Analysis of the Behaviour of Crack Emanating From Microvoid in Cement of Reconstructed Acetabulum

B. Bachir Bouiadjra, S. Benbarek, M. Belhouari, T. Achour, , and B. Serier

Department of Mechanical Engineering, University of Sidi Bel Abbes,
BP 89, Cité Ben M'hidi, Sidi bel Abbes, 22000, Algeria

bachirbou@yahoo.fr, sma_benbarek@yahoo.fr, belhouari@yahoo.com, tarik_achour@yahoo.fr, boualems@yahoo.fr

Keywords: Cement, reconstructed acetabulum, microvoid, cracks, stress intensity factors

Abstract. In this study, the finite element method is used to analyse the behaviour of crack emanating from microvoid and ordinary crack in cement of reconstructed acetabulum by computing the stress intensity factor at the crack tip. In order to predict the crack initiation location, the stress distribution around the microvoid is computed under three load cases. From stress results, one can note that there is a great risk of crack initiation in radial direction. From stress intensity factors computation, this same orientation is the dangerous because the mode I stress intensity factor is the higher in this direction. From comparison results on can see clearly that crack emanating from microvoid is most dangerous, and the difference in the stress intensity factors between the two cracks change with the crack inclination and this difference is constant for three load cases.

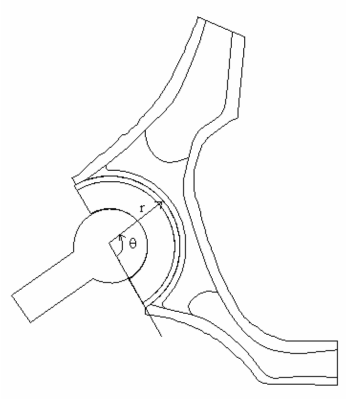
Introduction

Polymethylmethacrylate (PMMA) is an acrylic polymer used to fixate many designs of load-bearing implants, including orthopedic implants for the hip, knee, shoulder, etc. Loosening of cemented implants usually is caused by mechanical failure of the PMMA bone cement under cyclic loading. Studies of model implants under bending and torsion [1] have shown that mechanical failure can occur by a gradual process of damage accumulation in the form of the initiation and propagation of numerous microcracks from pores within the bulk cement mantle and on the cement/bone and cement/stem interfaces. Microcracking in acrylic bone cement has two main consequences: First, the mechanical integrity of the cement mantle is lost, causing direct loosening of the implant, and second, PMMA particles may be created by abrasion of crack surfaces, and these particles may react with the surrounding tissue, causing an inflammatory response leading to osteolysis and prosthesis loosening. If the functional lifetime of cemented joint replacements is to be further extended, the durability of the cement mantle must be improved; and for this, a deeper understanding of the factors determining the damage accumulation process in acrylic bone cement is required. Fatigue damage accumulation must occur in bone cement *in vivo;* this is known from analyses of cement mantles retrieved postmortem because microcracking was present in all retrievals implanted for more than 3 years [2]; the presence of striations on the fracture surfaces confirmed that microcracking was caused by fatigue. Methacrylic bone cements are prepared in the operation theatre, from a powder consisting of polymethylmethacrylate (PMMA) and an initiator, and a liquid component, generally methylmethacrylate (MMA) (or a mixture of MMA and butylmethacrylate) [3]. Mixing of powder and liquid, results after a few minutes in a mouldable material, which is, injected into the femoral channel. This is followed by implantation of the femoral stem and the subsequent self-curing of the cement results in anchoring of the prosthesis [4,5]. Cement specimen

realized in laboratory and radiographied shows well that it is about a porous material which contains a variable volume of bubbles.
Origin of these pores is double: introduced air into cement when mixing and specially a volatile monomer that not participate to polymerisation.
Mixing is carried out under vacuum to prevent the entrapment of air bubbles that would weaken the cement. However, significant porosity is always present in set material produced by polymerisation shrinkage [5]. Porosity seems to be a determining factor of the cement mechanical performances. Merckx [5] affirms that it affects primarily the tensile strength, that is already a weak parameter of cement, and with fatigue, what compromises its long-term stability. The study of crack behaviour in cement mantle is then necessary to predict the life span of cemented reconstructed acetbulum.
The aim of this study is to analyse by the finite element method the behaviour of cracks emanating from microvoid and ordinary cracks. The stress intensity factor at the crack tip is used as fracture criterion.

