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REGULAR ARTICLE

Numerical Modeling of the Cracking Process in a Hip Joint Endoprosthesis

Belkacem Meddour*

Laboratoire d'Ingénierie et Sciences des Matériaux Avancés ISMA Department of Mechanical Engineering, Abbas Laghrour University, Khenchela, Algeria

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Based on the linear elastic fracture mechanics, the propagating crack within the cup of total hip prosthesis was studied in this paper. Because of good advantages of zirconia it was proposed as a material of the cup, in the other hand zirconia like all bioceramics has an important weakness which is fragility. To predict the cracking of the cup under given conditions, a prior defect was created within the cup in two different locations. The approach is lying on determining the stress intensity factor by using extrapolating method involving a numerical method of interpolating; moreover the size of the prior crack is incremented and a new calculation of the stress intensity factor the same procedure is performed. The procedure is repeated until reaching a supposed threshold equal to the toughness fracture. The numerical simulation was performed using finite element software Abaqus. The results showed good behavior of zirconia against cracking.

Keywords: Hip, Cracking Process, Toughness fracture, Zirconia.

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1. INTRODUCTION

The hip joint consists of the acetabular fossa and the femoral head, its main function is to provide dynamic support to the weight of the trunk as the same time permitting force and load transmission from the upper part of the skeleton to the components of lower limbs [1, 2].The anatomical complexity of allows to the hip joint to get a large mobility meanwhile it can be a target for several diseases like osteoarthritis, rheumatology and Infectious diseases [3, 4]. When the treatments are considered ineffective an expected joint replacement (total hip arthroplasty) is considered as the most effective way of treatment for patients suffering from joint diseases [5].

The malfunctioning hip joint is replaced by a prosthesis composed of an artificial acetabular cup and femoral head, which replace the injured natural articulating surfaces [6]. Currently four main types of bearing surfaces are studied and applied in Ttotal hip arthroplasty: metal-on-polyethylene, metal-on-metal, ceramic-on-ceramic, and ceramic-on-polyethylene [7].

Metal-on-metal bearing surfaces are associated with metal reactivity, which is a lymphocyte-dominated reaction to metal ions that may cause osteolysis one of hip joint diseases, stainless steel and metallic alloys have some disadvantages which could lead to post-operative pain (high weight compared to the human biological environment, significant thermal conductivity, possibility of oxidation by other agents which may exist in the human body).

Ceramic-on-ceramic (alumina or zirconia) bearing surfaces made of second-generation materials have a small risk of brittle fracture [8, 9].

Zirconia as a bioceramic is known by following properties making it a replacement material for both implants of the total hip prosthesis: significant compressive strength close to 6000 MPa; purity up to 95.6 %; fine grain size up to 1.5 µm; good surface roughness approximately 0.02 µm; weak thermal and electrical conductivities; significant hardness; high biocompatibility with the biological environment; good resistance to corrosion; lightness compared to metals (volume density ~ 6 g/cm^3).

On the other hand zirconia presents an inconvenience like most ceramics, which is the fragility, its fracture toughness is approximately ($K_{IC} = 7$ MPa·m$^{1/2}$) [11, 12].

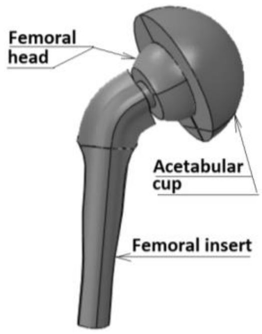

Fig. 1 – The total hip prosthesis

In this study we proposed zirconia as a material of the two implants (The cup and the Head). To investigate the mechanical behavior of zirconia to cracking we created a prior defect within the acetabular cup in three different areas (Fig. 1).

* Correspondence e-mail: samsum66@gmail.com

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The crack length is increased by a given increment ($p = 0.5$ mm) at every analysis until to reach the critical length. The used software of finite elements was Abaqus, after all necessary data were implemented we obtained results for each case of the study.

2. MATERIAL AND METHODS

The geometry and dimensions of the acetabular are given by Fig. 2.

