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Design Aspects of Hip Implant Made of Ti-6Al-4V Extra Low Interstitials Alloy

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Abstract

The main concerns in design of hip implants are fracture and fatigue related issues. In this paper, reverse engineering is used to re-design a hip implant produced by precision casting, using Ti6Al4V Extra Low Interstitials (ELI) alloy. As the most critical part, hip neck has been in the focus of this analysis, keeping in mind that the lower the thickness is, the higher the movement of joint may be, but affecting its structural integrity at the same time. Thus, 5 different models are created with different neck thickness and analyzed by using the Finite Element Method (FEM) for stress-strain calculation and extended FEM (XFEM) for fatigue crack growth.

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Keywords: Total hip replacement implant; Finite element method; Ti-6Al-4V ELI alloy; Reverse Engineering

1. Introduction

Loads acting on hip implants vary from approximately body weight up to 8.7 times the body weight (e.g. stumbling case, [1-3]), causing frequent premature failures. Extensive research has been performed in recent years to assess integrity of hip implants made of different materials, including stainless steel, Cobalt-Chromium and Titanium based

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alloys, [4-10]. Yet another issue is fatigue crack growth, related to amplitude loading, e.g. simple walking or running, also considered in number of research papers to assess structural life of hip implants, [11-13].

Different methods have been used to analyze fracture and fatigue behavior of hip implants, including sophisticated experimental techniques, such as Digital Image Correlation (DIC), [10, 14-17], and advanced numerical simulation, both FEM, [1-8] and XFEM, [11-13, 18-19]. They all contributed also to better understanding of hip implant design aspects, as shown in more details in [4], where static loading was taken into account. In this paper we extend analysis to amplitude loading, i.e. fatigue crack growth, using total hip replacement implant made of Ti-6Al-4V ELI by precision casting method. All basic data is already given in [4], so here we shortly describe most important results.

2. Static loading

Basically, the problem to be solved could be considered also as an optimization process. Namely, selected hip implant (Fig. 1), was designed with neck thickness 14.6 mm, which provided long structural life of the implant at a cost of lower oscillation angle, i.e. restricted hip joint movement. The research conducted, [4] included possible redesign of chosen implant in order to increase hip joint movement, using Finite Element Analysis (FEA) to demonstrate how redesign will affect structural life of the component. Reverse Engineering (RE) method is used as a tool to obtain CAD model of selected implant and to manipulate with geometry, as described in details in [4].

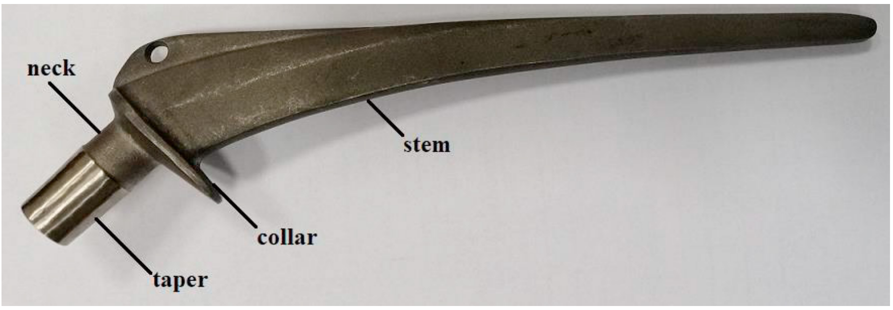

Figure 1. Selected total hip replacement implant

Finite Element Analysis was performed in Abaqus 6.14 software (Dassault Systems, France). Applied load, corresponding to stumbling was 8.7 times the body weight of a patient of 90 kg, defined as a concentrated force acting above the total hip replacement implant head [4]. All details about given assembly of total hip replacement head and stem, boundary conditions, material properties, and FEA mesh are given in [4].

Results for stress states located on and around implant neck are given for two cases, later analyzed with XFEM, for total hip replacement models with highest and lowest neck thickness, i.e. 14.6mm and 9mm diameter respectively, Fig. 2, 3.

