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Numerical modeless of the damage, around inclusion in the orthopedic cement PMMA

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Abstract. In orthopedic surgery and more especially in total arthroplastie of hip, the fixing of the implants generally takes place essentially by means of constituted surgical polymer cement. The damage of this materiel led to the fatal rupture and thus loosening of the prosthesis in total hip, the effect of over loading as the case of tripping of the patient during walking is one of the parameters that led to the damage of this binder. From this phenomenon we supposed that a remain of bone is included in the cement implantation. The object of this work is to study the effect of this bony inclusion in the zones where the outside conditions (loads and geometric shapes) can provoke the fracture of the cement and therefore the aseptic lousing of the prosthesis. In this study it was assumed the presence of two bones –type inclusions in this material, one after we analyzed the effect of interaction between these two inclusions damage of damage to this material. One have modeled the damage in the cement around this bone inclusion and estimate the crack length from the damaged cement zone in the acetabulum using the finite element method, for every position of the implant under the extreme effort undergone by the prosthesis. We noted that the most intense stress position is around the sharp corner of the bone fragment and the higher level of damage leads directly the fracture of the total prosthesis of the hip.

Keywords: finite element method; bone cement; biomechanics; bony inclusion; damage parameter (length and area)

1. Introduction

The acrylic polymetylmetacrylate (PMMA) cement used in orthopedic surgery is considered the weakest link in the chain of load transfer implant-cement-cup. This material is primarily responsible of the life of the total hip prosthesis (THP). To increase the expected duration of THP, the study of the behavior of this material has become essential to improve the quality of this material. Several works treated the fracture and damage of the orthopedic cement like (Stolk *et al.* 2004) who studied the damage accumulation and creep in acrylic bone cement and Amos Race, Mann Musculoskeletal (2008) did some experiments about accelerated fatigue of cemented implant constructs using cadaveric bone with modified PMMA cement. We can add the works of (May-Pat *et al.* 2013) which treated the bolt clamping force effect on the mixed mode fracture

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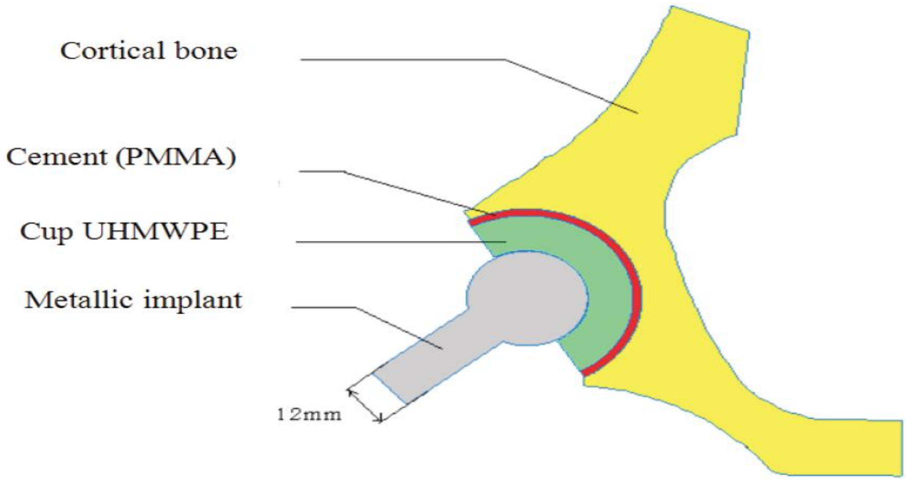

Fig. 1 Geometric model of the total hip prosthesis (Benbarek *et al.* 2013, Achour *et al.* 2010)

strength and stress intensity factor for an edge crack in PMMA specimen, also the work of Effect of the crack position in the cement mantle on the fracture behavior of the total hip prosthesis (Ouinas *et al.* 2010). The cement damage around inclusion and the interaction between two inclusions has not been treated previously. This work is a novel of its kind in the field of biomechanics, since we model the damaged area in the case of static loading and predict the crack length of the PMMA bone cement from a criterion of damage. In this study, we considered the existence in the cement two bone fragment of triangular shape. The calculation of the damaged area is for the three types of loading (0°, 25° and 50°) witch representing the human body postures, this damage is calculated using the finite element method, and a short FORTRAN script witch implement the damage criterion for each element and calculate damage area and one predict the length of the crack caused by the presence of this type inclusion.

2. Modeling

2.1 Model geometry

Model overview: Fig. 1 shows the two- dimensional geometric model of the pelvic bone cement, cup and stem head, which made the total hip prosthesis model Ting and Wong (2005). This model is close to the real structure of this human body part (Benbarek *et al.* 2013, Achour *et al.* 2010).

In this study we considered the existence in the cement of fragment's bone of triangular shape with a 7.071e-3mm^2 of area for each one (Fig. 2).

The positions of the defect in the binder are defined by its angles of orientation. This is obtained by rotation about the center of gravity of the inclusion one. Which means that the defect approaches the interface of the cup while increasing the θ rotation angle as shows in Fig. 3, in the three position of the implant (0°, 25°and50°) (Benbarek *et al.* 2013).

