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The Effect of Additional Layer between Liner and PMMA on Reducing Cracks of Cement Mantle Hip Joints

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Abstract

Loosening of the acetabular liner component caused by the failure of the cement mantle is a complex phenomenon in a total hip arthroplasty. This failure is often associated with the occurrence of cracking in the cement mantle. Investigation of this cracking can be performed by fatigue test or simulation. Cracking can be caused by initial cracks (porosity), defects of cement mantle, or stress due to repeated loading. An initial crack may be caused by material defects. The stress depends on the load and on the strength of the material itself. To reduce crack failure, one can minimize the initial crack or optimize the thickness of the cement mantle and reduce stress that occurs in the cement mantle. This study offers a solution for reducing the intensity of stress on the cement mantle by providing an additional metal layer between the liner and the acetabular component cement mantle. The study is performed by simulating static contact using finite element analysis. Results show that the additional layer between the acetabular liner and the cement mantle can significantly reduce the stress on the contact surface of the cement mantle.

Keywords: layer, cement mantle, cracking, fatigue, hip joint

1. Introduction

Operation of total hip replacement (THR) shows the increasing numbers and to be successful. Cemented system is most widely used in the total hip replacement. Reliability of the THR is important to patient, orthopedic, and surgeon. Therefore, improved design, technology and materials for inserting of hip replacements are highly needed. This also includes whether the design of the THR is cemented or uncemented. Bone cement is widely used to affix hip implants to the bone during total hip arthroplasty; therefore many studies have been performed to investigate the reliability of cement mantle in a total hip replacement. Fisher et al. [1] observed the effect of the cement mantle thickness on strains on total hip replacement experimentally on stem components. The study was conducted on two stem components by varying the thickness of the cement mantle. Strain gauges were embedded in the cement mantle, and then the stem components were subjected to an axial load in walking and standing conditions. The results showed that an increase in cement mantle thickness from 2.4 to 3.7 mm can decrease the strain on the cement mantle by about 40%-49%, so they concluded that by increasing cement mantle thickness the fatigue life of an implant may be increased.

In the total hip arthroplasty, system bone cement experiences repeated cyclic loading which can lead to fracture or crumbling of the cement mantle as the replacement recipient ambulates over time. For investigating the quality of cement with

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respect to the fatigue lifetime, a new bone cement was formulated by Jacobs et al. [2]. It was demonstrated that the performance of fatigue life of Osteobond Copolymer Bone Cement is better than Simplex P Bone Cement. Cement mantle failure is also often associated with cracking of the cement mantle. Cracking in a cement mantle is affected by material defects that cause initial cracks, less than optimal thickness of the cement of the mantle, and stress on the cement mantle due to a contact load that can increase an initial crack. To investigate this cracking problem, investigations can be performed by experimental fatigue testing and computer simulations. The question is how to overcome cracking in cement mantle? Solutions include resolving the material defects, optimizing the cement mantle thickness, and reducing the crack stress. A lot of researchers have tried to optimize the thickness of the cement mantle in hopes of reducing the stress on the cement mantle. Letters et al. [3] proposed an experimental model to predict the failure mechanisms and cement mantle stresses while Zant et al. [4] developed a simple multilayer model to calculate stress distribution in the cement mantle of an acetabular replacement from a plane strain finite element model. Even though their results were promising, they concluded that their 2D fatigue damage model may not representative of that of 3D model. Ramos and Simoes [5] conducted a study of the effect of cement mantle thickness on fatigue damage to two different hip prostheses. The inferred conclusion is that the thickness of the cement mantle is an important factor in the total success of a hip replacement. The thickness of cement mantle plays important role within the mechanism of cracking formation. The interface between stem and cement is critical for the damage mechanism initiation of the prosthesis. Lamvohee et al. [6] conducted research on the effect of cement mantle thickness, acetabular size, bone quality and body mass index on tensile stress in bone cement using finite element simulation. They found that the peak tensile stresses in the cement mantle decreased with an increase in cement mantle thickness, acetabular size and bone quality and body mass index. Some of these studies concluded that stress on the cement mantle can be reduced by reinforcing the cement mantle. With reduced stress on the cement mantle, it is expected that crack growth will be reduced.

