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Procedia Engineering 149 (2016) 229 – 235

Procedia Engineering

www.elsevier.com/locate/procedia

International Conference on Manufacturing Engineering and Materials, ICMEM 2016,
6-10 June 2016, Nový Smokovec, Slovakia

Numerical Simulation of Fatigue Crack Growth in Hip Implants

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Abstract

In this paper numerical analysis of hip replacement implant behaviour from a fracture mechanics perspective is presented. It is necessary to understand the fatigue crack initiation and propagation characteristics in order to prevent catastrophic failure of the implant. For the simulation of crack propagation extended finite element method (XFEM) was used, as being one of the most advanced modeling techniques for this type of problem. Short theoretical background information on the XFEM is provided, as well as the representation of crack and the stress intensity factors computation. For chosen titanium alloy hip implants numerical modeling and analysis were done in ABAQUS software. It is shown that is possible to assume hip implant mechanical behaviour to the existence of defects such as cracks by application of numerical simulation crack behaviour. The numerical results illustrate that XFEM is efficient for the simulation of crack propagation in complicated biomedical structures, without the need to re-mesh during the propagation if the finite element mesh is well defined.

Keywords: biomedical application design, extended finite element method (XFEM), Ti-6Al-4V alloy, stress intensity factor (SIF), fatigue crack growth

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1. Introduction

Total hip replacement is a surgical procedure in which parts of the hip joint are removed and replaced with artificial parts, known as the prosthesis. [1, 2] Currently, titanium-based alloys, especially Ti-6Al-4V & Ti-6Al-7Nb, are the most commonly used materials for joint prostheses, being registered in ASTM standard as biomaterials.

Joint prostheses have, in general, a short-term success rate, since biological and mechanical conflicts often cause implant failure. There are many potential hazards that can affect the long-term outcome of the operation, once an implant surgery is performed. In orthopedic applications, such as knee and hip joint prostheses, fatigue fracture and wear have been identified as some of the major problems associated with implant loosening, stress-shielding and ultimate implant failure [3-7]. During the surgical procedure and prosthetic handling scratches on its surface will occur inevitably, which can cause location for crack initiation. [8-10] Therefore, despite strict regulation, hip implant failures still occur. As the parameters to be considered in implant design are fracture mechanics parameters, therefore it is necessary to understand the phenomena of crack initiation and its further growth, in order to prevent catastrophic failure of the implant. [11]

While it is not possible to avoid failure, recent work has focused on predictive and design tools to enable more accurate prediction so as to avoid catastrophic failure *in vivo*. For complicated biomedical structures, such as artificial hip implants, it is

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doi:10.1016/j.proeng.2016.06.661

common practice to apply numerical simulations for preliminary studies. In the simulation of crack propagation classical FEM solutions are often very limited due to the requisite to create a new mesh after each crack growth step. In this paper, for modeling of the crack growth problem in biomaterials, the most advanced modeling techniques that include the use of the extended finite element method have been used. [12-14]

Conventional FEM is formulated with continuous media, so additional remeshing is necessary to accurately predict irregular crack propagation. The extended finite element method was based on the idea of partition of unity, developed by Belytschko et al., but has been gradually modified. [15-17] The XFEM exhibits a unique advantage in the analysis of discontinuous problems, because it can describe the discontinuity and singularity by introducing the enrichment function to the shape function of the conventional finite element method.

Though XFEM has originally been developed for fracture, because of its huge superiority in tracking the crack extension without re-meshing, its application has been extended to numerous problems. [18-23] This paper presents an application of the extended finite element method (XFEM) to the modeling of the propagation of a typical crack in hip implant.

2. Fatigue crack growth – numerical simulation using the XFEM

Following this, numerical simulations of implant behaviour were performed and fatigue fracture resistance was determined for an artificial hip during exploitation. Shown in figure 1 is the critical area, from the aspect of crack initiation due to fatigue, with a generated crack and finite element mesh.