2.2 Material model

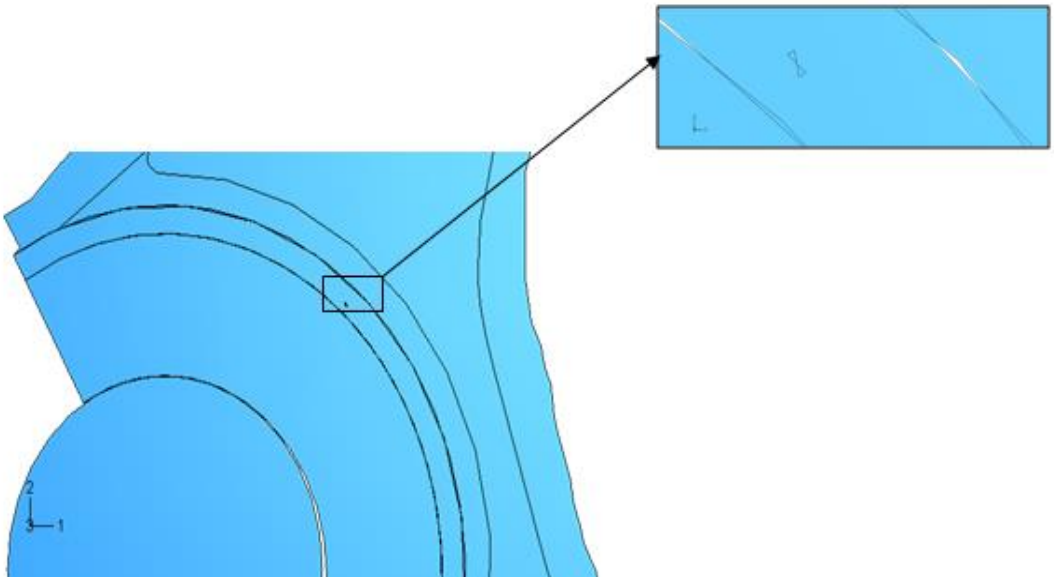

Fig. 2 Position and form of bone fragments in position cement interaction

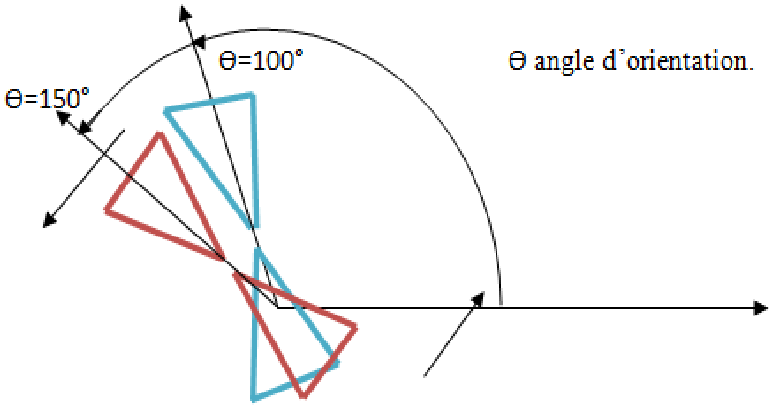

Fig. 3 Orientation of double the inclusions

PMMA is the most orthopedic cement used in total hip arthroplasty, it is brittle than the and the implant metal these it is the weakest link in the load transfer chain: bone-cement-prosthesis (Christipher *et al.* 2001, Poitout *et al.* 1997). Cements currently available have similar mechanical performance, the difference may appear in the literature are mainly due to variations in measurement techniques:

The average values usually published are (Benbarek *et al.* 2013, Merckx 1993, Bouziane *et al.* 2010):

* Young modulus 2000MPa
*fracture limit stress:
  * Tensile stress 25MPa

* Shear stress	40MPa
* bending stresses	50MPa
* Compressive	80MPa
* Deformation	5%
* Fatigue strength at 108 cycles	14MPa
* Toughness	1.03-2.32 MPa $\sqrt{m}$

PMMA is an elasto-brittle material in nature, cracks initiate after the Coalescence of micro cracks when the stress rice, this phenomenal is called the creasing. Several studies was conducted to understand the damage and fracture of the PMMA, among them we can find the study of GEARING.

2.3 Damage criterion implementations

We designed a program in FORTRON language for implementing the criterion of GEARING, the program calculates the damaged area from this criterion. This program tests the damage criterion for each elements, if this criterion is met (D>1), the program eliminates the stiffness of this element (the element whose criterion is reached remains undeformed).

Followings GEARING the PMMA is damaged when Gearing and Anand (2004), Oxborough and Bowden (1973):

1) The maximum principal stress and the average normal stresses are positive

$\sigma 1 > 0$, $\sigma = ½ (\sigma 1 + \sigma 2 + \sigma 3) > 0$

2) The maximum principal stress reaches a critical value dependent on the average:

$\sigma 1 \quad = \sigma 1$ or $(\sigma)>0$

$\sigma 1 \ (\sigma) = C1 + (C2/\sigma)$

$C1$ and $C2$: constants determined from the equation of criterion;

$\sigma 1 \ (\sigma) = C1 + (C2/\sigma)$

Where the constant are determined by the author himself:

$C1$ = 45.60 Mpa.

$C2$= 785.56 Mpa2.

2.4 The boundary conditions and mesh

There have been little studies about the forces acting on the pelvic bone (Flitti *et al.* 2013). Among them when choose (GRAFTING).

The boundary conditions are:

* The pubis is fully fixed,

* A nil displacement along the axis X=0 (unauthorized movement along X direction) on the wing of the Ilium,

* A uniformly distributed load of 20 Mpa Pustoc'h and Cheze (2009) amplitude applied to the implant (Fig. 4).

We opted for three orientations defined by inclinations 0°, 25° and 50°. They reflect the posture of the human body (Fig. 5).

The cement is an important element of the prosthesis. The refined mesh is therefore of great importance, we opted in our meshing strategy to the triangular element with six nodes for modeling the hip bone and an eight-node quadratic element for modeling the other components of

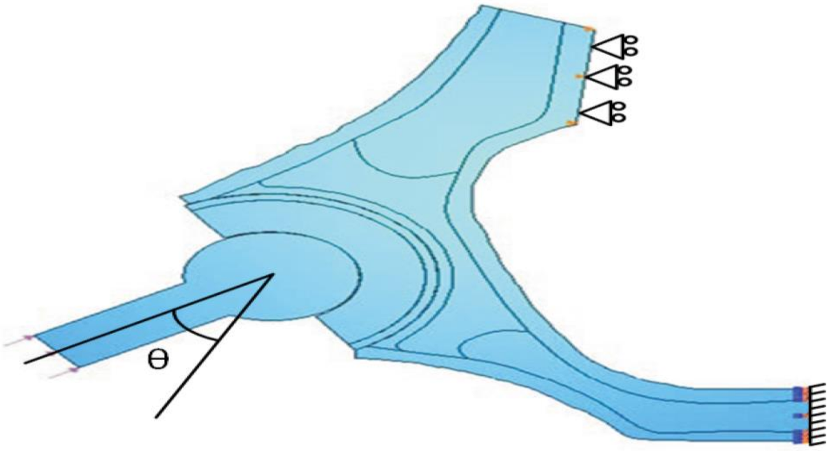

Fig. 4 Schematic of the boundary conditions imposed on the studied structure model

