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Procedia Structural Integrity 48 (2023) 215–221

Structural Integrity Procedia

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Second International Symposium on Risk Analysis and Safety of Complex Structures and Components (IRAS 2023)

Numerical simulation of fatigue crack growth in Ti-Al6-V4 hip implants under different exploitation conditions

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Abstract

One of the most important aspects of materials typically used in biomedical engineering is their resistance to various unfavourable exploitation conditions, which greatly impact their work life. In terms of extreme conditions, two major factors include fatigue and corrosion, and a combination of these can significantly decrease the expected life of various implants. The focus of this paper will be on hip implants made of Ti-Al6-4V titanium alloy, a material commonly used in such applications, due to its resistance to corrosion and bio-compatibility. Research shown here was based on experimental testing of said alloy in order to determine its mechanical properties under different working environments, including normal, salty and wet conditions. These properties were then used as input data for Extended Finite Element method (XFEM) numerical simulations of fatigue crack growth in hip implants with various geometries. This was of particular interest since specimens which were kept in salty and wet environment had a slight degradation of yield stress and tensile strength, but an increase in plasticity.

Keywords: Ti-Al6-V4 alloy; hip implants; fatigue crack growth; corrosion; Extended Finite Element Method

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1. Introduction

Research presented in this paper involves a more detailed analysis of fatigue behaviour of hip implants, based on the previous work by the same group of authors [1-3]. Hip implants in question were made of titanium alloy Ti-6Al-

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10.1016/j.prostr.2023.07.151

4V, which is commonly used in biomedical applications, for a number of reasons, most of which are related to its exceptional corrosion resistance, good mechanical properties and bio-compatibility. All of the aforementioned characteristics of this alloy make it an excellent material of choice for various artificial implants [4-6]. In order to better understand how hip implants made of said alloy behave under different exploitation conditions, a number of test specimens were made and subjected to various environments, for the purpose of determining how their exposure to unfavourable conditions would affect their fatigue life. This was an important issue to consider, taking into account the fact that both fatigue and corrosion heavily contribute to failures of hip implants - the former due to cyclic loading caused by everyday activities, and the latter by causing material loss and degradation of mechanical properties [7-11].

Specimens, made for the purpose of material characterisation via tensile testing (along with other types of experiments which will not be covered by this paper), were divided into three groups, and two of these groups were subjected to humid and salty conditions, whereas the third group specimens were tested in their original state. This approach had two goals: firstly, to determine how different environments affect the mechanical properties of specimens from each group, by comparing them to each other [2], as well as to specimens from different groups, and secondly, to use the obtained mechanical properties (with their differences) as the input data for the existing fatigue crack models, made in ANSYS R19.2 software [1,2].

2. Experimental determining of mechanical properties

In order to obtain necessary data for the numerical simulations, a number of experiments were performed, some of which are described in more detail in [2]. The goal here was to determine how different environments affect the mechanical properties of tensile test specimens made of Ti-Al6-V4, and three specimens were used for each group:

- First group included specimens which were not subjected to any aggressive environment, and were denoted as ZA-1, ZA-2 and ZA-3
- Second group of specimens, which were kept in a salty environment, denoted as ZS-1, ZS-2 and ZS-3 and
- Third group specimens, which were kept in a humid environment, denoted as ZV-1, ZV-2, ZV-3

Results obtained by tensile tests are shown in table 1. The most important input data needed for fatigue crack growth simulations were the yield stress and tensile strength of each specimen, providing a total of 9 models, three from each group, as was the case in the experiments.

Table 1. Mechanical properties of Ti-Al6-V4 tensile test specimens for three different cases (normal, salty and humid conditions) [2]

Specimen	Yield stress, $R_{p0,2}$, MPa	Tensile strength, R_m, MPa	Elongation, A, %
Z-A1	829	985	10.60
Z-A2	792	983	16.20
Z-A3	854	986	11.80
Z-S1	763	938	12.80
Z-S2	750	950	11.70
Z-S3	754	932	12.00
Z-V1	760	965	12.00
Z-V2	749	985	10.10
Z-V3	800	965	12.80

As expected, there were differences between the three groups, although they weren't too significant. The small degree of differences that were obtained can be easily explained by the fact that one of the main reasons for the wide application of this titanium alloy is its exceptional resistance to corrosion. However, these differences were still assumed to be sufficiently large to affect the fatigue behaviour of hip implants on their own, hence it was decided to create models for all nine specimens and compare them to each other (and between different groups) in terms of number of cycles.

