickness. The maximum contact radius to the PE liner variation took place at the highest liner thickness, while the highest contact radius to the cup variation occurred at the lower cup thickness.

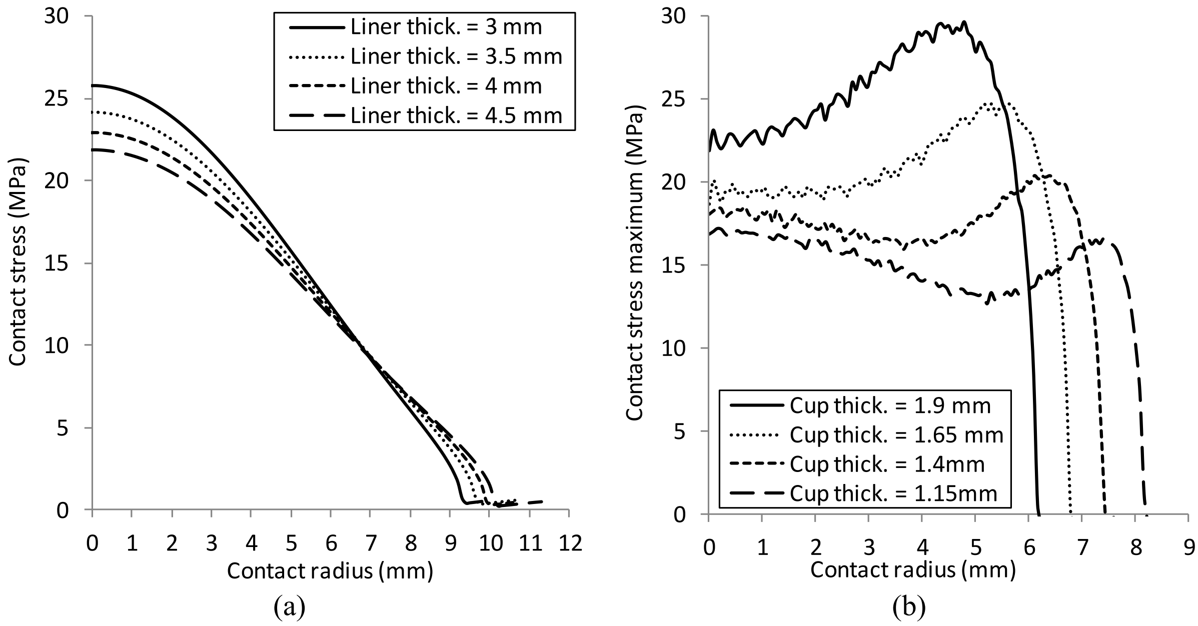


Figure 5. (a) The comparison between contact pressure distribution as a function of contact radius on the inner liner surfaceand (b) on the outer liner surface for Hertz, unipolar and bipolar condition.

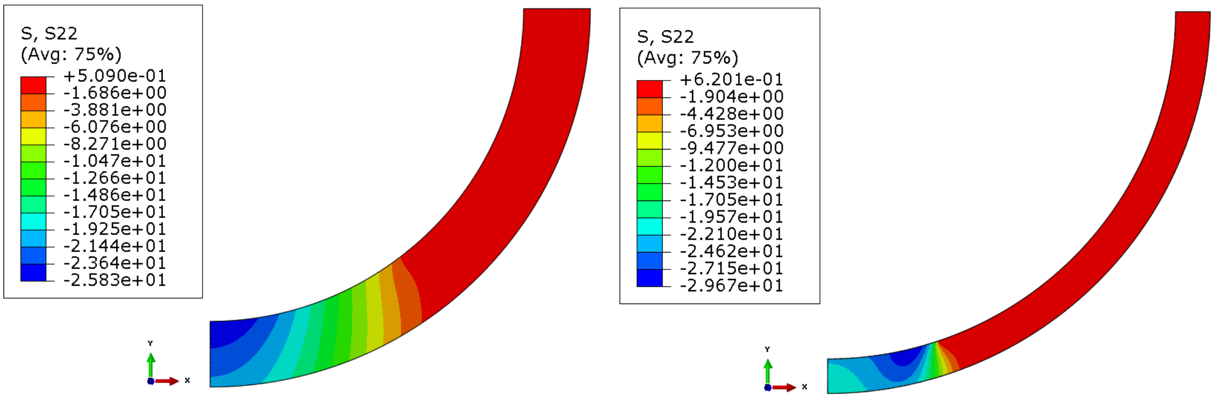


Figure 6. (a) The contour plot of contact pressure distribution on the surface of inner acetabular liner for theunipolar model and (b) the contour plot of contact pressure distribution on the surface of outer liner for the bipolar model.