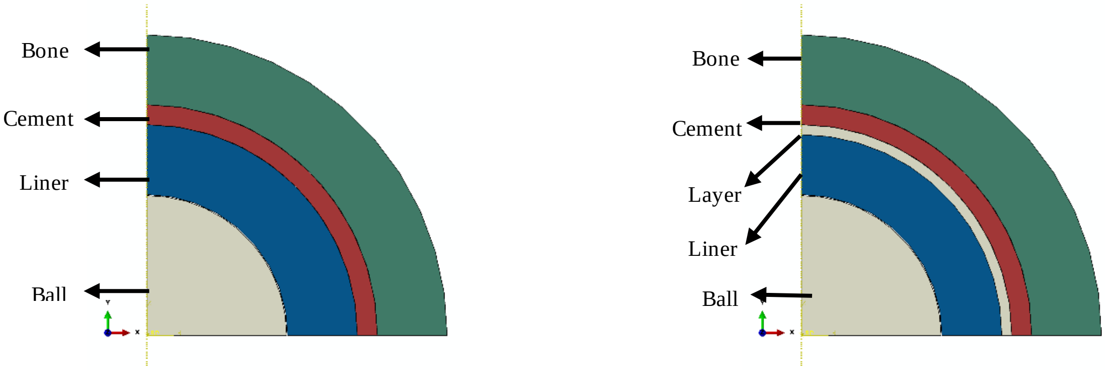
However, studies of Mann et al. [7-8] found that the rate of growth of fatigue cracks does not depend on the mantle thickness. They argued that increasing the thickness of the cement mantle only strengthens the cement mantle itself but does not reduce the cyclic load directly on the cement mantle. They also believe that there should be an additional layer before the cyclic load up to the cement mantle. This layer is expected to not only reduce stress on the cement mantle, but also reduce the cyclic load directly to the cement mantle. Based on these phenomena, therefore, a parametrical study of a metal layer inserted between the liner and the cement mantle is carried out in the present study. This study offers a solution to reduce the stress intensity of the cement mantle by providing an additional metal layer, as was suggested by Mann et al. [7-8], between the acetabular liner component and the cement mantle. Analyzing the impact of the additional layer of the acetabular liner on the stress on the surface of the cement mantle will be performed by finite element analysis. Similar finite element analyses procedure for studying the performance of artificial hip joint for human activities [9-11] will be applied in the present study.

2. Materials and Method

2.1. Geometry of the model

In general, the prosthesis of the cemented model has a stem, femoral head (ball), acetabular liner, cement mantle, and bone (acetabulum) [12]. Fig. 1 shows the construction of the general cemented model prosthesis. For simulation purposes, the arrangement of hip interaction modes of contact between the ball, liner cement, and bone is simplified by adopting an axisymmetric model. There are two proposed simulated models: model A and model B. Model A is the model using liner (without layer) which is arranged starting from the ball, and passing on to the liner, cement and bone, as depicted in Fig. 1(a). Model B is the model using liner (with additional layer) which also has similar arrangement starting from the ball, and passing on to the liner, layer, cement and bone, as shown in Fig. 1(b). The main difference between model A and model B is the addition in model B of a layer between the liner and the cement. For model A, the diameter of the ball, the outer diameter of the liner, the outer diameter of the cement, and the outer diameter of the bone are 28 mm, 42.2 mm, 46.2 mm, and 60.2 mm, respectively. Meanwhile, the thickness of the liner, the cement thickness, and the bone thickness are 7 mm, 2 mm, and 7 mm, respectively. The cement thickness used in this simulation refers to research by Gun et al. [13]. For model B, the overall dimensions are the same as for model A, and there is only an additional layer and a reduction in the outer diameter of the liner due to that additional layer. Thus, the outer diameter of the liner, the outer diameter of the coating, and the coating thickness are 40.2 mm, 42.2 mm, and 1 mm, respectively.

Fig. 1 Cemented hip prosthesis model [12]



(a) Model A (liner without layer)

(b) Model B (liner with layer)