3. Numerical simulations of fatigue crack growth

As in the previous cases [1-3], numerical simulations were performed using finite element method in ANSYS software. This is a commonly used approach in investigating the behaviour of biomedical implants under various loads, as shown in [1,2,12-14]. Finite element method provides a quick and reliable way of calculating stress/strain fields and simulating fatigue crack grow, hence it was chosen as the methodology for this research. Models shown in this paper were based on the already existing ones, i.e., the same geometry of the hip implant was used. Cracks were located in the implant neck, since previous analyses have confirmed this is the most critical location for crack initiation. Initial crack length was also kept the same as in [1]. The whole model is shown in figure 1, and its finite element mesh is shown in figure 2. The use of tetrahedron finite elements is a requirement of ANSYS software, in the cases when fatigue crack growth is simulated.

Boundary conditions were defined as fixed at the hip implant stem, whereas the load was applied in the form of concentrated force on the hip implant head as can be seen in figure 3. The load was defined according to literature data which corresponds to actual loads which occur in hips during walking (and other more extreme situations, such as running and falling down [15-17]). Boundary conditions, applied load and finite element mesh can all be seen in figure 1 below.

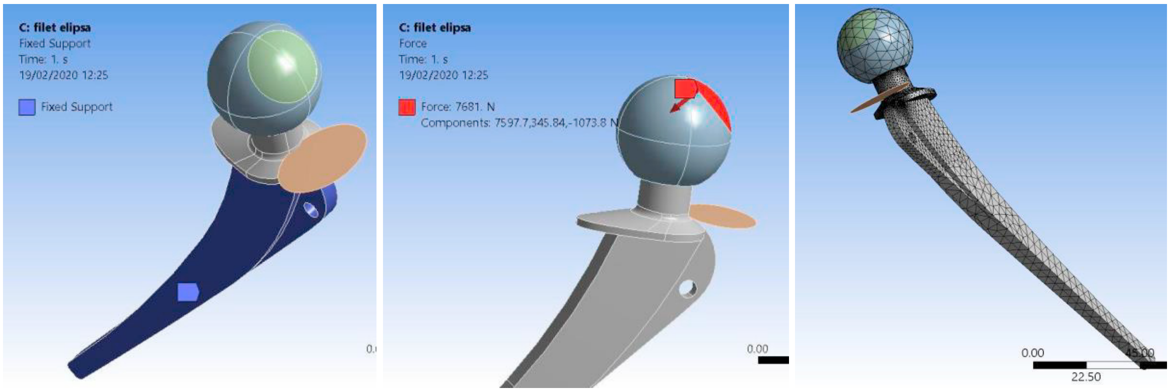

Figure 1. Boundary conditions (left), applied concentrated force (middle) and finite element mesh (right) for the hip implant models

The above figure also shows the location of the elliptical crack, which was placed at the location of highest tensile stresses, as determined in simulations which are more thoroughly described in [1]. In accordance with common practice with this type of simulations, finite element mesh was made finer in the vicinity of the crack, and in the region of the model where said crack was expected to propagate.

4. Fatigue crack growth simulation results and discussion

As was previously mentioned, a total of nine models were made, with mechanical properties defined in accordance with table 1, including three models for each group (normal, humid and salty conditions). Most representative results are shown in figures 2-5. These figures show the stress intensity factors for each model. The reason why some of the results were excluded is because it they were almost identical to other models within the same group, suggesting that the initial assumption that all 9 models will show somewhat different results was not entirely correct.

