Key Engineering Materials Vol. 443 (2010) pp 736-741
Online available since 2010/Jun/02 at www.scientific.net

doi:10.4028/www.scientific.net/KEM.443.736

Minimizing Stress Concentrations in the Femoral Heads of Hip Joint Prostheses: Effect of Borehole Shapes

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Keywords: Femoral head; Hip joint prosthesis; Borehole shape; Finite element; Stress distribution; Contact length; Interface friction

Abstract. This paper presents a stress analysis of the ceramic femoral heads of hip joint prostheses with different borehole shapes to evaluate their mechanical reliability in terms of stress concentration. Under the ideal loading conditions used for ceramic rupture tests specified by the ISO 7206-5 standard, a finite element (FE) modeling is performed to determine the tensile and hoop stress distributions in the ceramic femoral heads. Two borehole shapes that are currently used in the manufacturing industry for hip joint prostheses, namely the flat bottom and keyhole, were first studied. Two new borehole shapes, dome arc and dome ellipse, were then introduced by the authors in the paper to minimize the stress concentration. It was found that while the currently used borehole shapes lead to high tensile notch stresses at their critical corners causing possible fracture failure of ceramic heads, the authors' borehole designs can improve the mechanical reliability significantly. In addition, the effects of taper-bore contact length and their interface friction are investigated and discussed.

Introduction

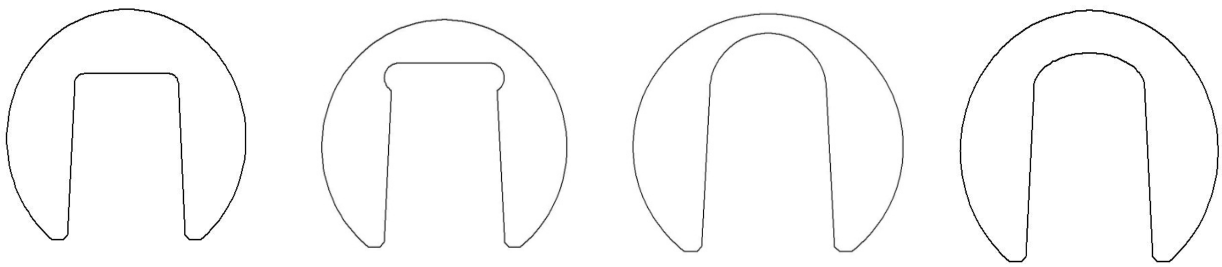
Because of their excellent mechanical properties and good biocompatibility, ceramic balls for total hip replacements (THR) have been widely used [1]. In THR, a ceramic ball head is mounted on a metallic stem by frictional fitting, and the system is then pivoted in ceramic or polyethylene cups. Although ceramic femoral ball heads have proved their exceptional mechanical reliability, recent clinical studies do show their fracture failure due to a number of causes [2, 3]. Among the possible causes to failure, improper assembly and contamination of the contact surfaces between the stem and the taper-borehole of a ceramic ball head during surgery are reportedly significant [4]. While these causes are, to some extent, unavoidable, the mechanical reliability of the ceramic ball heads has to be continuously raised by increasing the strength of component itself. One way to improve this is to optimize the design of the ceramic femoral heads.

In order to hold a ceramic head firmly, a metallic stem is fitted into the taper-borehole of the ceramic ball head. Depending on the preference of manufacturers and the ease of manufacturing, currently two types of taper borehole shapes are used in THR. One is the flat bottom shape with a filet at the corner of a ceramic taper-borehole, where a stress concentration occurs at the filet corner [5]. The other is the keyhole shape which has an undercut at the corner of the taper-borehole [6]. The surface with such an undercut shape is difficult to machine, which often leaves a low surface finish and causes further stress concentration sites. As ceramic is brittle and prone to fracture under a critical tensile stress, these currently used borehole shapes can actually reduce the mechanical reliability of ceramic femoral heads in THR.

This paper aims to study the stress distributions in the ceramic femoral heads, by analyzing both the existing taper-borehole shapes and some new designs of the authors to understand the effect of borehole shapes on the variation of stresses and hence to provide some useful guidelines for improving the mechanical reliability of the femoral heads. The finite element method will be used for the stress analysis. The loading conditions will follow the specification by the ISO7206-5 standard.