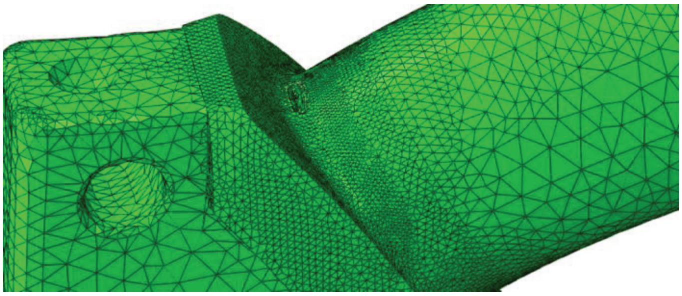

Figure 1. Critical area in the prosthesis

Initial crack was placed at the location where material fatigue and micro-damage in the material was expected, due to the fact that it was an area of contact with the other parts of the prosthesis. [8-11] Calculation was performed using numerical software package Morpheo, which is based on applying an extended finite element method, and is supported by simulation and finite element analysis software, ABAQUS. [24-26]

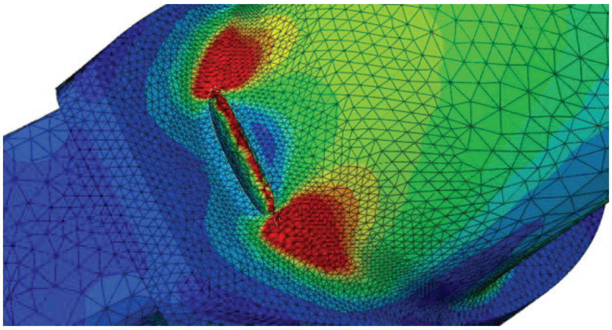

Figure 2. Crack geometry and Von Mises stress distribution along the crack

Crack propagation in the biomaterial was monitored until failure, and the total calculation included 21 steps. Shown in Figure 2 is the geometry of the crack, along with Von Mises stress distribution along the crack itself. Critical crack length initiated in step 21 is shown in Figure 3.

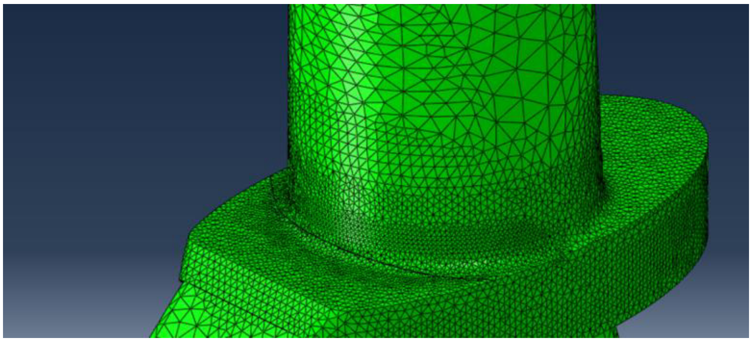

Figure 3. Critical crack length

Shown in Figure 4 is the crack propagation in the material and stress distribution along critical crack length.

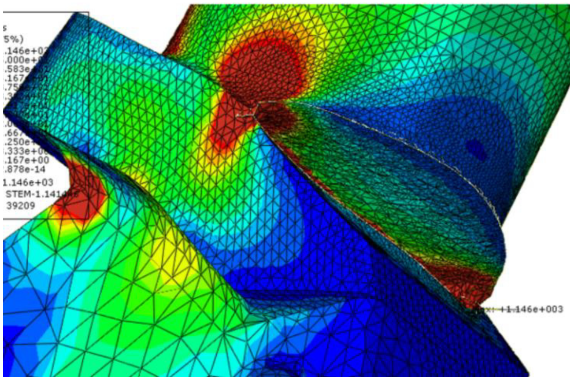

Figure 4. Stress distribution along critical crack length

Fracture mechanics parameters were numerically determined using an implant model, including the values of stress intensity factors K_{I}, K_{II}, K_{III} and K_{ef}. Based on theoretical considerations, it is clear that values of stress intensity factor in case I are significantly greater than those for II and III, and thus the obtained effective values are practically the same as the results for mode I. In that sense, only the values for crack opening mode I, i.e. the values of K_{I}, were analysed. It should be emphasized that values of all fracture mechanics parameters are determined at each step of the calculation, i.e. all defined parameters were determined for a total of 21 calculation steps. At each individual step of the calculation, the change in fracture mechanics parameters was determined along the crack front, defined in a three-dimensional space with coordinates *x*, *y*, *z*. Shown in Figure 5 is a diagram which describes the change of parameter K_{I} along the crack front in step 1 of the calculation.

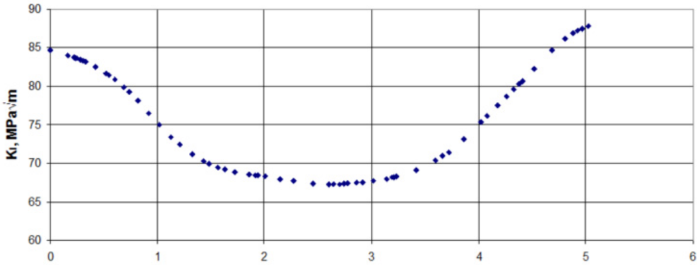

Figure 5. Change of K_{I} along the crack front

Analysis of given results clearly shows that numerical calculation produced a range of values for K_I, hence maximum, minimum and mean values were calculated along the crack front in every step. For steps shown in previous diagram, following values were obtained: calculation step 1 values: $K_{Imax}=88\ MPa\sqrt{m}$, $K_{Imin}=67\ MPa\sqrt{m}$. Obtained values of stress intensity factor K_I for all steps of the numerical calculation are shown in Table 1.