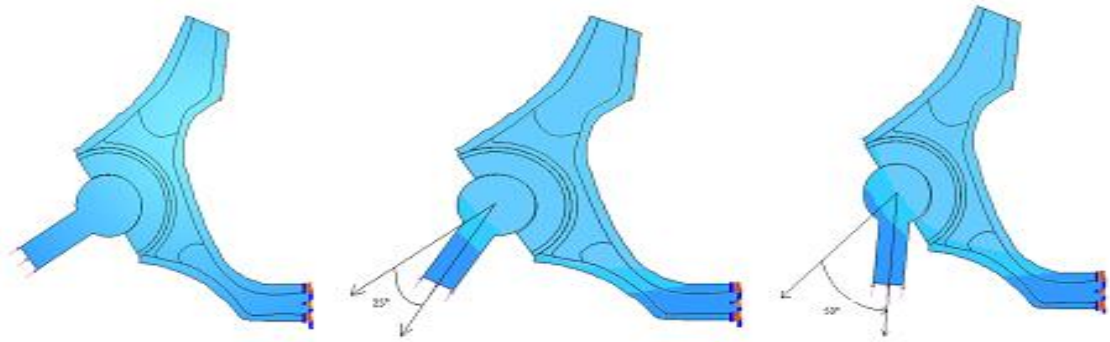

Fig. 5 The three positions of the implant

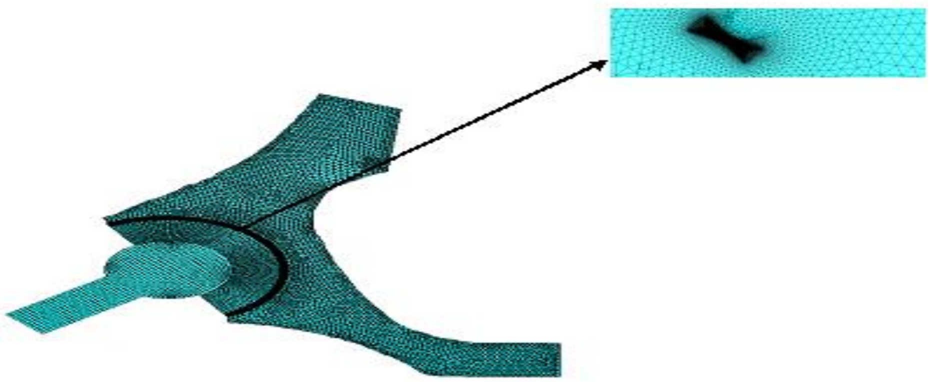

Fig. 6 The mesh of THP and around inclusions

the prosthesis. For both interaction inclusions, the choice of the mesh is taken as triangular element (Fig. 6).

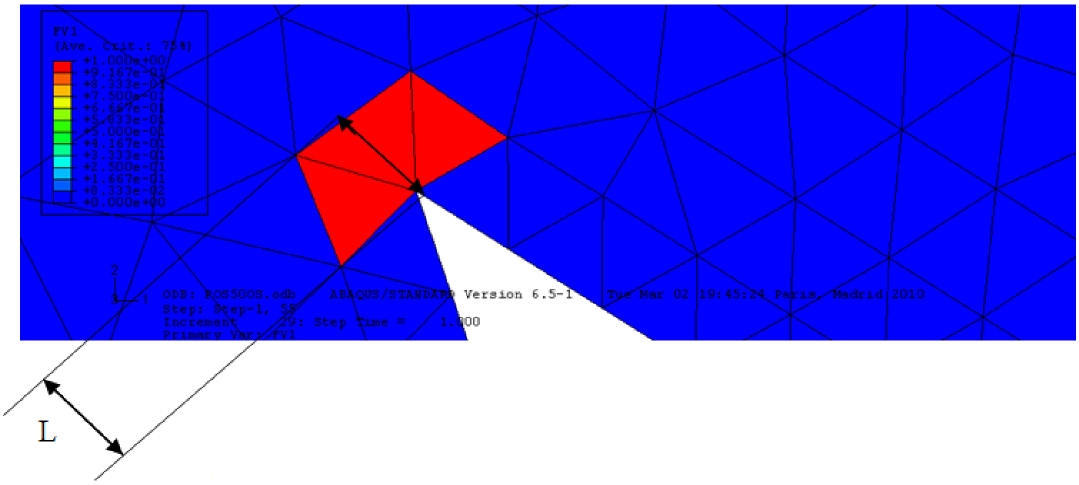

Fig. 7 The damaged area and crack length calculated for a single inclusion

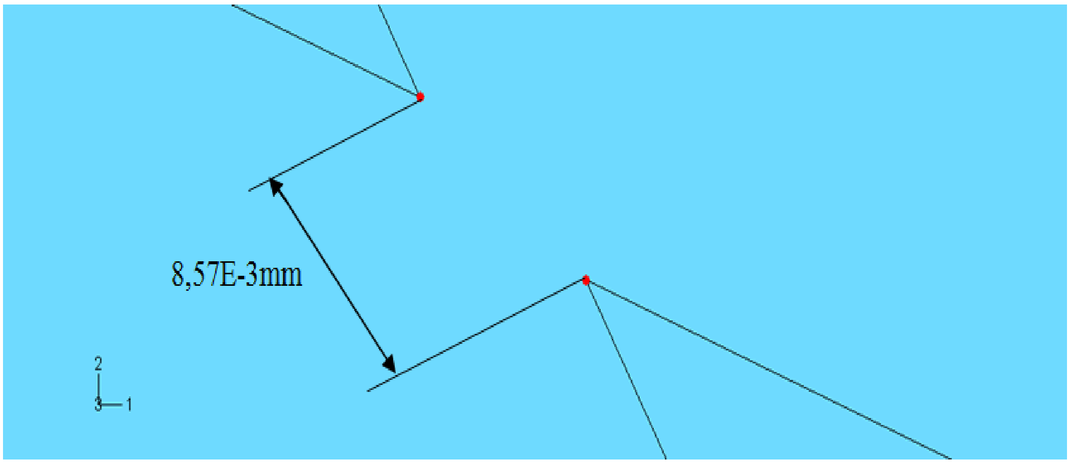

Fig. 8 Distance between two inclusions (interaction distance)

A very refinement was used with an advancing front meshing strategy to get the convergence of the numerical solution.