Borehole Designs

There are two existing designs of borehole which have widely been used for the ceramic femoral heads in THR. One is a flat bottom shape which is designed for easy production as shown in Fig. 1(a) [5]. Ceramic femoral heads with such a flat bottom are produced by drilling, creating a small fillet at the corner. This small fillet can cause local stress concentration, and often leads to the fracture failure of the ceramic heads. Another existing borehole design is a keyhole shaped internal geometry at the bottom of a ceramic taper-bore, as illustrated in Figure 1 (b), which is designed to avoid a possible impingement of the stem taper onto the bottom of the borehole under any unexpected loading or loosing of the stem taper assembly [6, 7]. The shape with an undercut in this design, however, is quite difficult to form during pre-sintering (Green Ceramic), and its surface is difficult to be finished by grinding or polishing, leaving a lower surface quality in such a critical area where local stress concentrations always occur.



(a) Flat bottom (b) Keyhole (c) Dome arc (d) Dome ellipse

Fig. 1 Shapes of borehole in ceramic femoral head

In order to minimize the stress concentrations, this paper introduces the following new borehole designs for stress evaluation: (1) dome arc, and (2) dome ellipse on the bottom of the ceramic taper-bore, as shown in Figure 1(c) and 1(d) respectively. In the case of the dome arc, a spherical dome is formed at the bottom of taper-bore, while for the dome ellipse, the taper-bore's bottom surface is a half of an ellipsoid. The radii of the dome arc and dome ellipse can be chosen such that the transition between the taper-bore and the bottom dome is smooth (tangent to each other) to avoid the local stress concentration. Since the geometric shapes of these new designs are simple, they are easy to fabricate in the pre-sintering stage of the ceramic heads to achieve a surface finish.

Finite Element Modeling

As the *in-vivo* (physiological) loading situation against the actual hip joint prosthesis is quite complex, the ISO 7206-5 standard proposes a simple test procedure to determine the rupture strength of a ceramic femoral head, which is considered to be able to approximately simulate the clinical performance of a ceramic femoral head used in hip joint prosthesis [8]. In this paper, as a first attempt, we consider only the static loading conditions specified by ISO 7206-5 to test the mechanical strength of ceramic femoral heads with the borehole designs described above. In the test configuration, as shown in Fig. 2, a ceramic femoral head with a taper stem is placed onto a 100˚ cone support under an axial load F. In this paper, the ceramic femoral head is considered to be of pure alumina, the taper stem is made of a titanium-aluminium-venadium alloy, and the 100˚ cone support is of stainless steel. Their Young's modulus (E) and Poison's ratio (υ) used in the calculations are (a) alumina: E = 380 GPa and υ = 0.245, (b) titanium-aluminium-venadium alloy: E = 105 GPA and υ = 0.3, and (c) stainless steel: E = 210 GPa and υ = 0.3, respectively. Throughout the tests in the paper, the diameter of the ceramic femoral heads is 28 mm and their borehole taper is 12/14 (known as "Euro-cone") [9].

A non-linear axisymmetric finite element (FE) model supported by ANSYS is constructed to perform the stress analysis. Figure 2 shows a finite element model of the testing system for the borehole design with a flat bottom, where the quadrilateral mesh is homogeneously constructed within all the object bodies. With other borehole designs illustrated in Fig.1, the FE model is similar.

