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ScienceDirect

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.

Peer-review under responsibility of the organizing committee of ICMEM 2016

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

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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Peer-review under responsibility of the organizing committee of ICMEM 2016
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.

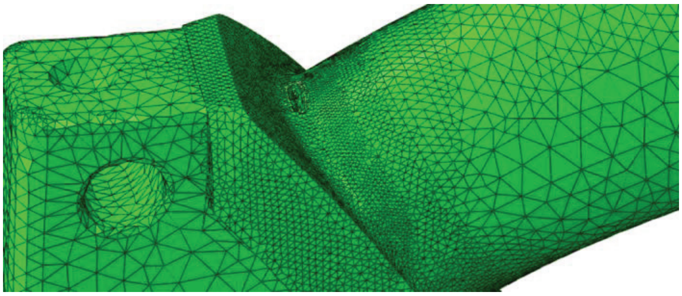

Figure 1. Critical area in the prosthesis

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]

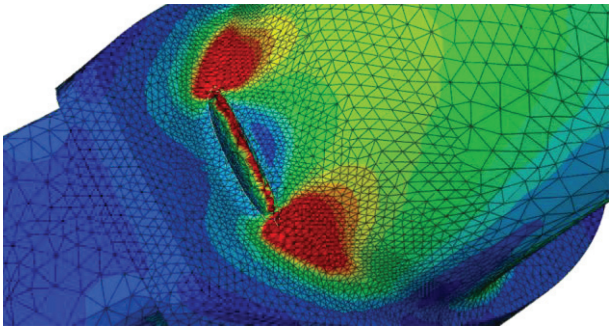

Figure 2. Crack geometry and Von Mises stress distribution along the crack

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.