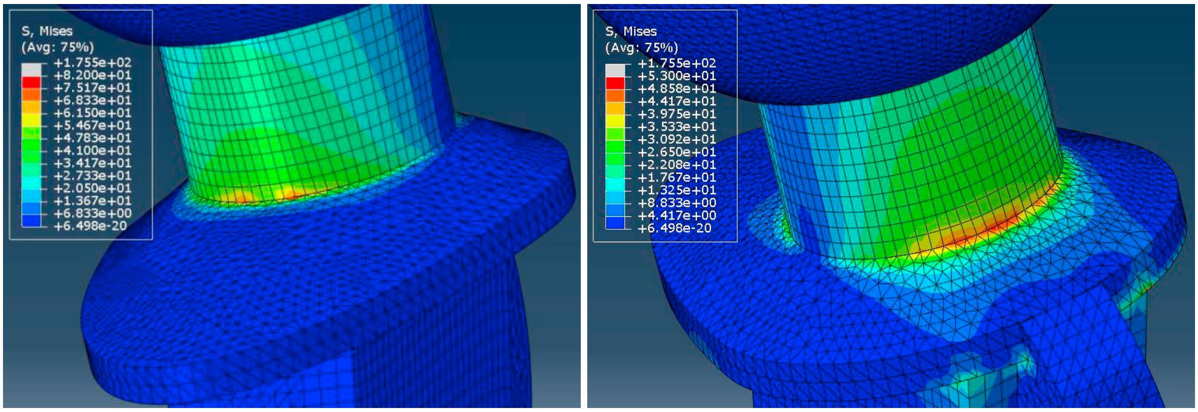

Figure 2. Total hip replacement implant with neck diameter of 14.6 mm (Left-front side, Right-back side)

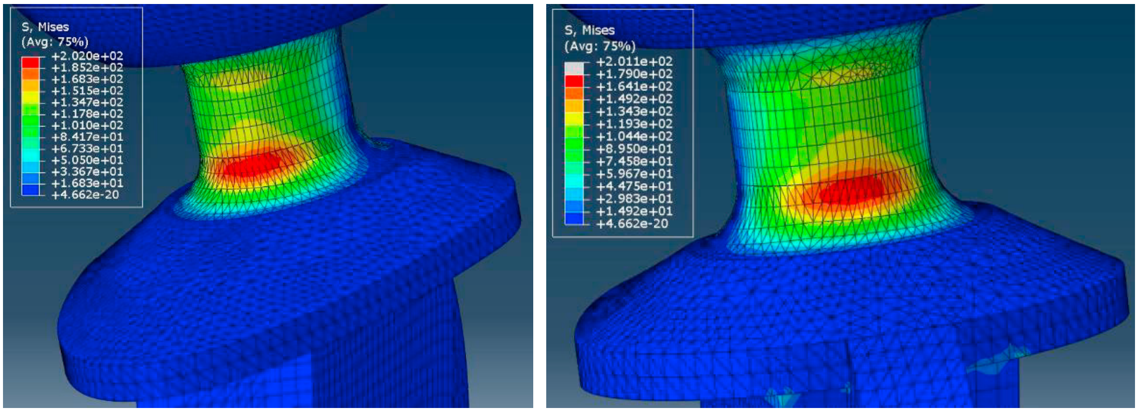

Figure 3. Total hip replacement implant with neck diameter of 9 mm (Left-front side, Right-back side)

Original model with neck thickness of 14.6mm (Figure 2) has maximum stress concentration in the neck area under compressive stresses (Figure 2 - front side), with maximum value of 81 MPa. On the tensile side (Figure 2 - back side) maximum stress value is 52 MPa. Stress concentration area is wider on the back side of the implant neck, and on the front side stress concentration area is sufficiently narrower-indicating potential location of crack initiation.

Additional four numerical models were made to evaluate maximum stress concentration at the front and back side of the neck with different thicknesses, i.e. 13.2, 11.8, 10.4 and 9 mm. The maximum stresses changed from 52 and 81 MPa, to 89 and 114 MPa (neck thickness 13.2 mm), 102 and 123 MPa (11.8 mm), 125 and 150 MPa (10.4 mm), 179 and 202 MPa (9 mm). Area of stress concentration, on the model with lowest neck thickness, is much thicker vertically and narrower horizontally (more compact), compared to the previous numerical model. As the optimal model, neck thickness 10.4 mm was chosen, since model with neck thickness of 9 mm had unacceptable level of maximum stresses. Due to recommendations for the implant neck thickness with the highest angle movement during exploitation [4] in the following XFEM analysis for fatigue crack growth is considered for total hip replacement numerical models for the model with original neck thickness of 14.6mm and for the one created total hip replacement of highest angle movement, which has 9mm neck thickness.

3. Fatigue

Fatigue crack growth has been simulated by using XFEM, as described in [11,12,18,19] for similar problems. Amplitude loading is 3 kN of magnitude, according to recommended values for normal walking load on hip joint for a person of 90 kg of mass [20], shown in Fig. 4. Normal walking condition is the most suitable for numerical simulation of dynamic loading for regular multiyear exploitation of the total hip replacement implant.