Fig. 2 Model geometry

2.2. *Material properties*

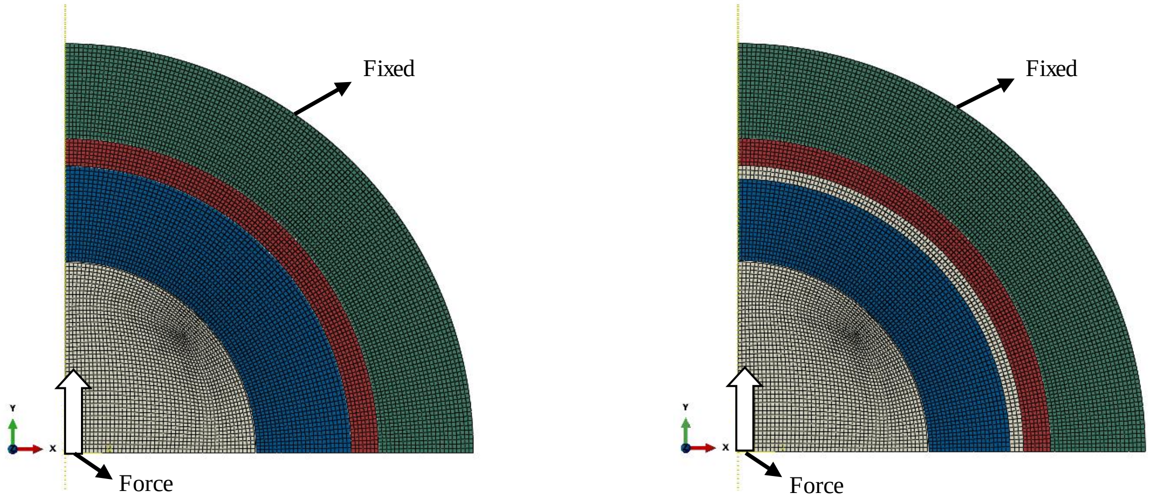
Several types of materials were used for the components in this simulation. These materials are summarized in Table 1. As is presented in Table 1 the material properties were taken from literatures. According to Anderson et al. [14], Sahli et al. [15] and Ouinas et al. [16] the cortical bone has elasticity modulus of 17000 MPa and Poisson's ratio of 0.3. Material for the cement mantle is adopted from Sahli et al. [15], Ouinas et al. [16] and Achour et al. [17] with Young's modulus ranging from 2000 to 2300 MPa and Poisson's ratio of 0.3. The liner used material as was used by Ouinas et al. [16], Achour et al. [17] and Eichmiller et al. [18] with modulus of elasticity of 690-945 MPa and Poisson's ratio of 0.45. The material properties of the hard ball have Young's modulus of 193000 MPa and Poisson's ratio of 0.3 [19]. So, the materials for bone components, cement mantle, liner, and ball were chosen to be cortical bone, polymethyl methacrylate (PMMA), ultra-high molecular weight polyethylene (UHMWPE), and 316L stainless steel, respectively.

Table 1 Material properties for all components

Material	Young's modulus (MPa)	Poisson's ratio
Cortical bone [14, 15, 16]	17000	0.3
PMMA [15, 16, 17]	2000-2300	0.3
UHMWPE [16, 17, 18]	690-945	0.45
SS316L [19]	193000	0.3

2.3. Simulation procedure

Static contact simulation was performed to determine the stress that occurs in the cement mantle. The simulation was performed using commercially finite element analysis software ABAQUS [20]. The applied contact force to the center of the ball is 3000 N, which was adopted from the walking gait load system of Bergmann et al. [21]. Symmetrical boundary conditions are applied on the left side of each model, while the outer surface of the bone is fixed, see Fig. 3. Contact interaction occurs only on the surface of the ball with the inner surface of the liner, while the other is made bound or tied. In this study the interaction between components at the surface layers are assumed to be neglected. The mesh used is CAX4R: A 4-node bilinear axisymmetric quadrilateral, reduced integration, and hourglass control. There were about 8236 elements and 8724 nodes used in the simulation.



(a) Model A (b) Model B

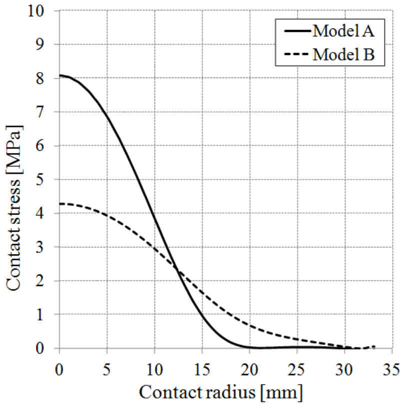
Fig. 3 Applied force, boundary conditions, and mesh

A parametric study [22] could be conducted as the first step for optimizing the design process. In the present study von Mises stress and deflection parameters were studied. The data obtained from each model is the von Mises stress on the cement mantle. The von Mises stress is taken to know the change of stress due to the addition of the metal layer. Data of deflection is also shown to know the effect of the coating on the displacement of the cement mantle.