Table 1. Obtained values of K_I

		K_{ef} MPa√m			K_I MPa√m		
step	crack length	max	min	avg	max	min	avg
1	1	88.7229	67.8217	76.20489	87.7803	67.265	75.29781
2	2	92.6004	72.1433	79.81443	91.52	72.4456	79.32348
3	3	96.2636	74.9925	82.98976	96.4056	75.1097	82.69565
4	4	97.9837	77.7177	86.02563	96.6726	77.5551	85.58692
5	5	99.2169	81.0311	88.31732	97.8871	80.8682	87.95037
6	6	100.08	83.5532	90.33756	100.757	83.2667	90.46774
7	7	101.394	86.2289	91.99896	101.596	86.3055	91.98673
8	8	101.266	89.0138	93.81827	101.541	88.8141	93.55515
9	9	101.843	92.0276	95.7006	100.93	92.05	95.82888
10	10	103.525	95.011	97.93667	103.362	95.0963	97.89474
11	11	105.645	98.1223	100.8858	103.963	97.8382	100.5491
12	12	105.294	101.306	102.9541	105.433	101.17	102.8503
13	13	107.53	103.562	105.3858	106.411	102.901	105.0779
14	14	110.485	105.53	108.6827	110.108	104.722	108.3863
15	15	113.423	107.163	111.9437	113.49	106.464	111.6942
16	16	116.952	109.411	115.2291	116.9	109.122	114.9601
17	17	120.006	108.923	117.7212	120.228	106.906	117.2907
18	18	126.489	112.926	123.0613	126.359	111.628	122.712
19	19	129.313	115.451	126.8489	128.894	113.046	126.0467
20	20	135.883	122.983	133.2647	135.634	119.794	132.2522
21	21	146.262	141.441	142.6254	142.732	141.169	141.9145

Change of stress intensity factor for one step of the calculation, shown in a three-dimensional coordinate system, is given in Figure 6.

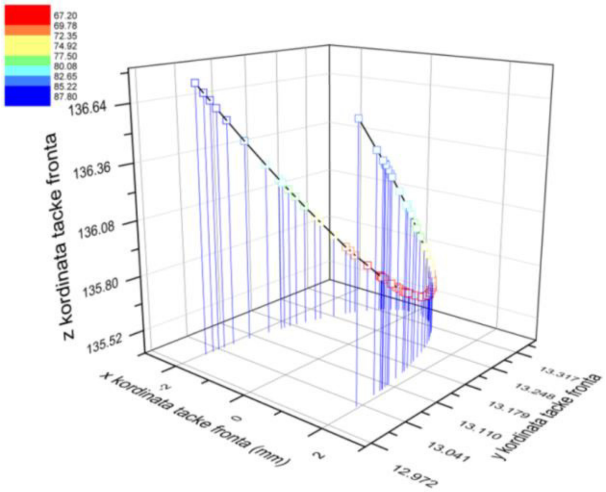

Figure 6. Change in stress intensity factor in one step

3. Discussion

The basis for this study was, on the one hand, the fact that despite strict regulations in terms of orthopedic implants there are still examples of prosthesis failure during exploitation – as in the case of hip replacements, where one of the causes is the presence of cracks in the material; and on the other hand, the fact that regulations and standards do not take into account the application of fracture mechanics for the purpose of assessing the integrity of orthopedic prosthetics. Additional research in this direction was conditioned by the fact that there is a possibility of implant fracture upon implanting and exploitation of prostheses. For the purpose of numerical analysis, types of prostheses in which fracture occurred were selected, Figure 7.

To implement the process simulation of tracking the crack propagation by using conventional finite element method, the structure containing cracks must be remeshed with the extension of cracks. The XFEM avoids the complicated mesh regeneration that must adapt the cracks after extension, and enhances conventional FEM capabilities by excluding the mesh requirement to conform to discontinuities. XFEM has been widely used in numerous fields with discontinuous problems, particularly in fracture mechanics, because XFEM is an excellent method of addressing discrete crack propagation in various types of materials. The displacement model of XFEM is specifically constructed by introducing the enrichment displacement functions reflecting discontinuous characteristic of crack and singularity at crack tip on the basis of the finite element displacement model.