Geometric and Finite element model

The model was generated from a roentgenogram of 4mm slice normal to the acetabulum through the pubic and ilium. Fig. 1 presents the geometrical model. The inner diameter of the UHMWPE cup is 54mm and the cement thickness was taken as 2mm [6]. Crack of 0.375mm of length is supposed to exist in the cement mantle. Two configurations of cracks are studied, firstly a crack emanating from microvoid with 0.2mm of diameter and secondly an ordinary crack located at θ=100° (Fig. 1). The model was divided in to 8 regions (Fig.2) of different elastic constants with isotropic material properties assumed in each region. The main regions were cortical bone, subchondral bone and spongious bone [7]. The femoral head was modelled as a spherical surface that was mated with congruent spherical acetabular socket. Tables 1 contain material properties of cement, cup and all sub-regions of acetabulum bone.



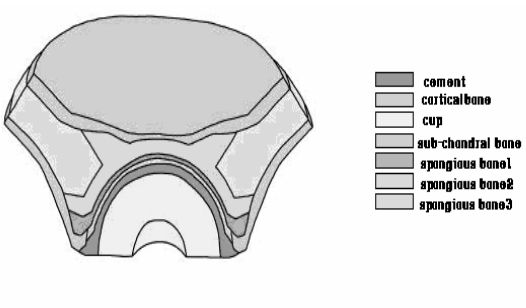


Figure 1: Cylindrical coordinate system(r,θ). Figure 2: Composition of a reconstructed acetabulum.

The acetabulum was modelled using finite element code Abaqus [12]. In order to simplify the study the 2D model of acetbulum was considered. Plane stress approximation was used. This 2D representation was used to be representative of a cut taken thought the transverse plane of the acetabulum. Bergman et al [8] found that the variation of the resultant forces acting of the acetabulum was greatest in the transverse plane. A very high descritisation were used with an advancing front meshing strategy to represent as possible the reality, and a focused mesh was used near a crack tip. Fig. 3 show the finite element model.

Materials	Young modulus E (MPa)	Poisson ratio ν
Cortical bone	17000	0.30
Sub –chondral bone	2000	0.30
Spongious bone 1	132	0.20
Spongious bone 2	70	0.20
Spongious bone 3	2	0.20
Cup (UHMWPE)	690	0.35
Cement (PMMA)	2300	0.30
Metallic implant	210000	0.30

Table: Material properties.

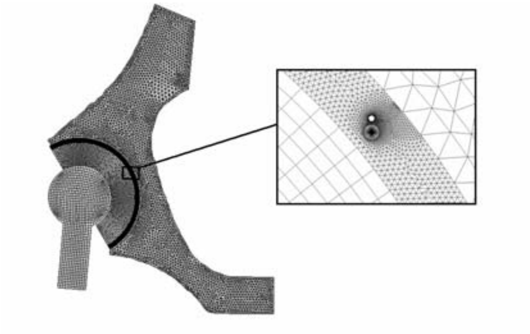


Figure 3: Mesh model.

There has been a limited amount of research carried out into loading distribution acting on the acetabulum caused by the transfer of force from the femoral head. Three selected load cases were used with an average body weight of 70 kg assumed. The sacroiliac joint was fully fixed while the pubic joint was allowed to in sagittal plane, boundary conditions considered to be representative of anatomic configuration [8]. The contact between bone and cement and between cement and cup was taken as fully bounded, and between femoral head and cup was assumed to be frictionless under small sliding condition (Fig. 4-6).

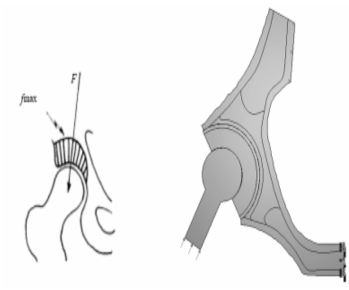


Figure 4: Load type 1.