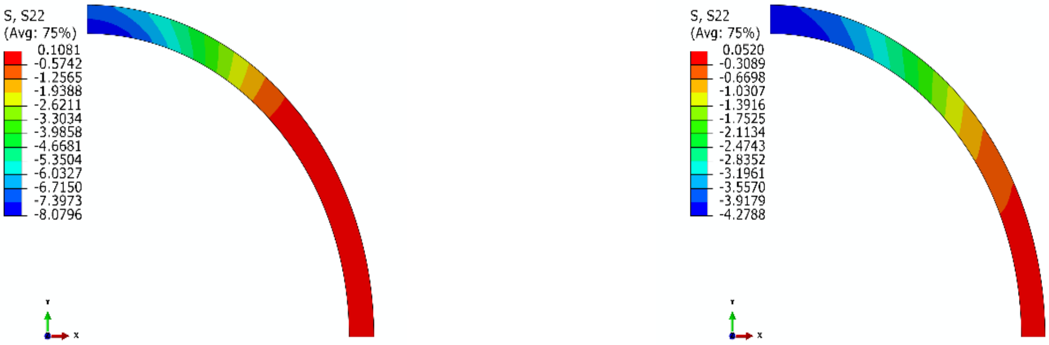
3. Results and Discussion

Some mechanical behaviors have been observed to study the consequence by giving an additional layer on a cemented hip joint system. The results of the simulation of static contact on both hip prosthesis design models are presented in the distribution the contact stress, the von Mises stress, and the displacement on the cement mantle surface due to normal load. The examined mechanical behavior of contact stress, von Mises stress and displacement on the cement mantle surface are directly associated with the loosening and failure or damage of the cement mantle as a consequent. Detail examination was performed due to the fact that on the cement mantle surface all the failure initiation is likely occurs. Fig. 4(a) shows the value of the contact stress distribution on the cement mantle surface of models A and B as a function of the contact radius. Model A is shown with a full line whereas model B is indicated by dashed lines. The y-axis or S22 in the post-processing ABAQUS feature [20] is used to present the stress on the surface of the cement mantle. Based on Fig. 4(a) it can be seen that the maximum contact stress value on the surface of cement mantle of model A and model B is at the center of the cement mantle. At the center of the contact the stress is maximum and then decreasing as the contact radius increasing. The rate of contact stress decreasing of model A is higher than model B, therefore for the same mean contact pressure model A give a lower contact radius. The maximum contact stress value in model A is higher than model B, but the contact radius value in model A is lower than model B. The maximum contact stress of model A is recorded at about 8.08 MPa and the maximum contact stress of model B is about

4.28 MPa. It means that the addition of a metal layer between the liner and the cement mantle could reduce drastically the maximum contact stress by about 47%. Shape of the contact stress as a function of the contact radius, however, is similar. Fig. 4(b) and Fig. 4(c) show detail contour distribution of the contact stress on the cement mantle component for both model A and model B. Both models exhibit similar contact stress distribution where the maximum occurs at the contact center and the minimum takes place at the outmost of the contact. At the center of the contact, the value of contact stress is maximum and then decreasing along the *y* direction (thickness) and along the *x* direction (contact radius).



(a) Comparison of model A and B as a function of contact radius

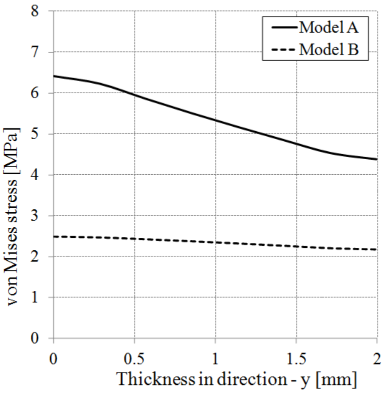


(b) Contact stress contour on cement mantle component of model A

(c) Contact stress contour on cement mantle component of model B

Fig. 4 Plot of contact stress

Fig. 5(a) shows the distribution of von Mises stress on the cement mantle of model A and model B as a function of the thickness in *y* direction of the cement mantle. The von Mises stress of model A is shown with a full line whereas for model B is indicated by dashed lines. The von Mises stress distribution was taken from the ABAQUS post-processing features [20]. It can be seen from the figure that the maximum von Mises stress on the cement mantle component of model A and model B is take place at the center of the cement mantle. The maximum value of von Mises stress of model A is higher than model B. Nevertheless, the maximum values of von Mises stress for both models are still below the elastic limit of the supporting material (PMMA). The tensile strength of the supporting material PMMA is about 25 MPa [15-17]. The maximum value of von Mises stress of model A was recorded at about 6.42 MPa, while model B was recorded at about 2.49 MPa. This result shows that the addition of a metal layer between the liner and the cement mantle can lower significantly the maximum value of von Mises stress by about 61%. Interestingly, in model B (with the additional layer) there is almost no peak of von Mises stress distribution along the thickness in *y* direction. Detail contour distribution of von Mises stress on the cement mantle component for model A and model B are presented in Fig. 5(b) and Fig. 5(c), respectively. Both models display almost similar von Mises stress distribution. The maximum value occurs at the bottom of the contact center and then decreasing along the *y* direction (thickness) and along the *x* direction (contact radius).