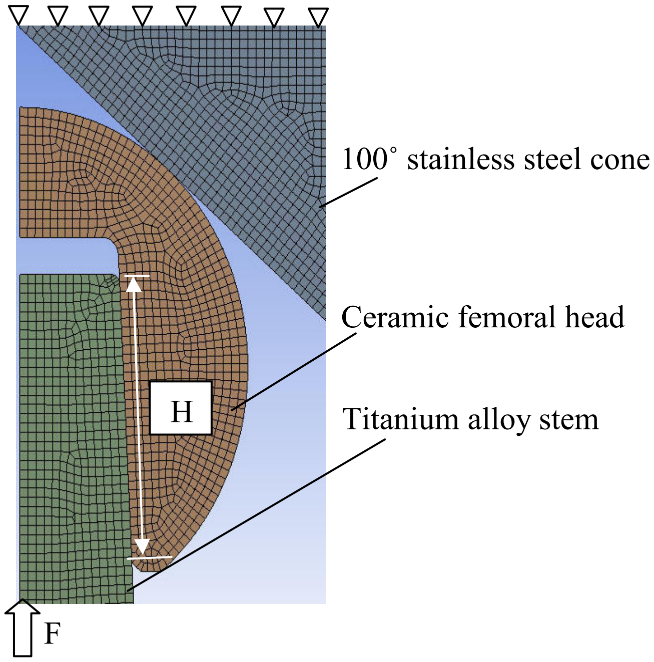


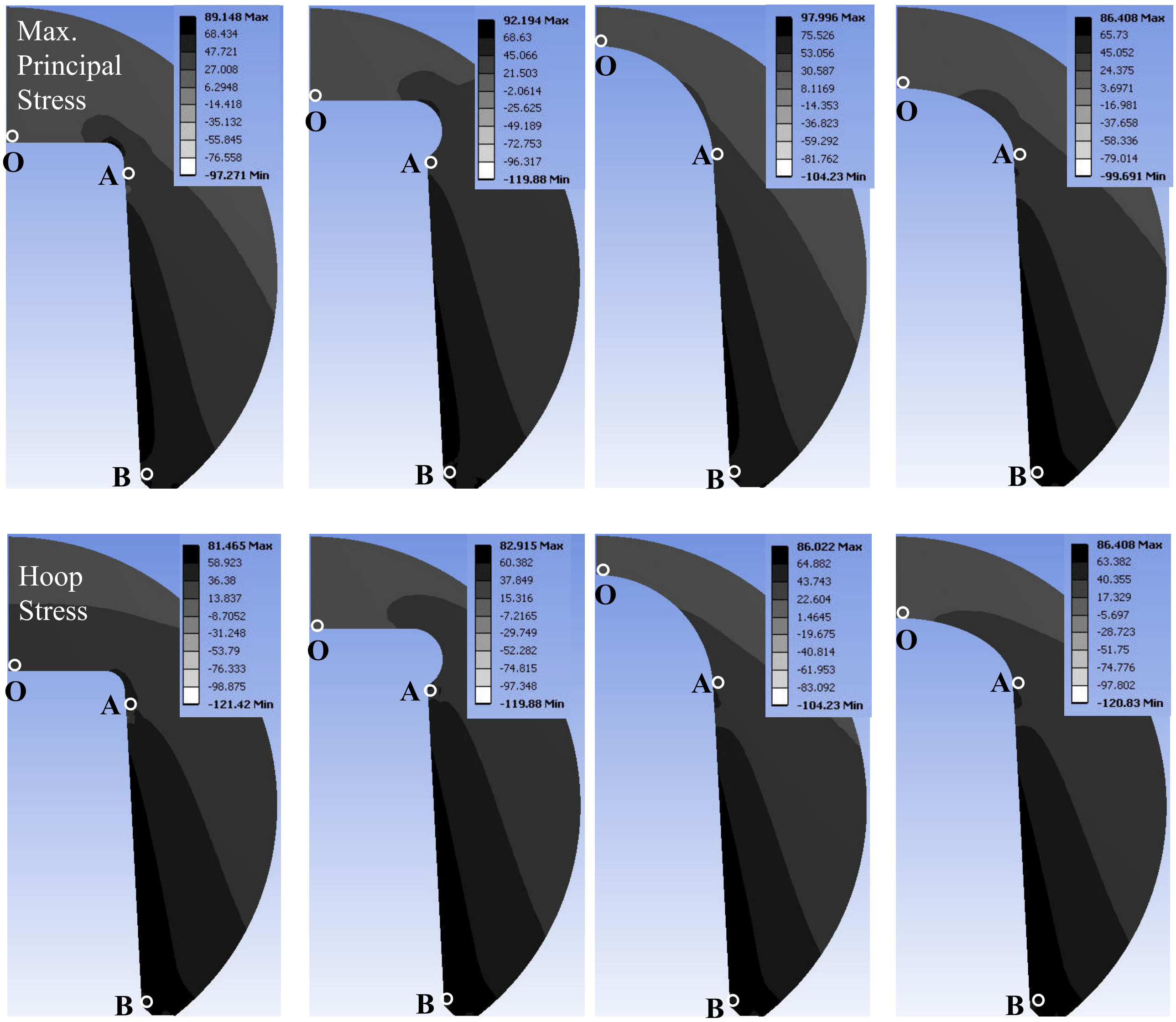
Fig. 2 Finite element model of the ISO 7206-5's test configuration

There are two interfacial contact regions with friction, one between the metallic stem taper and the ceramic femoral head (friction co-efficient, μ = 0.35) and the other between the femoral head and the cone support (friction co-efficient, μ = 0.30) [10]. The axial load applied is F = 14.2kN. This load magnitude is considered to be higher than the maximum physiological load that occurs in a human body femoral hip joint due to different moving activities such as walking and jumping [11].