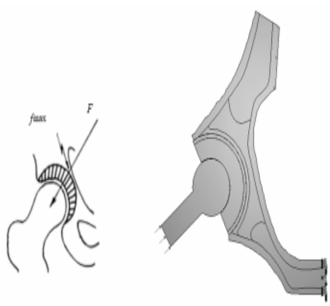


Figure 5: Load type2

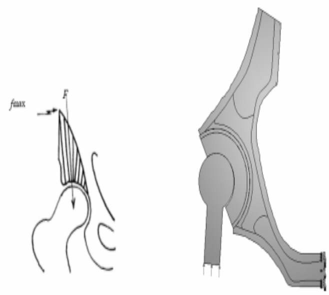


Figure 6: Load type3

Analysis and results

Before analysing the stress intensity factor at the crack tip, it is necessary to analyse the stress distribution around the microvoid without crack in order to predict the crack initiation location. The following notation are used for the stress: radial stress (σ_{rr}), angular stress ($\sigma_{\theta\theta}$) and shear stress($\sigma_{r\theta}$). Fig.7 present the distribution of the radial stress around the microvoid for the three load cases. It can be seen that the stress distribution was not uniform around the microvoid. It is also noted that there is tow peaks of compressions and tow ones of tensions. Compression peaks can reach 16MPa and those of tension reaches 3MPa. Without microvoid, The stresses lies between -2MPa and -7MPa. The cement without microvoid is subjected to compressive stresses. The risk of crack initiation is then higher with the presence of microvoid. Fig.8 present the distribution of the angular stress around the microvoid for the three load cases. The Stresses level are very important, they can reach 17MPa, what permit us to conclude that the risk of crack initiation is higher according the radial direction. Without micrvoid stresses in cement lie between 0.1 and +6MPa. Thus with the presence of microvoid the angular stresses almost increased 3time. What show the dangerous effect of microvoid. Fig. 9 present the distribution of the shear stresses($\sigma_{r\theta}$) around the microvoid for the three load cases. It is noted that the shear stresses lie between -4MPa and +5MPa. The risk of crack initiation by shearing is then lower.