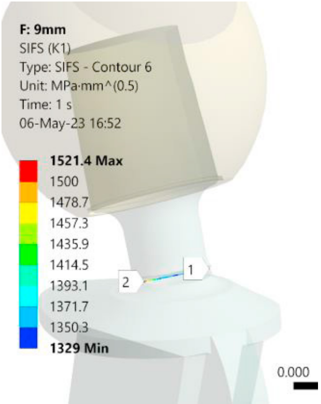

Figure 2. Stress Intensity Factors for the fatigue crack growth simulation of specimen Z-A1

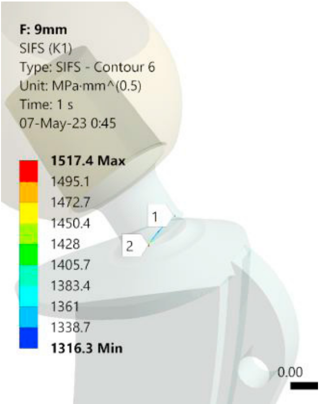

Figure 3. Stress Intensity Factors for the fatigue crack growth simulation of specimen Z-A3

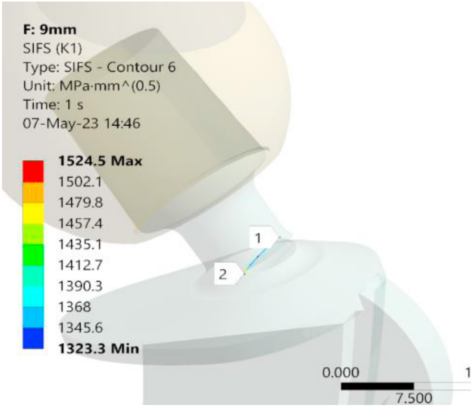

Figure 4. Stress Intensity Factors for the fatigue crack growth simulation of specimen Z-S1

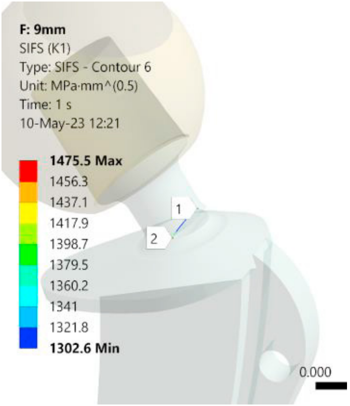

Figure 5. Stress Intensity Factors for the fatigue crack growth simulation of specimen Z-V2

The most important aspect of determining the fatigue life of various structures, including biomedical implants, is the total number of cycles until failure. In this case, critical crack lengths, i.e. lengths at which the fatigue crack would enter its unstable growth rate, were around 3.5 mm. Crack length versus number of cycles (a-N) diagrams are shown in figures 6-9.

Based on the results shown in figures 2-5, it can be seen that the lowest stress intensity factors were observed in the humid environment specimen model, Z-V2 (1475 MPa√mm), whereas the highest values were observed in Z-S1, the model representing the specimen kept in salty environment, and were 1524.5 MPa√mm. SIFs for the other two models, both belonging to the specimen group that was not subject to adverse environments, were close to each other, with values of 1517.4 and 1521.4 MPa√mm for Z-A1 and Z-A3, respectively. As can be seen, humid conditions model had SIFs noticeably lower than the rest, which were within 0.5% of each other, while this model was 2.9% lower than the closest one (Z-A1).