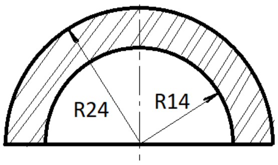


Fig. 2 – Cup dimensions

The subject is assumed to undergo a total hip arthroplasty. The femur with its resected head and the ilium supporting the acetabular cup are replaced by intermediate parts ensuring the transmission of stresses.

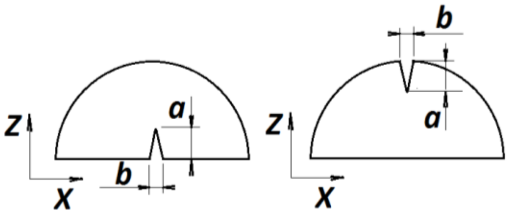


Fig. 3 – Locations of the prior crack

The dimension b was set to 0.5 mm in the three cases (A) and (B) and (C), in the other hand the initial dimension a was fixed to 0.5 mm and increased by 0.5 mm in the three cases.

The mechanical characteristics of each component of the total knee prosthesis are shown in Table 1.

Table 1 – Characteristics of materials

Component	Material	Young Modulus (MPa)	Poisson ratio
Femoral head	Zirconia	201000	0.31
Acetabular cup	Zirconia	201000	0.31
Femoral component	Stainless steel	197500	0.27
Illium	Bone	20000	0.33

The study is considered when the patient is walking and precisely when he leans on one foot and the other foot is free (Fig. 4). According to Pauwels [13], in this position, the head is subjected to 4 times the weight of the patient body. By assuming the patient weight is equal to 100 Kg, the weight to be considered consists of the whole body except the lower limb on which the patient is leaning [14].

The finite element used here is the quadratic tetrahedron C3D4, it is appropriate for complex geometries such implants ones. The mesh around crack tip, in the three cases, was refined to get accurate results.

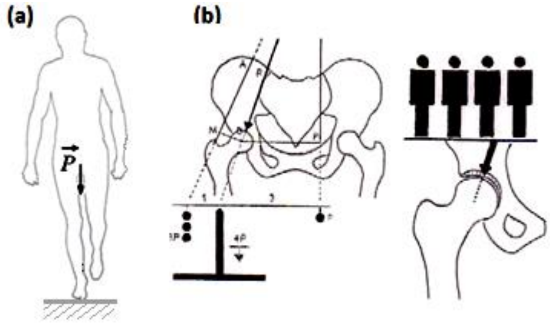


Fig. 4 – Load applied to the hip joint [13]

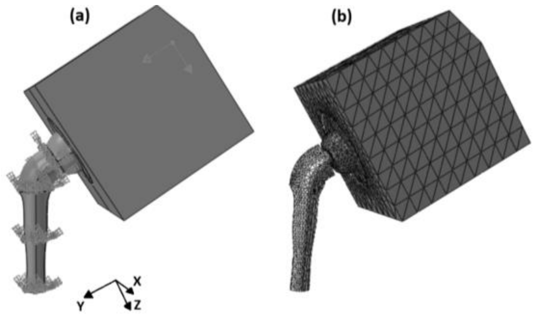


Fig. 5 – Load and boundary conditions (a) and mesh (b)

The failure occurs in one of the three following modes (Fig. 6).

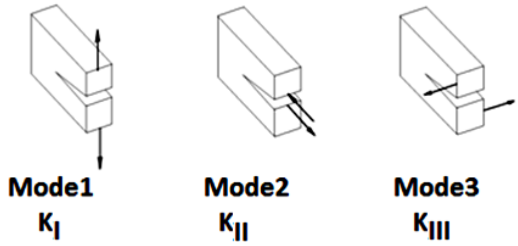


Fig. 6 – Modes of failure

The first mode, where the load is perpendicular to the plane through the crack, is considered to be the most dangerous one [15]. The stress intensity factor K_I is used to check the propagation of the crack and the relationship between stress and stress intensity factor is given by the following expression [16].

$$\lim_{r\to 0} \sigma_{ij}^{(I)} = \frac{K_I}{\sqrt{2\pi r}} f_{ij}^{(I)}(\theta) \qquad (1)$$

where:

$\sigma_{ij}^{(I)}$: Components of tensor of stresses in the xy plane in first mode.

r, θ : Polar coordinates.