Boundary conditions include fixed support on stem surfaces that are facing the inner bone, and fixed vertical movement and rotations around both horizontal axes on bottom surface of the implant collar. Defined boundary conditions are the same as in previous research, [1,4]. Material properties appropriate for XFEM analysis for the chosen Ti-6Al-4V ELI alloy are taken from the previous research [11]. Namely, average values of tested samples under tensile load in [11] are used for the following XFEM analysis-$R_{p0.2}$=881 MPa, R_m=971 MPa, K_{IC}=2100 MPa$\sqrt{\text{mm}}$, and coefficients for Paris equation n=2.2, C=6.72e^{-13}. Modulus of elasticity was set at 120 GPa and Poisson coefficient 0.3. Initial crack length was set at 1 mm and placed on a junction between implant neck and collar, where the highest stress states are located according to previous research, [4], Fig. 5. The XFEM analysis is performed in software package Ansys 2019R2 (Ansys Inc., Canonsburg, PA).

Implementation of XFEM allows for a greater flexibility during modelling, which implies to enrichment of numerical model finite elements with additional degrees of freedom, especially related to the nodes of elements that are in the crack path. XFEM requires only one mesh generation, allowing for introduction of discontinuity (in this case crack) into the existing numerical model without changing of the discretization. The method is therefore convenient for fatigue crack assessment in structures, [11-13]. In this particular case, model is assumed to be homogeneous, isotropic and linear elastic. Any flaws in material are avoided and not considered in XFEM analysis.

According to the abovementioned conditions two total hip replacement numerical models, original with 14.6 mm and 9mm, are taken into consideration for the XFEM. First one mentioned is the originally 3D scanned model and the other is the one with recommended neck thickness for the best angle movement of the total hip replacement implant. Stress states of the two mentioned numerical models are shown of Fig. 6

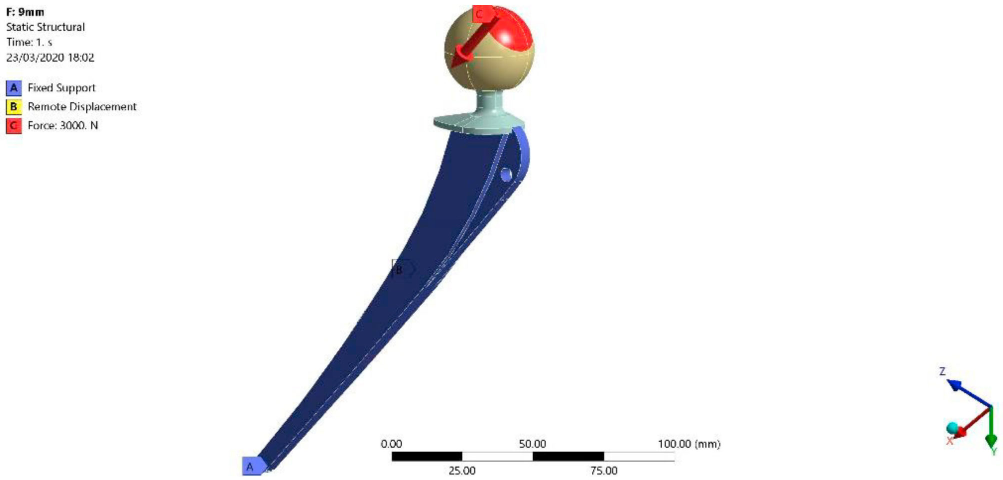

Figure 4. Total hip replacement implant numerical model for XFEM with applied load and boundary conditions