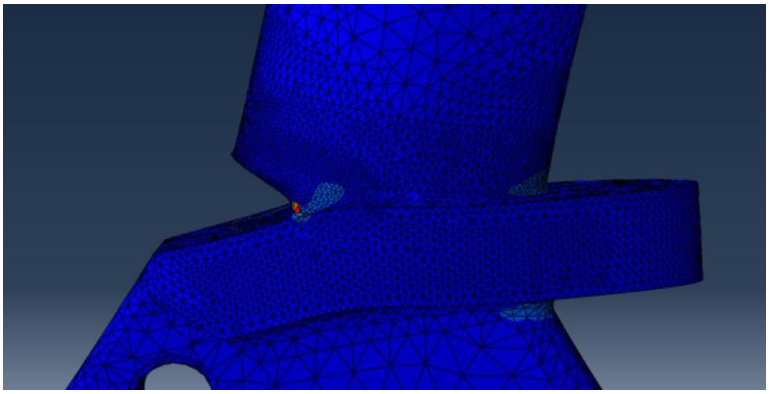

Figure 7. Prosthetics in which fracture has occurred

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It is clear that numerical simulation of crack growth in material also leads to an increase in the numerically determined values of stress intensity factor. Diagram of stress intensity factor change relative to crack growth is shown in Figure 8.

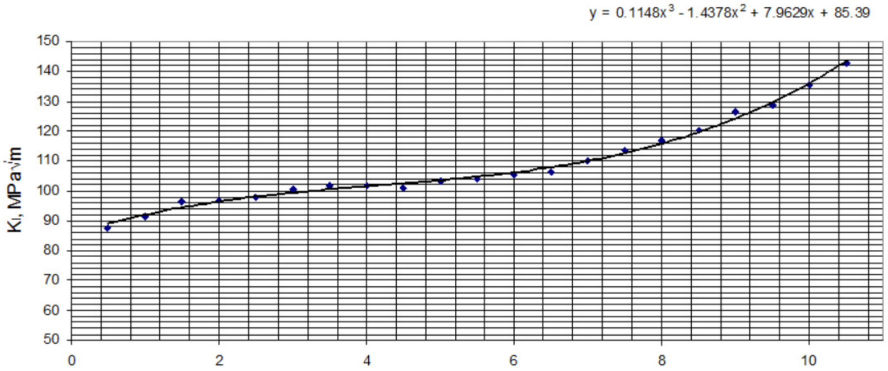

Figure 8. Change in K_I relative to crack growth

Finite element and strain field accuracy must also be taken into account. Software packages for FEM include various types of elements. These elements use different interpolation functions for representing coordinates and calculating strain. These interpolation functions can be relatively simple, e.g. bilinear function for a two-dimensional element with four nodes, or a trilinear function for three-dimensional brick-shaped elements with eight nodes. The advantage of these simpler elements is that the number of degrees of freedom is relatively small, which reduces time necessary for the calculation. However, these elements may not be able to represent load and strain states generated in reality. For example, these relatively simple elements behave too rigidly when subjected to bending. The reason is that variation of linear shear strain, which is present during bending, cannot be described using simple interpolation functions.

The extended finite element method (X-FEM) uses the partition of unity to remove the need to mesh physical surfaces or to remesh them as they evolve. Crack is a typical discontinuity, and XFEM is an effective method in researching fatigue crack growth characteristics in the titanium alloy. In this paper, the XFEM method based on the ABAQUS is employed for analyzing crack growth characteristics in the titanium alloy hip implants, and the results obtained could be compared with the experimental results. [4, 11, 27, 28].

4. Conclusion

Based on the results presented and discussed in this paper, one can conclude the following:

- It has been shown that by applying modern numerical methods to biomaterial behaviour analysis, it is possible to monitor three-dimensional crack behaviour in a material, as well as to determine fracture mechanics parameters.
- XFEM is able to get the true crack growth characteristic and an it is an effective method for crack growth analysis in the application of titanium alloys in biomedicine.
- By comparing the obtained results with experimentally determined values of fracture toughness for alloy Ti-6Al-4V - 67.5 MPa√m, CoCrMo - 110 MPa√m and S 316L - 200 MPa√m, [11], it can be seen that the Ti alloy has the highest risk of fatigue (brittle) fracture.

ACKNOWLEDGEMENT

We acknowledge the support for this investigation by Ministry for Education, Science and Technological Development, project TR 35040.

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