The mesh models include:

• 140000 quadratic triangular element which constitutes the cement part;
• 7150 quadratic triangular element which constitutes the bon part;
• 900 rectangular quadratic element which constitutes the implant;
• 1600 rectangular quadratic element which constitutes the cup.

2.5 The crack length estimation

The Fig. 7 is the schematic representation of the crack length estimation method.

The estimated crack length is taken between two points that belong to the perimeter of the damage area. One took the coordinate of two points and calculates the crack length.

L: estimated length of the crack

The calculation of the damaged surface is made, at first by a recording of the coordinates of the curve of the outline of the damaged zone; in continuation, we inject these coordinates in another program, which calculates this surface.

S : Area of the damage surface [μm^2]

The number of damaged element depends on the damaged area, which also depend on the geometric, material, and loading condition. The program stops damaging elements when the damage is not met. The number of damaged element can be calculated only after the analysis complete.

3. Analysis and results

3.1 Single inclusion results

3.1.1 Effect of the inclusion position on the damaged area (S) and the crack length estimation (L)

First we proceed to the modeling of damage around a single inclusion (inclined with 130°) for all the circumferential cement with the variation of the position of this impurity from 0° to 175°. The Figs. 9 and 10 show the variation of the damage area and the estimated crack length with respect to the position of the impurity in the cement and the stem orientation. Because the cement has a semi circular shape, we opt for a circular coordinate.

The results show that the highest values of these variations are obtained when this fragment of bone is positioned in the regions between 80° and 110° in all three positions of the implant. The max important damaged area registered can reaches 5.44 μm^2 and the max crack length found is 2.25 μm.

The other positions can lead to a weak damage level or not. indeed, this defect, when moving from 0° to 175°, produces a very low level of damage except for the three positions 80°, 100°, 110° where the crack length is important, which means that the break risk is higher if the inclusion

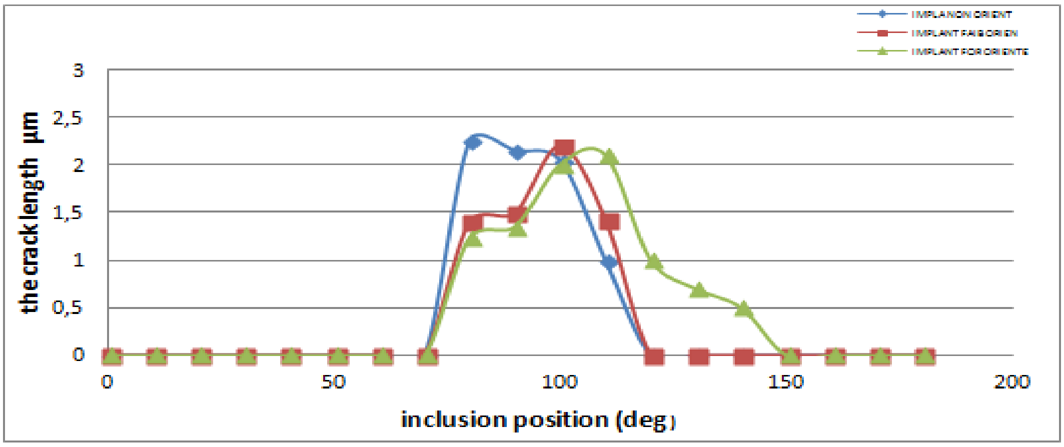

Fig. 9 The crack lengths *L* as a function of the position of the implant and inclusion