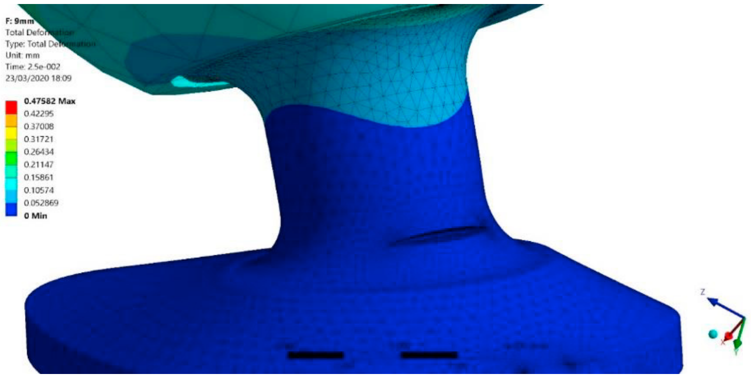

Figure 5. XFEM analysis of total hip replacement implant with initial crack

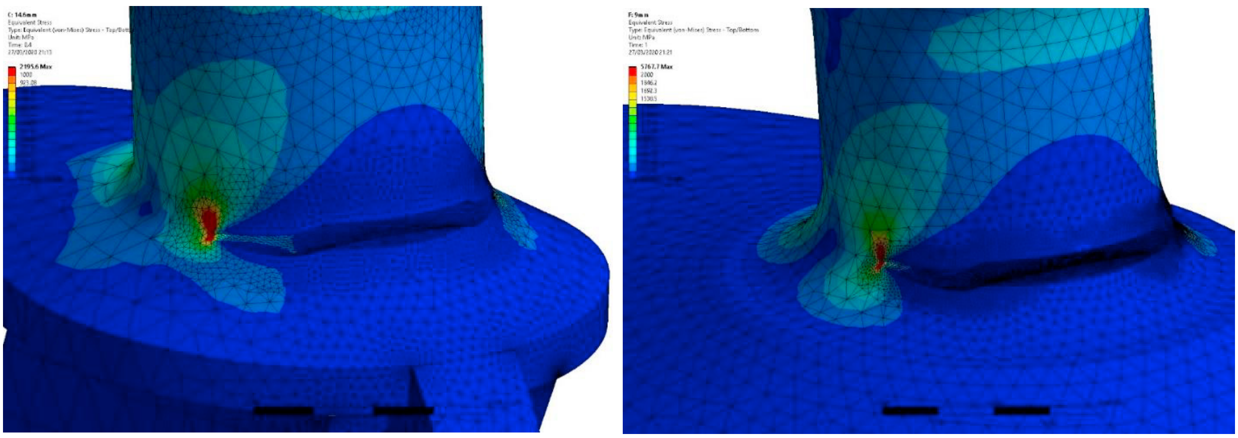

Figure 6. Stress states during fatigue crack growth on total hip replacement implant with neck diameter (a) 14.6mm (b) 9 mm

In both XFEM analysis highest stress states are located on and in the vicinity of the crack front. Created XFEM analysis considers ratio between minimal and maximal load as R=0, i.e. the numerical model after applied load is unloaded -similarly as in walking cycle. The XFEM analysis of total hip replacement implant numerical model with 14.6mm neck thickness can withstand 5.2 million walking cycles from the occurrence of the crack until structural failure while a numerical model with 9mm neck thickness can do 1.56 million cycles. Hence, the implant with the highest angular movement has 3.3 times lower structural life than original implant. Figure 7 shows the dependence of the number of walking cycles and crack length.

