Failure Risk of Crack Emanating from Microcavity in the Cement of Femoral Stem: Comparative Study Between External and Internal Parts

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Abstract: Femoral loosening is one of the most prevalent causes of revision orthopaedic surgeries. It may be related to the cement strength, cement-prosthesis and cement-bone interfaces. Interfacial porosity and within the cement arises from its shrinkage during curing and presents as pores randomly located along the stem. A comparative study between the internal and the external parts of femoral implant, to investigate the mechanical consequences of crack emanating from microcavity, by computing SIF $K_I$ and $K_{II}$ at the front crack emanating from porosity existing in different positions: within the cement mantle (PMMA), between implants/cement and bone/cement interfaces. The study concerns different zones of femoral stem: proximal, medial and distal. The extreme failure risk of cement mantle occurs in the distal zone of internal part by both opening and shearing modes.

Key words: Microcavities • Crack • FEM • Implant loosening • PMMA • Stress Intensity Factors

INTRODUCTION

In total hip Arthroplasty (THA), a metal stem should be securely fixed to the femur. Since, the original Charnley system was introduced, PMMA (polymethylmethacrylate) cement has been used successfully to fix the stem [1]; many studies have suggested improvements in modern cement techniques over the original cemented femoral fixation. However, some premature failures of cemented implants have been observed clinically [2-5]; aseptic loosening is still a dominant factor in mechanical malfunction of the stem-cement-bone system [6] and it is accepted as the primary reason for revision of cemented THR [7, 8]. The stem-cement interface has consistently been cited as a weak link and it contributes to premature failure of cemented THR [9, 10].

With respect to the variability of material properties, the most used type of bone cement is self-curing polymethylmethacrylate, or PMMA. Acrylic bone cement has two components, a solid one called polymethylmethacrylate (PMMA) powder and a liquid component (MMA), which are normally mixed. There are different mixing techniques that have a strong influence on the variation of the mechanical properties of the cement [11, 12]. Nevertheless, independently of the specific mixing technique, there is a large variation in fatigue properties of this type of cements [12]. The main reason of these differences is the pore distribution that appears in the cement mantle during the mixing procedure. Pores act as stress raisers, largely modifying the cement fatigue properties especially for the vacuum-mixed cement (Figure 1). The initial stability of the cemented hip stem...
Fig. 1: Microcavities presence in the cement mantle

and the number of cracks in the cement layer are considered important factors in determining the long-term clinical success.

Cement type and surface finish have been correlated with long-term failure associated with the formation of micro-cracks [13, 14]. Some studies have associated failure with the thickness of the cement mantle [15-17]. Other studies have focused on the development of composite stems to overcome some of the referred problems [18, 19].

Cemented hip Arthroplasty is subjected to cyclic loads, which sometimes lead to the mechanical failure of components of the implant system, with the subsequent long-term failure of the whole fixation. There are usually recognized four vulnerable regions: the cement-stem interface, the bulk cement, the cement-bone interface and bone [20, 21]. According to several experimental, theoretical and computational works [22], damage accumulation in the cement is considered the most important cause of long-term failure for the femoral component of cemented hip replacements.

Fracture of the cement mantle in cemented total hip replacements is often indicated as a precursor to eventual clinical loosening of the implant [23]. One factor that could affect the fracture toughness is porosity, although some investigators have suggested otherwise [24]. Since, pores have been identified in vitro as stress risers and crack initiators [25, 26]; higher degrees of porosity may contribute to microcracking [23, 27]. Generally, the cement rupture is caused by the accumulation of the cracks initiated from Microcavities and in different orientations (Figure 2) [28].