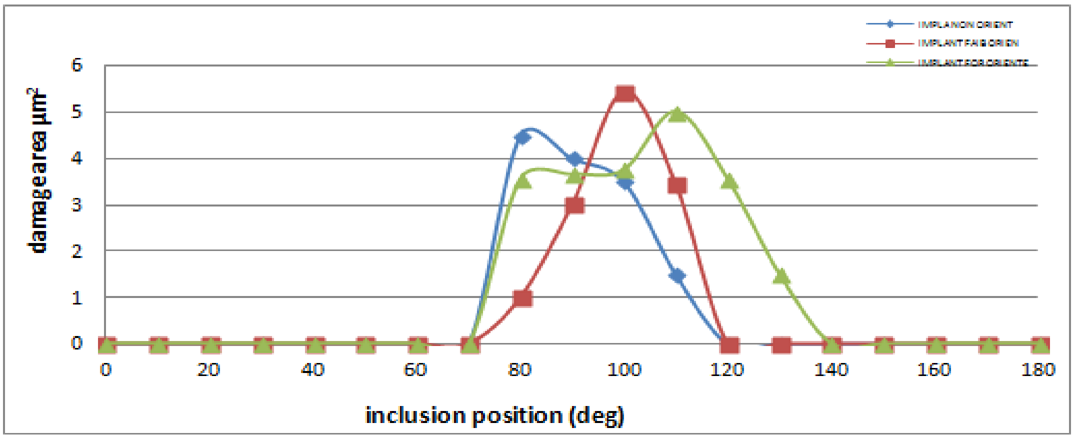

Fig. 10 The damage area *S* as a function of the position implant and inclusion

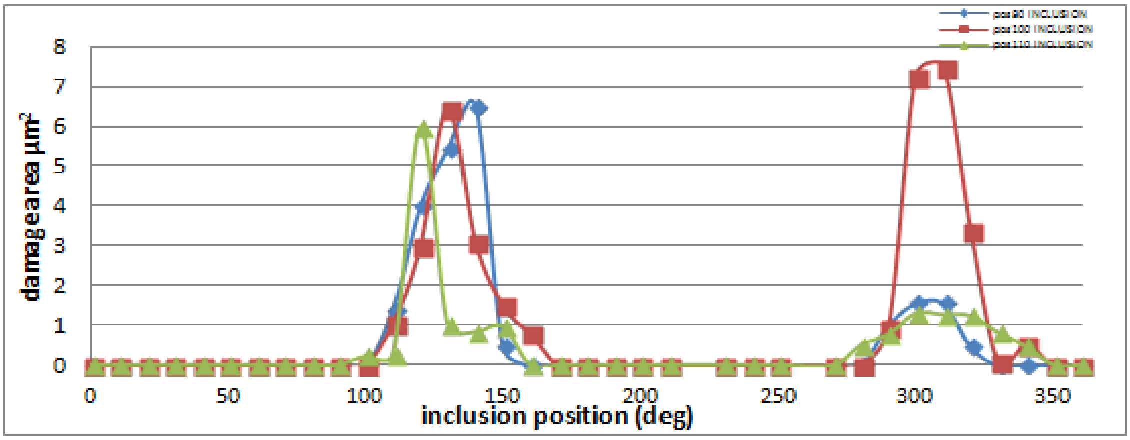

Fig. 11 The damage area *S* as a function of the inclusion orientation inclusion with pos 1

is in these three positions. They constitute a risk of losing the cement.

The presence of strange body in the cement promotes the loosening of the hip prosthesis. However, if a micro crack exists close to the body, it can lead to a breakdown of the cement.

3.1.2 Effect of the implant on the damage area of the cement:

The human posture (standing or sitting) influence the stress distribution of the cement, also the extreme human body position can provoke the fracture of the cement such as for example stumbling of the patient. To show this effect one conduct study on the influence of human body posture defined by the implant orientation Fig. 11, on the damage of the orthopedic cement.

The most intense values of damage are generated around the sharp angle of the triangle. When the defect is inclined in the range between 100° and 160° the damaged surface are between 6.45 $\mu m^2$and 1.38 μm as a crack estimated length, and when the defect is inclined between 300°and 360° one can find 7.5 μm^2 and from this area one can estimate a 1.38 μm crack length Fig. 12.

This orientation of the implant (pos2) leads to a decrease of these parameters whose intensity in

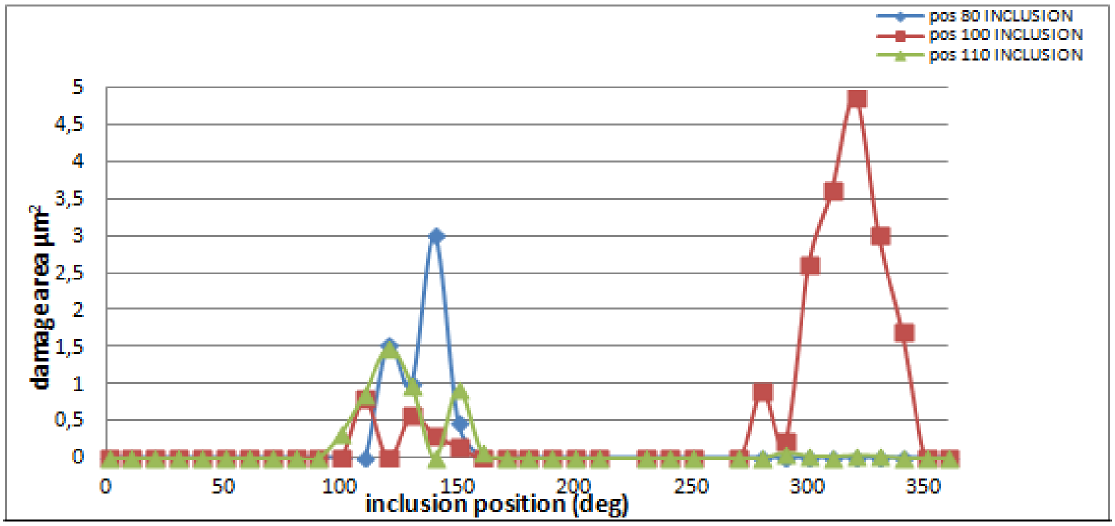

Fig. 12 The damage area *S* as function of the inclusion orientation, with the implant at pos 2

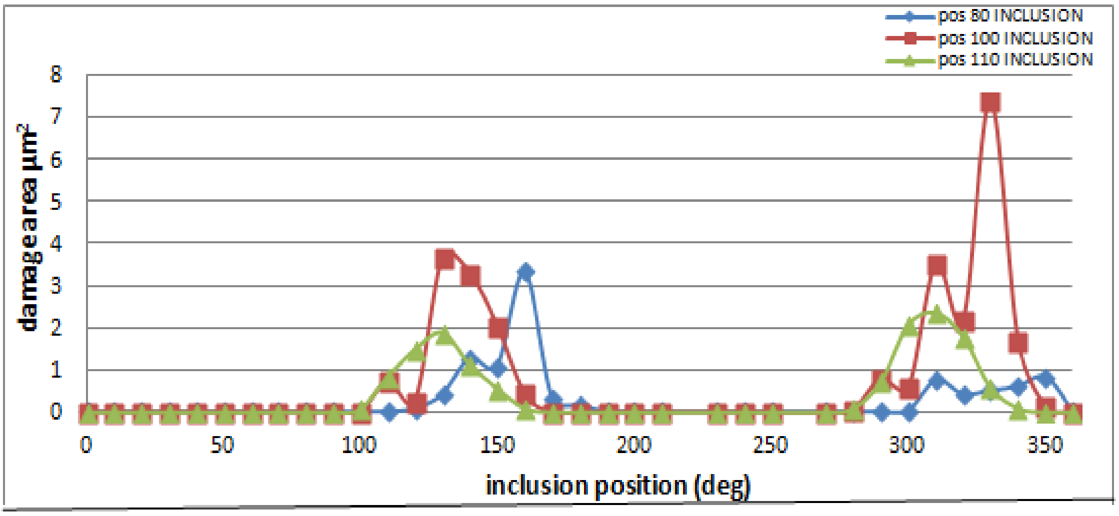

Fig. 13 The damage area *S* as a function of the inclusion orientation, with pos3

the vicinity of this body has maximum values when the inclination is from the position 110° to 150° to register a crack length of 1.38 μm and then fall to 0 μm. This reduction of damage shows that these positions do not expose to danger the binder. This curve continues on its way with a critical value of 4.86 μm^2 damage corresponding to the position 320°.