Results and Discussion

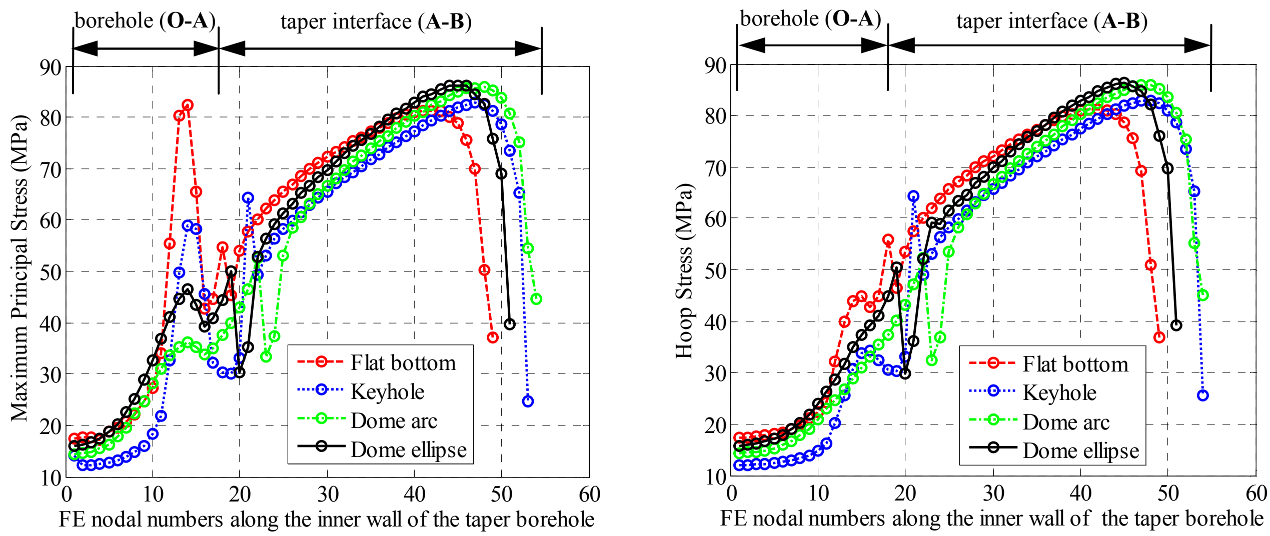
Due to the lower fracture strength limit of alumina, the most critical stress in a ceramic femoral head is tensile stress. Thus, in this paper, we focus on the distribution of the maximum principal stress and hoop stress.

Effect of Taper-borehole Shape. Figure 3 shows the contour plots of the maximum principal stress and hoop stress in the ceramic femoral heads with flat bottom, keyhole, dome arc, and dome ellipse borehole designs. To clearly interpret the results, the stresses are plotted along the running FE nodal numbers on the inner wall of the taper-borehole, starting from Point *O* to Point *B* as marked in the figure, where *O-A* indicates the borehole region and *A-B* the taper interface. Figure 4 shows the tensile and hoop stress profiles for all borehole designs. It is shown from Fig. 4(a) that a femoral head with a flat bottom or a keyhole has the critical local stress concentration (maximum tensile stress) in the borehole region, which may cause fracture of the heads. On the other hand, the femoral heads with dome hemisphere and ellipsoid do not have such notch stresses in the above region. This can be attributed to the larger filet and smoother transition between the dome and taper-bore. As can be seen in Fig. 4(b), the hoop stresses in all the borehole designs are quite high at the taper-bore interface (*A-B* in the figure). This is due to the almost same contact length and friction at the taper interface used in the tests for all the borehole designs. However, by determining an appropriate contact length and friction coefficient, stresses at the taper-bore interface can be reduced, which will be discussed in the following sections of the paper. From the above analysis, it can be seen that the new borehole shapes can potentially improve the mechanical reliability of the ceramic femoral heads in THR. As both the new designs are geometrically simple, they can be readily formed and fabricated by the machining processes available.



(a) Flat bottom (b) Keyhole (c) Dome arc (d) Dome ellipse

Fig. 3 Contour plots of stresses in ceramic femoral head with four borehole shapes



(a) Maximum principal stress (b) Hoop stress

Fig. 4 Stress profiles for ceramic femoral head with four borehole shapes

Effect of Stem and Taper-Borehole Contact Length. The taper-bore contact length H, as defined in Fig. 2, is important, which affects the stress distribution and mechanical reliability of a ceramic femoral head. In the current analysis, three taper-bore contact lengths are considered for the case of the femoral heads with the dome arc: (1) 100% contact length, (2) 75% contact length from the top of the taper-bore, and (c) 50% contact length from the top of the taper-bore. Figure 5 shows the maximum principal stress profiles along the inner wall of the taper-borehole. With the decrease of the contact length, the stress increases. This is due to the less contact area at the interface to withstand the applied load. A reduction of H by 50%, causes an increase in the maximum principal stress by about 11%, indicating that H should be as large as possible in the design of a borehole to minimize the stresses and hence to maximize the mechanical reliability of a ceramic femoral head.