The present work focuses on, the comparison of the parts (A and B) basing on the stress intensity factors variation, of crack emanating from a microcavity, in different zones (proximal, medial and distal zones)

Fig. 2: Crack emanating from microcavity in the cement mantle

Finite Elements Analysis:
Geometry Model and Mesh: For this study, two-dimensional finite elements model of idealized stem-cement-bone cross-sections from the femoral side in the total hip Arthroplasty were developed. One analyzes

Fig. 3: femoral implant model
(Figure 3) and, in different positions (among the cement/implant interface, within the cement and among cement/bone interface) (Figure 4) of femoral implant.
Fig. 4: Different positions of microcavity a crack emanating from a microcavity in the cement mantle of THA. The diameter of the microcavity was assumed 200µm. Stress intensity factors (SIF) $K_i$ and $K_{ii}$ are calculated at the crack front, to evaluate crack risk in both parts (A and B). The whole model is subjected to a distributed compression loading of magnitude $F=30$ N [29] (Fig. 3). The crack length is considered constant in all cases of the study ($a=375$µm). $\alpha$ represents the crack orientations of a step angle of 15° (Figure 4). The behaviours of the constituent materials are linear and elastic. The mechanical properties are reported in the Tables 1 and 2.

Finite element analyses of cracked reconstruction were performed and stress intensity factors $K_i$ and $K_{ii}$ were calculated for each crack.

$$K_{\beta} = \frac{\sigma_y \sqrt{\pi a}}{f_\beta (\beta)} ; \beta = I, II$$  \hspace{1cm} (1)

Where:

- $K_{\beta}$ : Is the stress intensity factor (SIF) for mode I and II, with $\beta = I, II$;
- $A$ : Is the length of the crack;
- $\sigma_y$ : Are the stresses distribution near the crack tip;
- $f_{ij}$ : Is a dimensionless quantity that depends on the load and geometry [30].

Fig. 5: Model mesh; a) 2D FEM model; b) Crack emanating from microcavity;

The finite elements code ABAQUS 6.5.1 was used to analyze the effect of a crack existing in the cement mantle, eight nodded quadrilateral plane stress (CPS8R) were used for this analysis. The mesh parameters are also introduced in order to control elements size in various areas of THA (Figure 5).

**RESULTS AND DISCUSSION**

**Proximal Zone:** In this section, one focuses on the proximal zone. Figures 6 and 7 illustrate the results of SIF $K_i$ and $K_{ii}$ evolution according to crack angles. One realizes that, the presence of a crack in all positions (among cement-bone interface, within the cement and among the cement-implant interface) of proximal zone, conduct to different values of $K_i$ and $K_{ii}$ according to its’ orientations.

In the case of microcavity situated between interfaces (cement/stem and cement/bone) for both parts (A and B) (Figure 6), the SIF in mode I are positives. Thus, the two parts are solicited in traction. Moreover, the SIF $K_i$ takes positive values for crack orientations range $[0^\circ, -90^\circ]$ and are null for the remaining angles, contrary to the part (B) the SIF values are positive between $[0^\circ$ and $90^\circ]$. Therefore, when the part (A) is solicited in compression,
Table 3: Comparison of peak values of SIF for proximal zone

<table>
<thead>
<tr>
<th></th>
<th>SIF  ( K_1 ) (MPa.m(^{1/2} ))</th>
<th>SIF  ( K_\sigma ) (MPa.m(^{1/2} ))</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cavity between cement/bone interface</td>
<td>0.099 0.089</td>
<td>0.115 0.106</td>
</tr>
<tr>
<td>Cavity between cement/implant interface</td>
<td>0.094 0.093</td>
<td>0.118 0.118</td>
</tr>
<tr>
<td>Cavity within the cement</td>
<td>0.177 0.044</td>
<td>0.103 0.058</td>
</tr>
</tbody>
</table>

Table 4: Comparison of peak values of SIF in different positions

<table>
<thead>
<tr>
<th></th>
<th>SIF  ( K_1 ) (MPa.m(^{1/2} ))</th>
<th>SIF  ( K_\sigma ) (MPa.m(^{1/2} ))</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cavity between cement/bone interface</td>
<td>0.12 0.215</td>
<td>0.182 0.246</td>
</tr>
<tr>
<td>Cavity between cement/implant interface</td>
<td>0.123 0.192</td>
<td>0.574 0.645</td>
</tr>
<tr>
<td>Within the cement</td>
<td>0.12 0.157</td>
<td>0.182 0.101</td>
</tr>
</tbody>
</table>

For the shearing mode (Figure 7) the values are negative, be null then become positive. The maximal SIF are noted for the case of interfacial crack (oriented by 90º and -90º) for both parts (A and B). The difference of SIF values between the two parts is not marked, except for a microcavity within the cement in part (B) (Table 3).