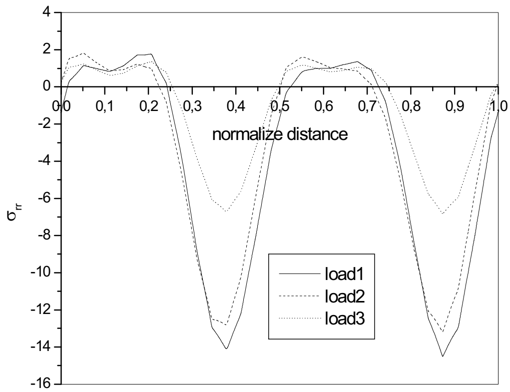


Figure 7: Distribution of radial stresses along inner microvoid edge

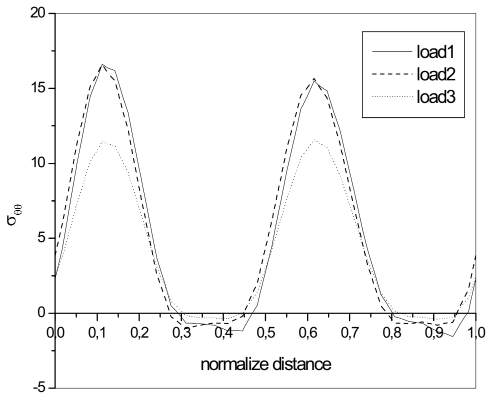


Figure 8: Distribution of circumferential stresses along inner microvoid edge

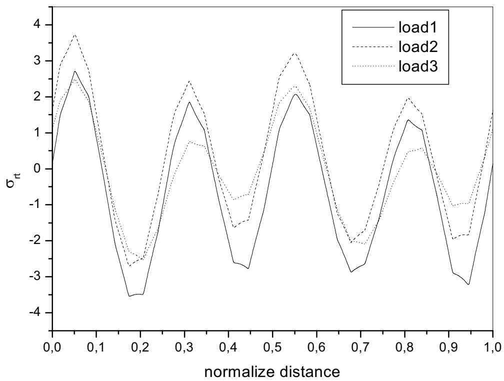


Figure 9: Distribution of shear stressesalong inner microvoid edge

The behaviour of a crack emanating from microvoid

Fig.10 and 11 represent computed stress intensity factors (K_I, K_{II})of crack emanating from micrvoid for the three load cases as function of the crack inclination in the cement mantle. One notice for the three load cases the stress intensity factors have positive values when the crack orientation lies between 0° and 100°, the other inclinations gives negatives K_I values. The K_I at the crack tip have a lower value when the crack inclination is 0°(horizontal position), it reaches the Maximum value α=45°. The risk of crack propagation is high according this orientation. K_{II} is less important between 0° and 70° and it is more important between 70° and 90°.

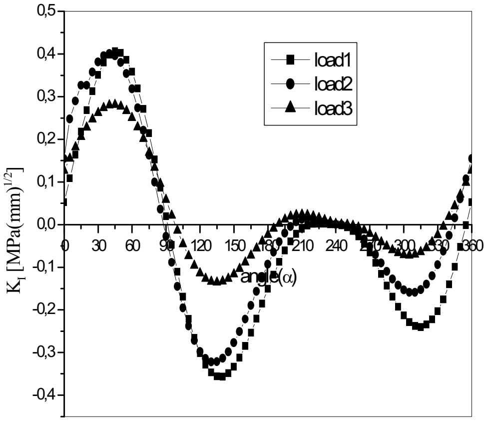


Figure10: Variation of K_I vs α.

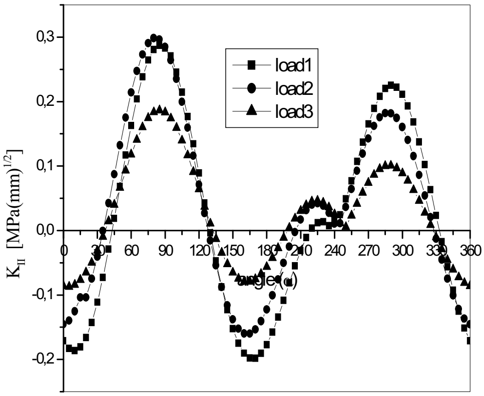


Figure11: Variation of K_{II} vs α.

Comparison between crack emanating from microvoid an ordinary crack:

Fig.12 and Fig.13 represent the stress intensity factors (K_I, K_{II}) for both, crack emanating from microvoid and ordinary crack. One notice that the behaviour remains the same for both type of cracks. It is clearly showed that the stress intensity factors for crack emanating from microvoid is higher than the ordinary crack. One noted that both cracks under all loading cases have the same mode I stress intensity factor K_I for α=10°, 85° and 245°, and for the mode II stress intensity factor K_{II}, theses orientations are α=45°, 125° and ≈243°. K_I and K_{II} are approximately null for crack inclination equal to 245° and 243°. It is also noted that the difference in the stress intensity factor between the two crack remain constant whatever the load case.

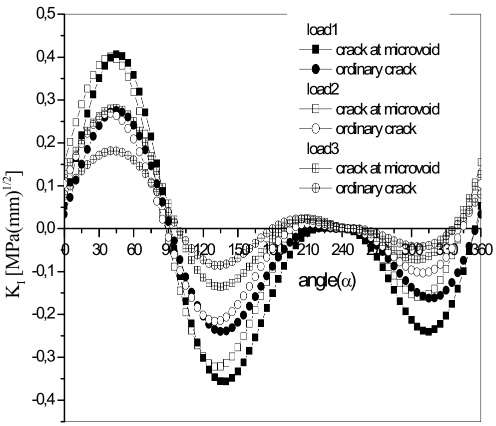


Figure12: Comparison of the K_I between. the tow cracks.