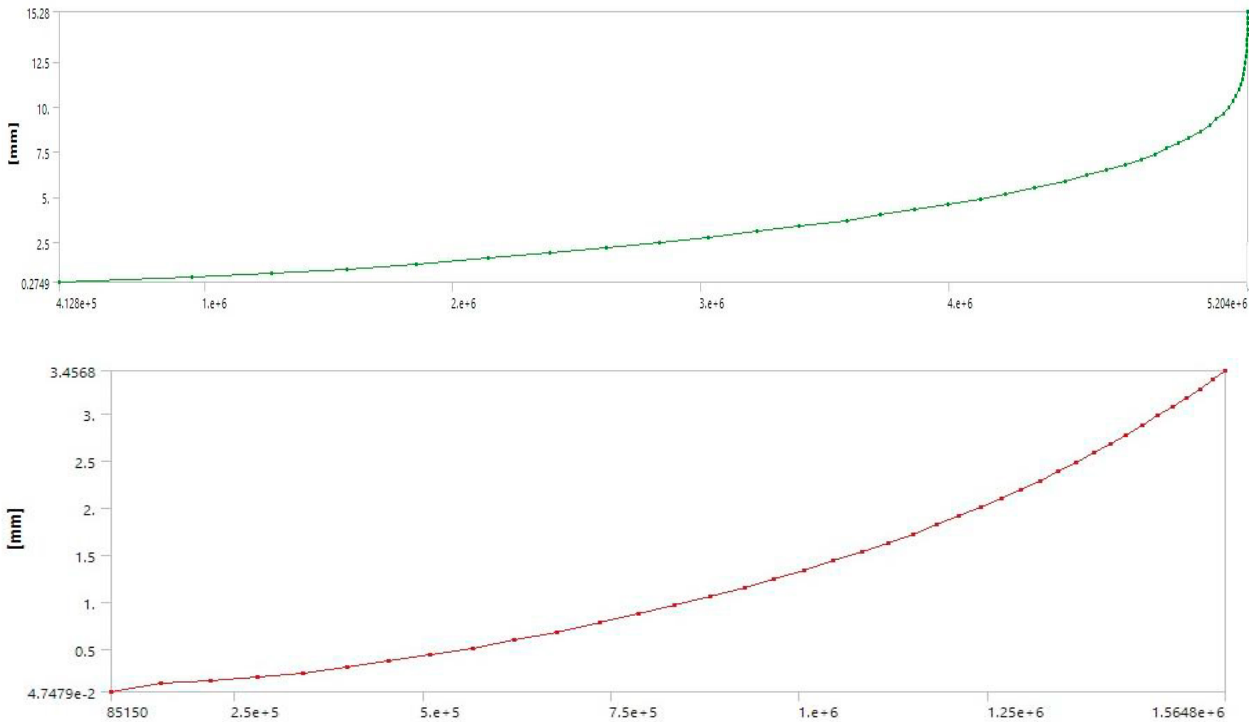

Figure 7. Diagrams showing dependence of crack length (ordinate) vs. number of walking cycles (abscise)
(Up-14.6 mm diameter implant, Down-9 mm diameter implant)

Total hip replacement implant with 14.6 mm neck thickness has a maximal crack length of 15.28 mm, and implant with 9 mm neck thickness fails at only 3.45 mm crack length (Fig. 7). Caption of final step of fatigue crack propagation before structural failure for both numerical models are shown in Fig. 8, indicating that 9 mm neck thickness has a larger area under static failure. After about 5 million cycles implant with 14.6 mm neck thickness shows an occurrence of unstable crack propagation, while implant with 9 mm neck thickness has a stable crack growth throughout the entire crack propagation to failure. This behavior can be explained with much shorter crack length of the implant with the thinner neck and apparently larger area under static failure.

4. Conclusions

Based on results presented here, one can conclude that the reverse Engineering allows efficient modelling of geometry of total hip replacement implant stem. Using CAD modelling software an existing digitized model may be redesigned according to demand. As a control for this endeavor FEM analysis was used in previous research [4] to locate areas with highest stress concentration, i.e. places with highest possibility of crack initiation. On selected total hip replacement implant highest stress states are located around the neck area. Previous research [4] shows that the thickness of the neck area affects the possible hip joint movement and structural life. In this paper, two total hip replacement implants are chosen from the group of five implants with a variation in neck thickness from original to 9 mm, in which case the angular movement of possible implant is at its maximum. Choosing these two implant designs shows the difference between models with longest structural life and highest angular movement.

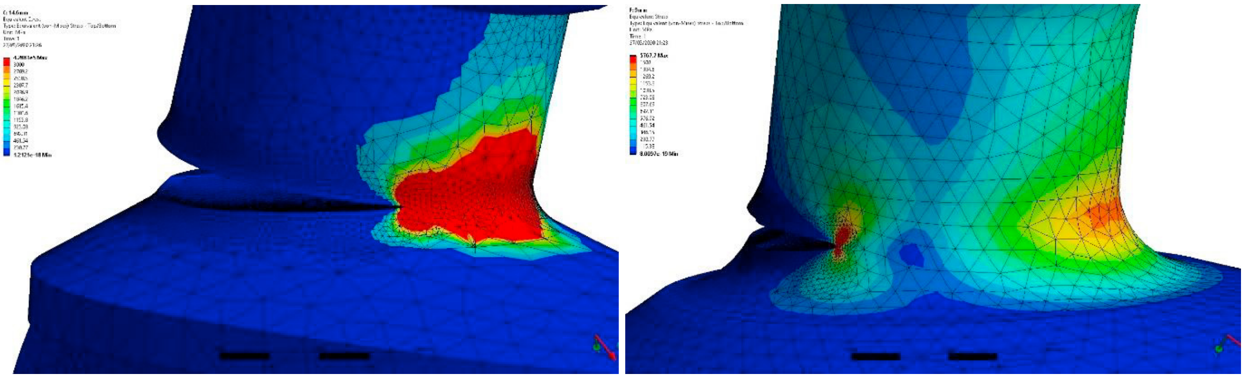

Figure 8. Final step of fatigue crack growth (Left - 14.6 mm neck diameter, Right – 9 mm neck diameter)

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