3.4. Von Mises Stress

Figure 7 presents the von Mises stress on the liner and the cup. The thickness of the liner and cup was represented with the symbols of thickness 1 up to 4, see Table 2. The purpose of Figure 7 is to show the failure boundary of the liner and cup due to the contact load. Based on this figure, the von Mises stress to the liner thickness was relatively similar, while the von Mises stress to the cup thickness showed different results at each of the cup thickness. On the variation of cup thickness, the highest von Mises stress occurred at the highest cup thickness, while the lowest von Mises stress occurred at the lowest cup thickness. The contour of von Mises stress of the liner and cup can be seen in Figure 8.

Based on reference [15], the yield stress of the UHMWPE material was 23.56 MPa. Therefore, it can be concluded that the liner thickness in this bipolar model was safe because the highest von Mises stress of the liner was under the yield stress. It was also shown that the applied load was allowedin this bipolar model.

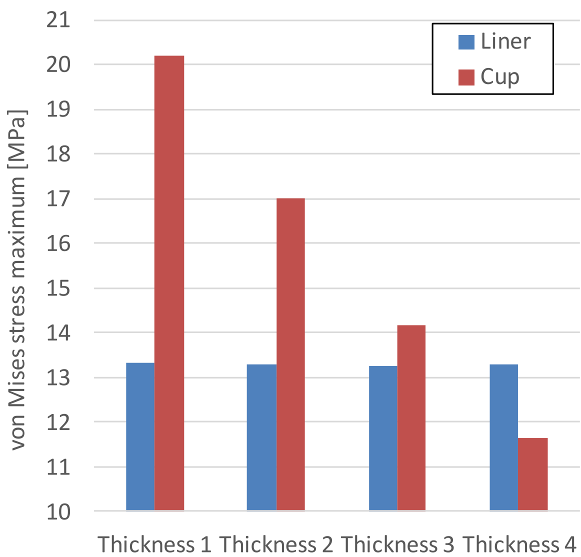


Figure 7. The von Mises stress of liner and cup

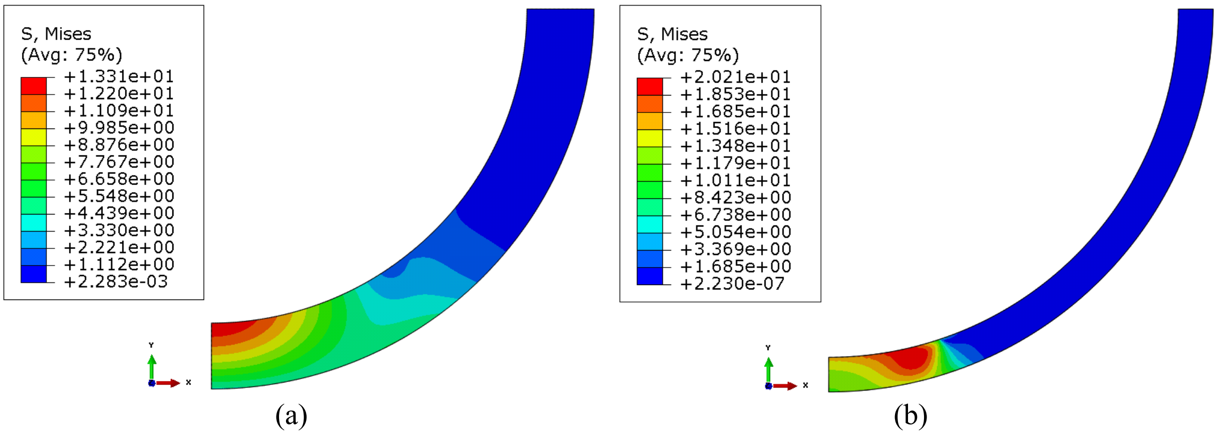


Figure 8. (a) The contour plot of contact pressure distribution on the surface of inner liner for theunipolar model and (b) the contour plot of contact pressure distribution on the surface of outer liner for the bipolar model

4. Conclusion

A study of the effect of the PE liner thickness onthe contact area and stress distribution on the surface of the contact between head and PE liner and the contact between outer liner and cup in the bipolar model has been performed. This study was carried out using finite element analysis simulation. The results of the study showed that the highest contact stress on the liner occurredat the lowest liner thickness. The highest contact radius on the liner surface took place at the highest liner thickness. The bipolar model with the liner thickness of 4.5 mm in this research gavethe lowest contact stress.

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