The analysis of this curve shows that the level of damage brand values larger than those of the second loading but comparable to the first load whose position corresponds to a significant damage, it is always in the case where the fragment bone is 100°. It's correspond to the orientations 130° to 160° and 310° to 330° with a maximum value at 330° which leads to a damage area of 7.4 μm^2 while recording a crack length of 2.4 μm (Fig. 13).

3.2 Doubles inclusions results

3.2.1 Effect of double inclusions on the damage parameters L and S

One has evenly analyzed the behavior of two inclusions interaction in the cement. The presence of the double inclusions in an interaction skill can be simulated as two bone fragment in the cement during the putting of the cement in-situ.

For this reason, the existence of two inclusions in the cement is considered, it have a triangular shape of 7.071e-3 mm^2. One opted for two interactions positions in the cement which are 100° and 110° Fig. 14 and for three implant inclinations as loadings condition. One analyzes the cement damaged and one estimate the crack length from the damaged area.

Fig. 15 gives an example of a damage area between two inclusions.

3.2.1.1 Position one of the stem

The obtained results are given on Figs. 8 and 9. These last show the damage variation thus the

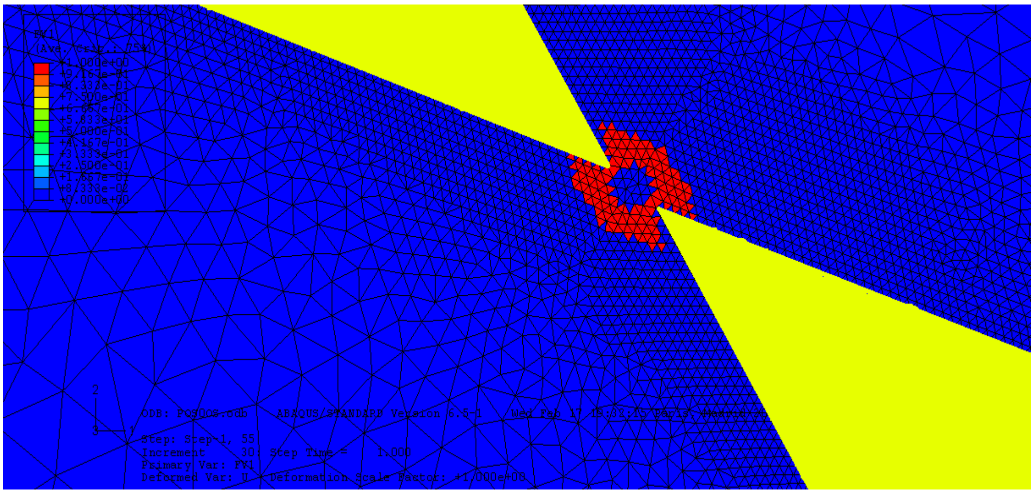

Fig. 14 Modeling of damage around the two inclusions

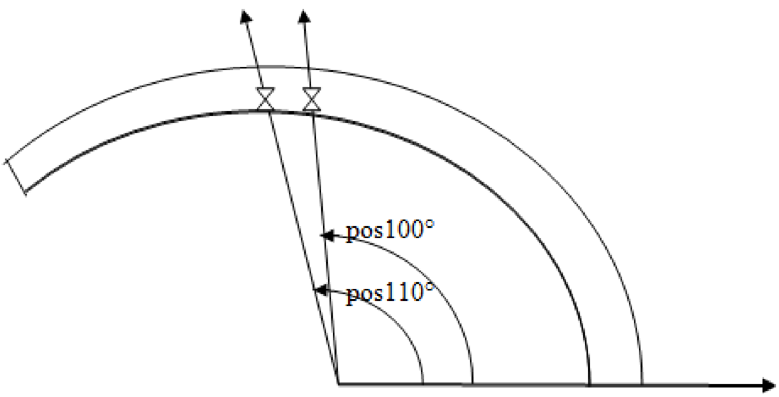

Fig. 15 The two positions of the interaction of the two inclusions

crack length estimation in the vicinity of the bone fragment in the orthopedic cement with respect to the inclination of the double inclusion.

Here is modeled the two positions 100° and 110°. Thus according to the results obtained from these two graphs, one can deduce that the damage and the crack, can't exist when the inclination of the double inclusion is between 0° and 110° and between 170° and 290°. There are two ranges for a probable damage, the first between 110° and 160° and the second between 300° and 350°. The important damage values can be found in these ranges especially at 320° orientation, which has a damage area of a surface of about 200 μm^2. Orientations that have a significant damage area correspond to an alignment of the two inclusions, with the loading axis. Thus, this behavior can be explained by the nature of the stresses generated around the inclusion which are essentially circumferential traction. The second range of orientations is the most important by its proximity to the cup-cement interface (Figs. 16 and 17).

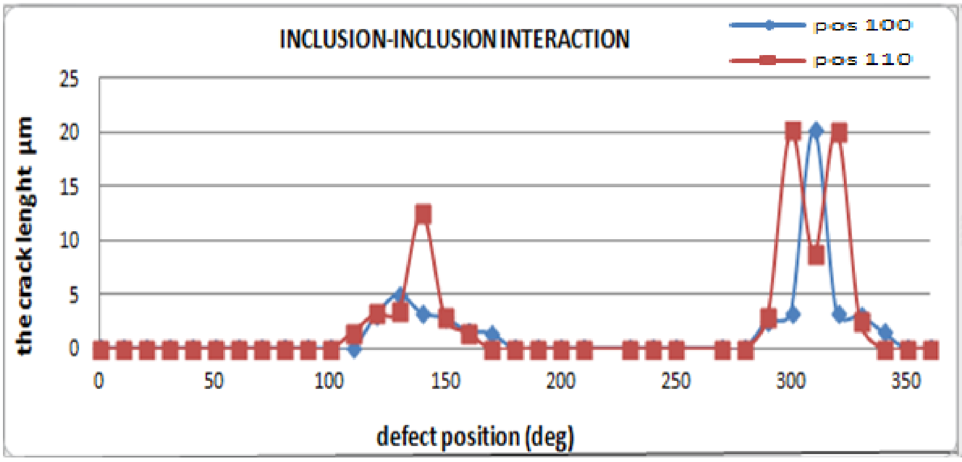

Fig. 16 The crack length variation with respect to the double inclusion orientation for the position one of the implant