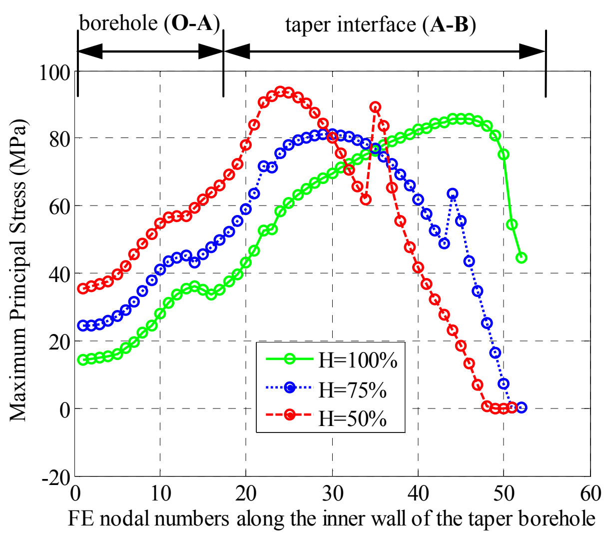


Fig. 5 Effect of stem and taper-borehole contact length

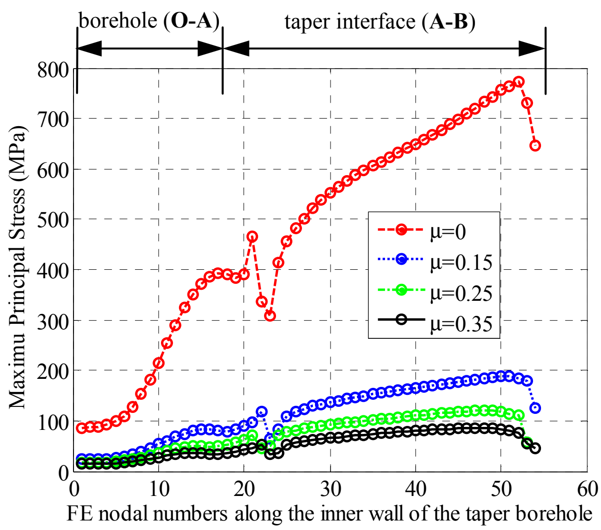


Fig. 6 Effect of friction at taper-bore interface

Effect of Friction. The interfacial characteristics such as friction is another factor which influences load transmission, and hence the stresses in a ceramic femoral head. Figure 6 shows the maximum principal stress profiles in the femoral heads (dome arc borehole) when the friction coefficient at the stem-bore interface changes while the friction between the ceramic head and the stainless steel cone remains constant ($\mu = 0.3$). The maximum tensile stress along inner wall of borehole becomes the highest when the stem-bore friction vanishes (i.e., $\mu = 0$). The increase of the stem-bore friction decreases the maximum tensile stress. When the friction coefficient at this interface reaches 0.35, maximum tensile stress along the taper interface reduces by a factor of eight. This means that an assembly of the stem and femoral head with a high friction is better.

Conclusions

This paper has carried out a stress analysis of ceramic femoral heads in hip joint prostheses by considering the design of borehole geometry, stem taper-bore contact length and the stem-head interface friction. It was found that the new borehole shapes introduced in this study, namely the dome arc and dome ellipse designs, can reduce the maximum tensile stress significantly and hence can enhance the mechanical reliability of the ceramic femoral heads. Because of their simple geometries, these borehole shapes can be readily manufactured with superior surface finish. It was also found that the stem taper-bore contact length should be maximized to minimize the stresses in a ceramic head and that a greater friction between the stem and the femoral head in the assembly of a hip joint prosthesis can reduce the magnitude of the maximum tensile stress in the ceramic femoral head and thus improve its mechanical reliability.

Acknowledgement

The authors wish to thank the Australian Research Council for its financial support to carry out the research work presented in the paper.

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Advances in Materials Processing IX
doi:10.4028/www.scientific.net/KEM.443

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