$f_{ij}^{(I)}(\theta)$: Factor depending on the mode of solicitation, the stress state and the geometry of the cracked body.

The crack propagation will occur when the stress intensity factor K_I reaches a level (fracture toughness) K_{IC}

$$K_I = K_{IC} \qquad (2)$$

The stress intensity factor K_I could be determined by the extrapolation method [17, 18].

$$K_I(r) = \sigma_{ii}^{(I)}\sqrt{2\pi r} \qquad (3)$$

Writing $K_I(r)$, as an extrapolated function using Newton method 19], will give:

$$K_I(r) = K_I(r_0) + \frac{\Delta K_0}{h}(r - r_0) + \frac{\Delta^2 K_0}{2!h^2}(r - r_0)(r - r_1) + ... + \frac{\Delta^n K_0}{n!h^n}(r - r_0)(r - r_1)....(r - r_{n-1}) \qquad (4)$$

where:

r_i ($i = 0, n - 1$): Interpolating data points

$\Delta^j K_0$ ($j = 1, n$): Progressive finite differences

$h = r_j + 1 - r_j$: Distance between two consecutive data points

The data points are illustrated by Table 2.

The value of K_{IC} will be calculated at the abscissa ($r = 0$).

Table 2 – Number of data points used for extrapolating

Case of the defect location	Defect length (mm)	Number of data points
(1)	0.5 to 5.0	9
(2)	0.5 to 5.0	9

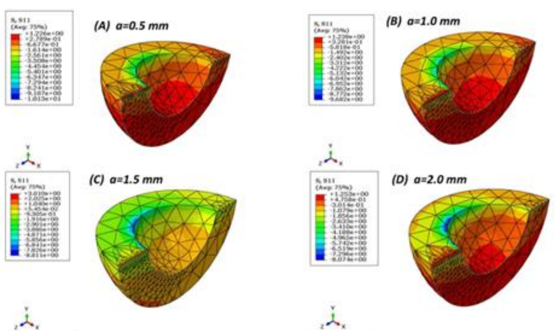
3. RESULTS AND DISCUSSION

3.1 First Case

The results in this case are shown by figures (7A to 7J), Fig. 8 and Fig. 9.

In this case it is observed in the pack of figures (Fig. 7A to Fig. 7J) that the maximum value of normal stress σ_{xx} is approximately equal to 3 MPa at crack length equal to 1.5 mm and it is almost equal 1.7 MPa in the remaining cases of the crack length. Fig. 8 is an extended investigation to previous results; it shows the evolution of the normal σ_{xx} along the perpendicular line to the crack plane. The different illustrated curves of the evolution of σ_{xx} show that the normal stress σ_{xx} is compressive along the line passing perpendicularly by the crack tip. Fig. 9 illustrates the evolution of the stress intensity factor K_I as function of crack length, it is almost zero, except for values of the crack length: 3.5, 4.0 and 4.5 mm where it reached 0.25 MPa·m$^{1/2}$ which is relatively lower.

It is observed overall that σ_{xx} is compressive in this configuration, therefore the stress intensity factor K_I is considered zero, hence the crack will not propagate.



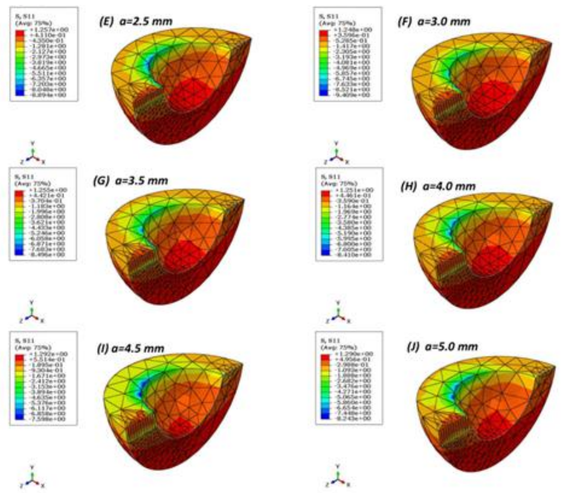


Fig. 7 – Distribution of normal stress σ_{xx} in the first case at different values of the crack