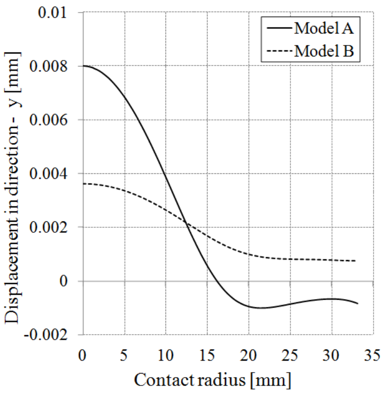


(a) Comparison of model A and B as a function of thickness in *y* direction

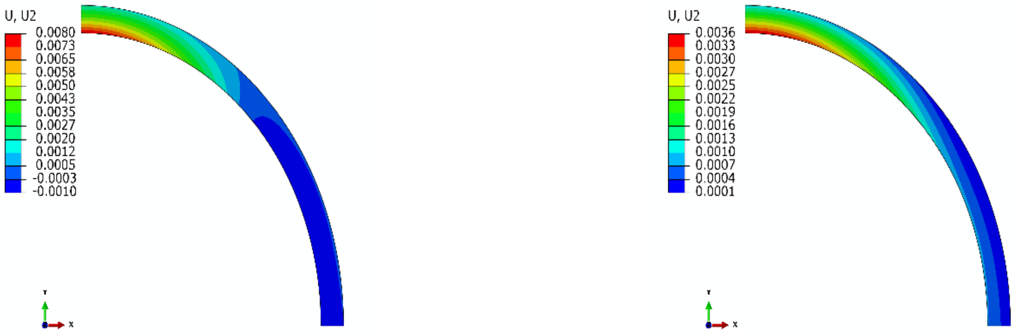
(b) Von Mises stress contour of cement mantle component for model A

(c) Von Mises stress contour of cement mantle component for model B

Fig. 5 Plot of von Mises stress



(a) Comparison of models A and B as a function of contact radius



(b) Displacement of cement mantle component of model A

(c) Displacement of cement mantle component of model A

Fig. 6 Plot of displacement in *y* direction

In addition to the contact stress distribution and von Mises stress, the effect of adding an additional layer can also be seen from the deformation or displacement of the cement mantle relative to the ball. Fig. 6(a) shows the displacement in *y* direction of the cement mantle of model A and B as a function of the contact radius. The *y* direction or U2 displacement in the ABAQUS post-processing feature is used to present the displacements on the cement mantle surface. Based on Fig. 6(a) it can be seen that the maximum displacement of the cement mantle surface of model A and model B is at the center of the cement mantle. The maximum displacement in model A is higher than model B. The maximum displacement of model A was recorded at 0.008 mm, while model B was recorded at 0.0036 mm. A reduction of about 55% of the maximum displacement was found by giving or adding a metal layer between the liner and the cement mantle based on this simulation results. For model A, the distribution of displacement is decreasing as the contact radius increases. The displacement reaches to zero at the contact radius of about 16 mm. After this value, the displacement keeps decreasing and then starts to increase at the contact radius of 21 mm. This means that at the contact radius above 16 mm the cement mantle component is lifting up. Interestingly this does not occur for model B with the additional layer. In model B the value of displacement never reaches zero and the distribution of the displacement relatively smooth. Fig. 6(b) and Fig. 6(c) show detail distribution of displacement on the cement mantle component for model A and model B, respectively. Along the thickness, all the *y* direction displacement of the cement mantle can be predicted in these figures.

4. Conclusions

A static contact simulation of a model of a hip prosthesis has been performed using finite element analysis to study the effect of an additional layer between the liner and the cement mantle. There are two simulated hypothesis prosthesis models: a hip prosthesis model without the additional layer (model A) and a hip prosthesis model with the additional layer (model B). The contact stress and the von Mises stress at the cement mantle surface and the cement mantle displacement were used for the analysis. Based on the simulation results, it was found that the contact stress at the cement mantle surface, the von Mises stress at the cement mantle surface, and the displacement of the cement mantle component in model B were lower than those in model A. There was a drastically decrease of maximum contact stress, maximum von Mises stress, and maximum displacement of 47%, 61%, and 55%, respectively. Due to the reduction of all these mechanical behavior values, the possibility of cracking the cement mantle can be reduced. So, it can be concluded that by adding a metal layer between the liner and cement mantle can reduce loosening of the cement mantle which is often associated with the occurrence of cracking or other failure mechanism.

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