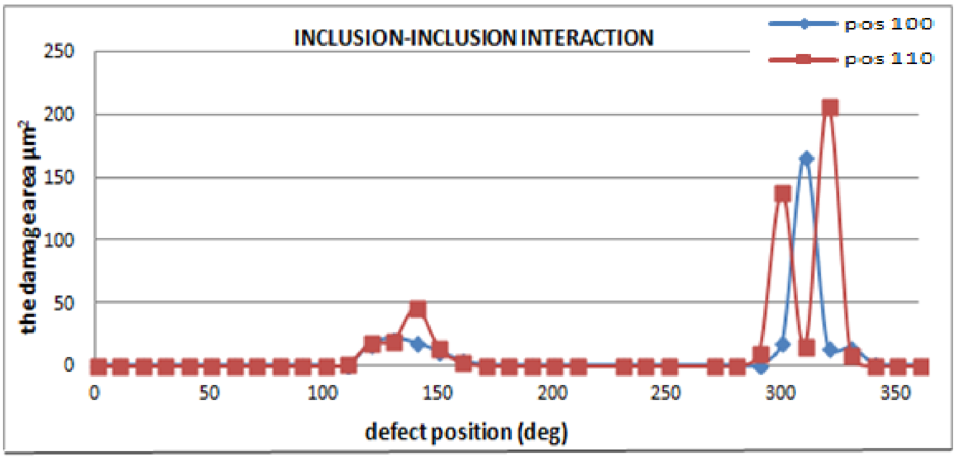

Fig. 17 The damage area *S* as a function of the orientation of the interaction inclusion-inclusion for the position one of the implant

After calculating the size of the damage area, the estimation of the crack length is carried out. The estimated crack length must be perpendicular to the maximum principal stress. For this reason the crack length is estimated perpendicularly to the orientation of the double inclusion.

One can also predict a cracks emanating from the tips of the inclusion and estimating their lengths. For purpose, four cracks emanating from two inclusions are considered and a single crack at right angles to the axis of orientation. Areas of damage are those that lead to crack initiation. Thus, we find that the lengths are important over the same areas of damage. A crack of 21 μm can be appears in the damaged area to an orientation between 300° and 330°.

3.2.1.2 Position two of the stem

We also analyzed and modeled the damage for small inclination of the implant (implant weakly oriented) Figs. 18 and 19, the results show that the size of the crack decreases compared with the

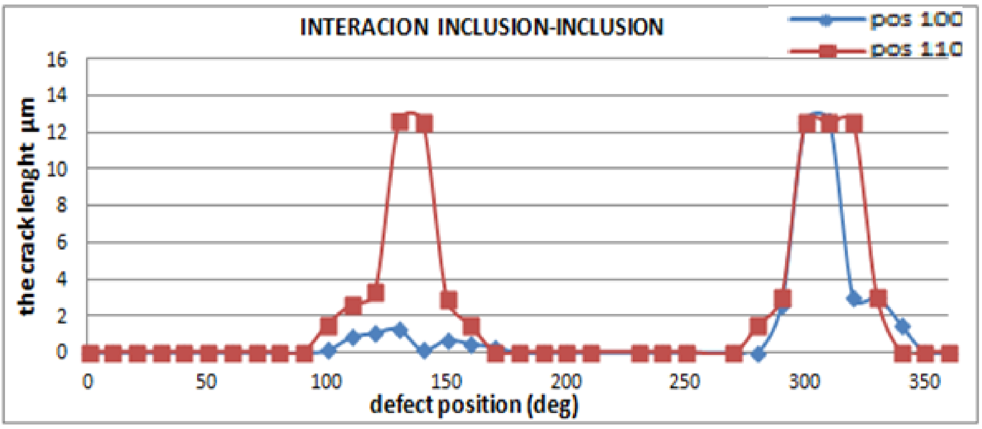

Fig. 18 The crack length *L* as a function of the orientation of the inclusion-inclusion for the position two of the implant

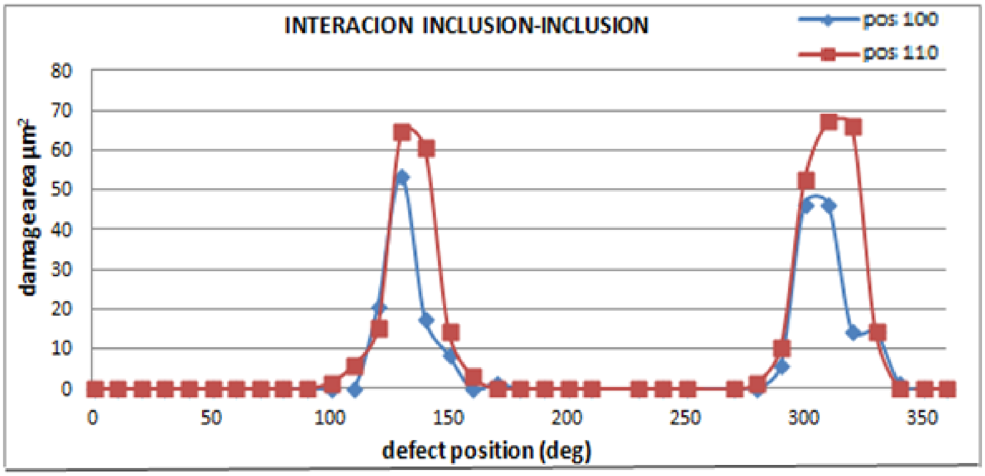

Fig. 19 The damage area *S* as a function of the oriented inclusion interaction, for the position two of the implant