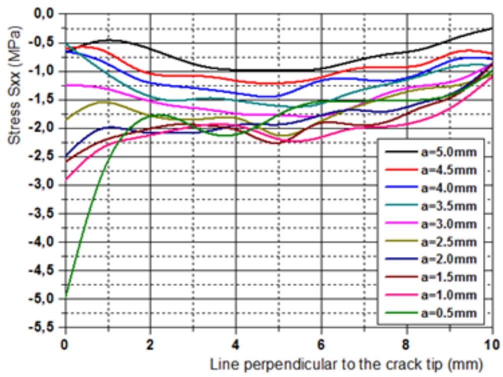


Fig. 8 – Evolution of the normal stress σ_{xx} on the perpendicular line to the crack tip at different values of the crack length in the first case

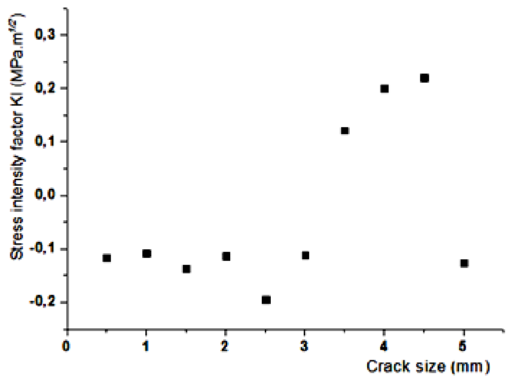
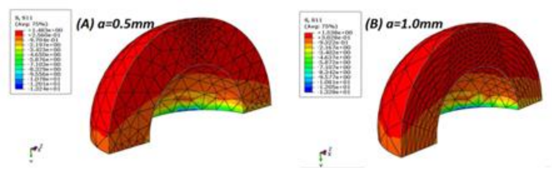


Fig. 9 – Evolution of stress intensity factor K_I vs crack length in the first case

3.2 Second Case

The results in this case are shown by figures (10A to 10J), Fig. 11 and Fig. 12.



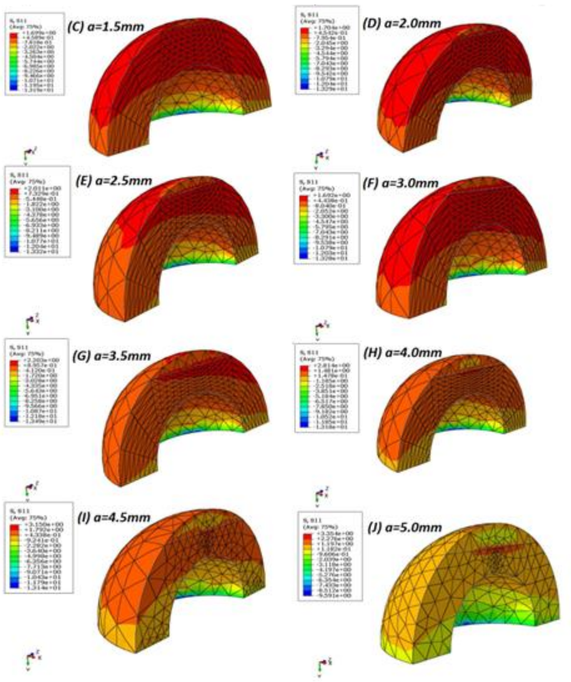


Fig. 10 – Distribution of normal stress σ_{xx} in the second case at different values of the crack length

Figures (10A to 10J) showed that normal stress σ_{xx} increased with the crack length, it reached the maximum value 3.35 MPa. Fig. 11 showed the evolution of σ_{xx} along