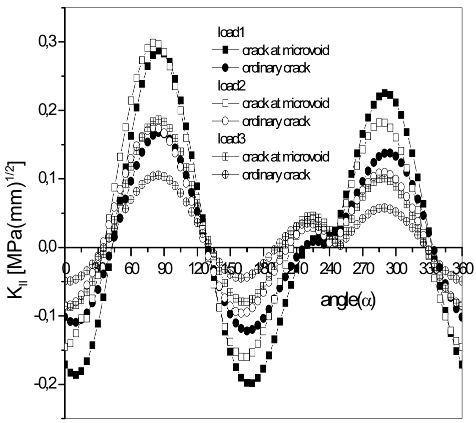


Figure13: Comparison of the K_{II} between the tow cracks.

Conclusion

This study was carried out with an aim of analyzing the behaviour of crack emanating from microvoid and compared with ordinary crack. The obtained results suggest the following conclusion:

-Existence of Microvoid in orthopaedic cement rise angular stress and create tensile radial stresses.

- The risk of crack initiation in orthopaedic cement is in the radial direction.

-When the crack was initiated from microvoid, the radial direction presents the best favourite orientation to crack propagation. In anti-radial direction, results give negative values of K_I.

-The stress intensity factor for crack emanating from microvoid is higher than for ordinary crack. The risk of crack propagation is then greater for crack emanating from microvoid.

-Difference of stress intensity factor between both crack changes with the crack inclination, but remain constant under different loading conditions.

References

[1] B. P. Murphy "The relationship between stress, porosity, and nonlinear damage accumulation in acrylic bone cement" Department of Mechanical Engineering, Trinity College, Dublin 2, Ireland

[2] M. Jasty WJ. Maloney , CR. Bragdon , DO. O'Connor, T. Haire, WH.Harris. The initiation of failure in cemented femoral components of hip arthroplasties. J Bone Joint Surg 731991, B:551–558.

[3] L. McCormack, Prendergast "the relationship between cement fatigue damage and implant surface finish in proximal femoral prostheses" Medical Engineering & physics 25 2003,pp. 833-841.

[4] El'sheikh, MacDonald, Hashmi" finite element simulation of hip joint during stumbling: a comparision between static and dynamic loading" Journal of Material Processing Technology 143-144 2003, pp. 249-255.

[5] D. MERCKX, Les ciments orthopédiques dans la conception des prothèses articulaires.

Biomécanique et biomatériaux. Cahiers d'enseignement de la SOFCOT. Expansion scientifique française, 441993, pp. 67-76.

[6] J. Tong and K Y Wong "mixed mode fracture in reconstructed acetabulum". Department of Mechanical and design Engineering. University of Portsmouth. Anglesea road, Portsmouth. PO1 3 DJ. UK.

[7] Cr, Peter, Ken, Bachus, Marcis, Craig, Higginbotham" the Effect of Femoral Prosthesis Design on Cement Strain in Cemented Total Hip Arthroplasty" The Journal of Arthroplasty vol. 16, 2 2001.

[8] G. Bergman. "Hip joint loading during walking and running measured in two patients". Journal of biomechanics, 26, pp. 969-990.

[9] A. Phillips "Finite Element Analysis of the Acetabulum after impacting Grafting". The University of Edinburgh. School of civil and environmental Engineering. Crew Building. Kings Buildings. Edinburgh EH9 3JN.

[10] L. Chaodi , G. Cristopher , H.Del Schuttte Jr, B. Serrill , A. L. Robert " Failure analysis of composite femoral components for hip arthroplastiy". Department of bioengineering and department of mechanical engineering. Clemson University. Clemson , SC.

[11] D. Christian "Prothèse totale de Charnley où en est aujourd'hui le « le Gold-Standard » de l'arthoplastie primaire de hanche". Clinique de l'Yvette – 91160 longjumeau.

[12] D. Poitout "Biomécanique orthopédique". Edition Masson.

[13] H.K. Sorensen. Abaqus user manual.

[14] S.J. Chatarina "Mechanical behavior of a new acrylic radiopaque iodine-containing bone cement". Center for Biomaterials Research, University of Maastricht, P.O. Box 616, 6200 MD Maastricht, The Netherlands.

[15] D. Buddy, A.S. Hoffman "BIOMATERIALS SCIENCE" for Bioengineering and Department of Chemical Engineering University of Washington

[16] J M. Yaszemski "Biomaterials in Orthopedics" Mayo Clinic, Rochester, Minnesota, U.S.A