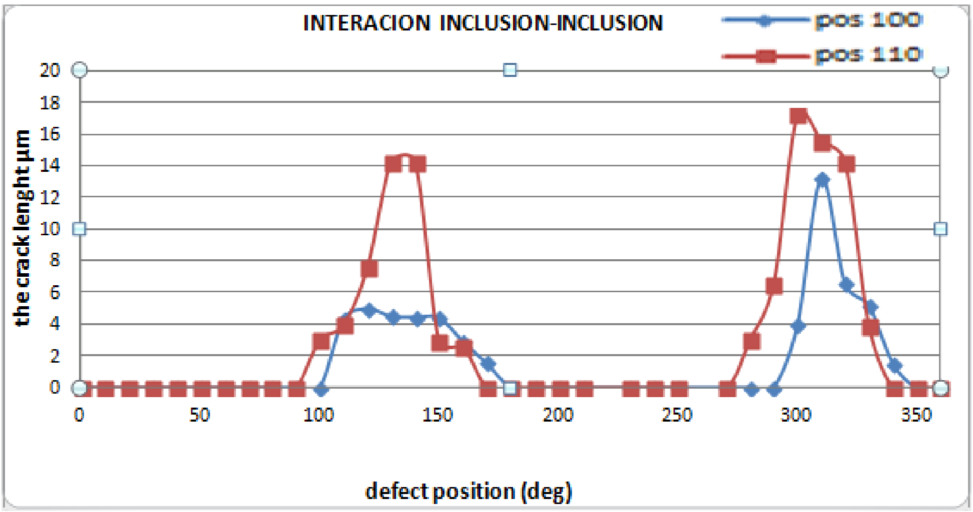

Fig. 20 The crack length *L* as a function of the orientation of the inclusion interaction, for the position three of the implant

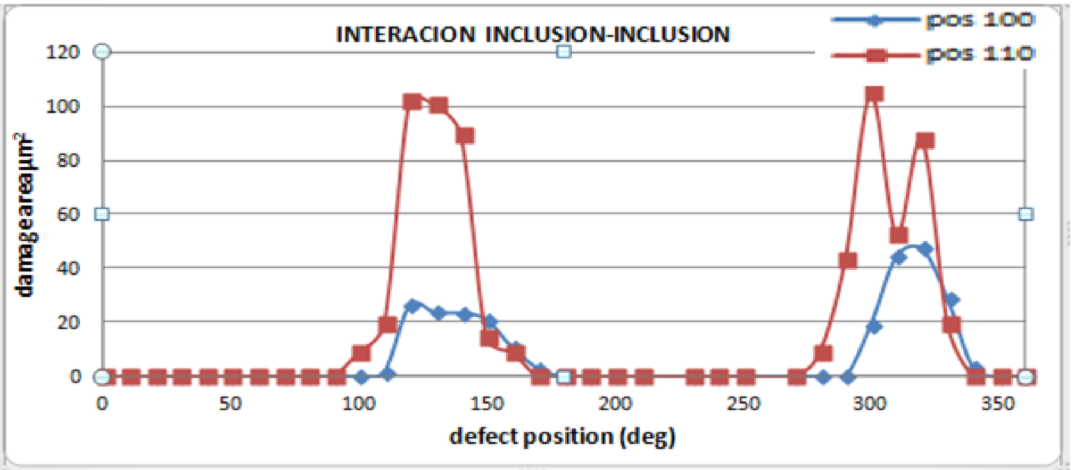

Fig. 21 The damaged area depending on the orientation of the inclusion-inclusion for the position three of the implant

first load, but with an enlargement the range of damage from 100° to 160°, and 280° to 330°, the maximum values of these parameters corresponds to the position of the double inclusion 110°, the five orientations of the double inclusions 130°, 140°, 300°, 310° and 320° give this time similar results, the crack length is approximately 13 μm taken a from damaged area of 65 μm^2. These values remain less than the first loading, but they still critical for the total hip replacement.

3.2.1.3 Position three of stem:

For third type of load corresponding to an inclination of 50° of the implant axis with respect to the axis of the cup, the cement is highly solicited such behavior causes an increase in the damage area.

A strong orientation of the implant with respect to the axis of the cup gives less damage than that resulting from an alignment with the axis of the implant and more important than the second loading, the maximum values always located for the double inclusion orientation of 110° Figs. 20 and 21. The position generates a very high stress field, which leads to damage for the orientations 120°, 130°, 140°,and 300° with an area of 104 μm^2 which generate estimated cracks between 8 and 17 μm close to the half value of the first loading. This position of the double inclusions increase the probability of failure of the binder and the expected danger in this junction mostly the material that provides adhesion between the implant and the cup, this risk is defined by high stress concentration, such a stress state leads to the creation of a damage area resulting in the formation of a network of cracks that developed in a single large crack.

4. Conclusions

The orthopedic cement (PMMA) is mechanically fragile. Indeed, the presence of a bone fragment in cement orthopedic disturbs the stress distribution in this least and can be the site of stress concentration that can cause crack initiation and the loosening of the prosthesis. This study was conducted to analyze using the finite element method, the damage and the computation of the size of cracks which may be created around the bony defect (inclusion-inclusion) in bone cement fixing the hip prosthesis. The results obtained allow us to deduce the following conclusions:

* The presence of an inclusion in pure orthopedic cement increases the stress around in this last and can provoke cement damage created as a network of micro cracks witch my growth to make a main crack.

* For a single inclusion the critical position corresponds to 100° and with an inclination of 320° for all the implant positions.

* For a single inclusion, the position one of the stem is the most important, the second position the lesser one. The case when the inclusion exist at the 100° position with orientations: from 100° till 140° and from 310° till 330° give the maximum values of the D parameter.

* For the case of the double inclusion:

*The damage is a function of the position of double inclusion (only two orientations which give substantial damage).

*The damage may be more important if the defect is close to the interface cup-bone cement (PMMA).

*The present study show that some founded cracks can be considered as macroscopic crack and affects the fracture behavior of bone cement.

*The nature of the load (the implant position) affects both parameters (damaged area and the length of the crack), and the position 110° of the defect is the one which gives the important values.

*The orientation of 110° is the one which present a reel danger on the system, the damage increases when the implant tends to be aligned to the cup axis and reaches the important damaged area of 207,8 μm^2 associated with a crack length of 20,23 μm corresponding to an orientation of 320°. This value is the most important in all our analysis.

*The damage depends on the position of the double inclusion two positions: 100° and 110° lead to significant damage.

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