Medial Zone: For the median zone, a comparative study between parts (A) and (B) is made, basing on the computation of SIF \( K_1 \) and \( K_\sigma \) of crack emanating from microcavity for different orientations (Figure 8 and 9). The Microcavities are located in three positions: cement/stem, cement/bone interfaces and within the cement mantle.

The results indicate that, the SIF \( K_1 \) values can be positive and null, explaining the closing and opening of the crack by changing its’ orientations (Figure 8). The peak values of SIF \( K_1 \) are noted in both parts (A) and (B), are respectively 0.12 and 0.216 MPa.m\(^{1/2} \), representing 45% of difference. Based on the results, the values of SIF \( K_1 \) of part (B) are important than the part (A) (Table 4).
Table 5: Comparison of peak values of SIF in different positions.

<table>
<thead>
<tr>
<th>SIF K_\text{II} (\text{Mpa.m}^{1/2})</th>
<th>SIF K_\text{II} (\text{MPa.m}^{1/2})</th>
</tr>
</thead>
<tbody>
<tr>
<td>Part A</td>
<td>Part B</td>
</tr>
<tr>
<td>Cavity between Cement/bone interface</td>
<td>0.252</td>
</tr>
<tr>
<td>Cavity between cement/implant interface</td>
<td>0.298</td>
</tr>
<tr>
<td>Cavity within the cement</td>
<td>0.177</td>
</tr>
</tbody>
</table>

For the shearing mode evolution (Figure 8), the case of a microcavity situated between cement/implant and cement/bone interfaces present the major risk of cement mantle rupture. The values are dominant in both parts (A and B) when the cracks are inclined by 90° and -90° (0.58 and 0.651 MPa.m^{1/2} respectively). The crack is interfacial for these angles, leading to an important shearing mode (Table 4).

**Distal Part:** In the distal zone, the evolution of SIF K_\text{I} and K_\text{II} values according to the crack angle are illustrated on the Figures 10 and 11.

The SIF K_\text{I} values of the part (B) are two times greater than the part (A) (Figure 10), for a microcavity situated between the two interfaces, by a difference of 45%. Except, for the case of a microcavity within the cement, we find that the part (A) presents the greater values; SIF K_\text{I} arise by 78%. The peak amounts are registered for a crack oriented by 45° and -45° in the part (B) (0.567 MPa.m^{1/2} for a microcavity located between cement/implant interface and 0.548 MPa.m^{1/2} for a microcavity located between cement/bone) (Table 5).

For the shearing mode (SIF K_\text{II}), the interfacial crack (crack angle between 90° and -90°) gives the maximum values. Consequently, it can provoke a relatively prominent risk of rupture. The shearing mode is particularly identical for both sides (part A and B). Except in the case of microcavity within the cement, the part (A) values arise by 43% comparing to part (B) (Table 5).

**CONCLUSION**

This paper has introduced a comparison of the external and internal parts of femoral implant. Based on the FEM, one calculated the SIF K_\text{I} and K_\text{II} of a crack emanating from microcavity, to predict the most dangerous zone or position that, can lead to the loosening of femoral stem. The orientations of the crack effect on the values of SIF K_\text{I} and K_\text{II} for all position and zones of femoral implant; the crack closes or opens depending on the crack orientations. The distal zone is the most influenced area in the femoral implant, representing the highest values of SIF. In the medial and distal zones, the risk of stem failure in Part (B) is the greater comparing to the part (A). The extreme damage risk of cement mantle is located in the distal zone of part (B) for both opening and shearing mode.
REFERENCES