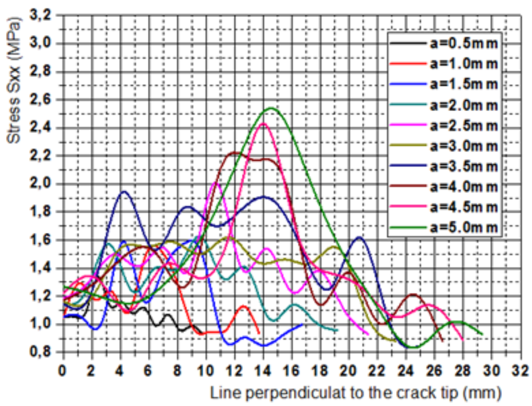


Fig. 11 – Evolution of the normal stress σ_{xx} on the perpendicular line to the crack tip at different values

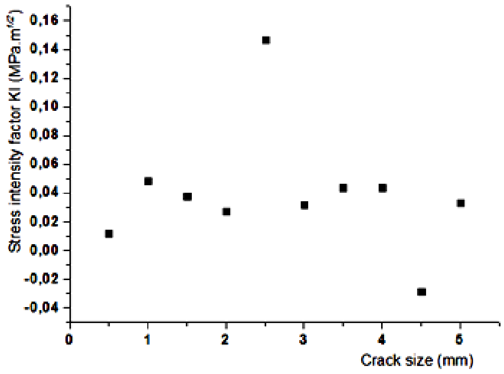


Fig. 12 – Evolution of stress intensity factor K_I vs crack length in the second case

the line passing perpendicularly by the tip crack, the peak is increasing with the crack length to reach the maximum value approximately 2.6 MPa at the value of 5 mm of the crack length and it is observed that the peak is located at the middle of the crack. Despite the positivity of σ_{xx} (extensive stress) its maximum value keeps being weak.

Fig. 12 illustrates the evolution of the stress intensity factor K_I, in this case it is observed weak values of K_I except for 2.5 mm it reaches a maximum value equal to 0.15 MPa·m$^{1/2}$ and it is almost zero for 4.5 mm. For all values of the crack size K_I is much lower than the fracture toughness (K_{IC} = 7 MPa·m$^{1/2}$), it could be said that mostly the stress intensity K_I factor is weak in this case consequently no crack propagation is expected.

4. CONCLUSION

In this work we considered the acetabular cup of the hip prosthesis, we proposed zirconia as its material because of its advantages but the main aim of this work was to reveal its strength to cracking for the reason that its main inconvenience is fragility. Two different cases of the prior defect location were considered. We used a software of finite elements, all necessary data were implemented. The numerical simulation was performed and for each case of defect location by increasing the defect size. The values of obtained stresses are close to those reported literature [20, 21]. Moreover the results relating to the stress intensity factor showed that the acetabular cup behaves well considering the loading severely applied. The values of the stress intensity factor through the paper were further from the fracture toughness of zirconia K_{Ic} = 7 MPa·m$^{1/2}$

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Чисельне моделювання процесу розтріскування в ендопротезі кульшового суглоба

Belkacem Meddour

Laboratoire d'Ingénierie et Sciences des Matériaux Avancés ISMA Department of Mechanical Engineering, Abbas Laghrour University, Khenchela, Algeria

На основі лінійно-пружної механіки руйнування в даній роботі досліджується процес розтріскування, який поширюється, всередині чашки протеза кульшового суглоба. Як матеріал чашки був запропонований цирконій, але він, як і вся біокераміка,крихкий. Для прогнозування розтріскування чашки за заданих умов, у чашці було створено попередній дефект у двох різних місцях. Підхід полягає у визначенні коефіцієнта інтенсивності напружень за допомогою методу екстраполяції, що включає чисельний метод інтерполяції; крім того, розмір попередньої тріщини збільшується, і виконується новий розрахунок коефіцієнта інтенсивності напружень за тією ж процедурою. Процедура повторюється до досягнення передбачуваного порогу, що дорівнює в'язкості руйнування. Чисельне моделювання було виконано за допомогою програмного забезпечення скінченних елементів Abaqus. Результати показали хорошу поведінку цирконію проти розтріскування.

Ключові слова: Протез, Процес розтріскування, В'язке руйнування, Цирконій.