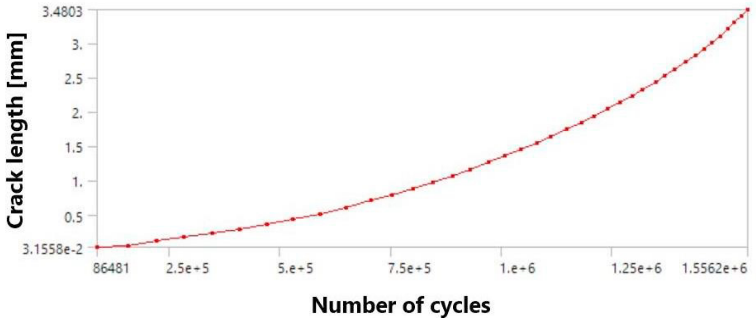

Figure 6. a-N diagram for the fatigue crack growth simulation of specimen Z-A1

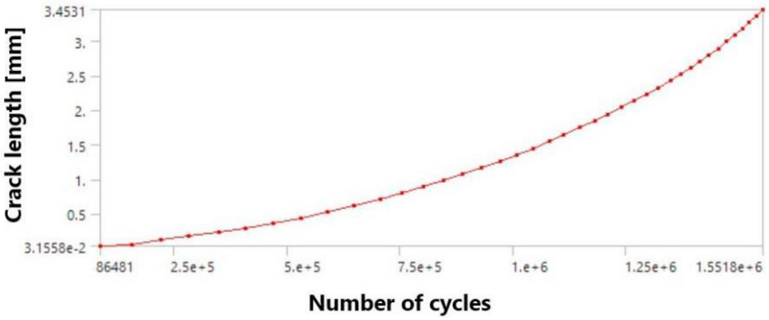

Figure 7. a-N diagram for the fatigue crack growth simulation of specimen Z-A3

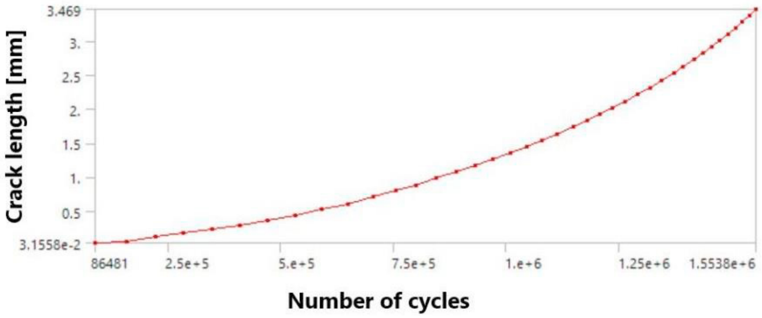

Figure 8. a-N diagram for the fatigue crack growth simulation of specimen Z-S1

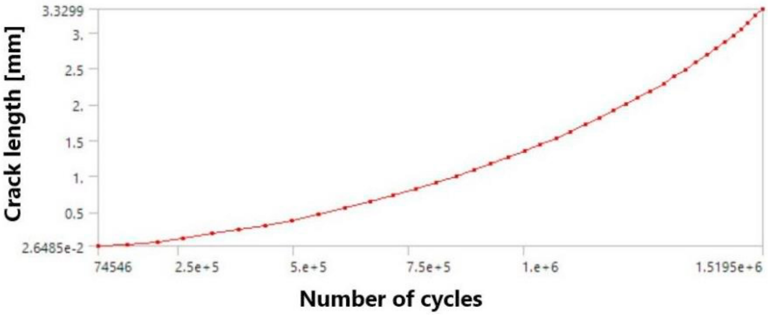

Figure 9. a-N diagram for the fatigue crack growth simulation of specimen Z-V2

Crack lengths have shown a similar trend, with specimen model Z-V2 having the shortest crack length of 3.33 mm, which was noticeably smaller than the remaining three models. The fact that a difference of 0.12 mm is referred to as “noticeable” clearly implies that the other models had nearly identical crack lengths - between 3.45 and 3.48 mm. These differences do not play a significant role in terms of fatigue crack growth resistance, hence there is no need to analyse them further. What remains to be seen is if said differences would increase in similar cases, i.e., when using slightly different hip implant neck geometry and larger initial crack lengths. This, among other things, will be the goal of further research into the fatigue behaviour of Ti-Al6-V4 hip implants.

Total number of cycles was around 1.55 million for specimens Z-A1, Z-A3, ZS-1 and, as expected, slightly lower for Z-V2 where it was 1,519,600 cycles. Specimen model Z-A1 was the best in terms of number of cycles, with a total of 1,556,200. The differences between this model and Z-A3 and Z-S1 were around 20,000 cycles. Once again, the model representing the specimen group from the salty environment outperformed one of the regular conditions models, which is a somewhat unexpected result, which will require additional attention and analyses.

Better performance of salty environment specimen Z-S1 compared to Z-A3 was an unexpected result, since the latter was not subjected to any aggressive environments. Possible explanation could lie in the fact that, according to tensile tests, this specimen had shown greater levels of deformation. In addition, its lower yield stress suggests this specimen would reach plasticity faster than the regular one. The combination of these two factors implies much higher plastic reserve of the specimen in question, which could explain a slightly higher number of cycles, despite a near-identical final crack lengths in these two cases.

5. Conclusion

Work presented in this paper involved the analysis of fatigue behaviour of Ti-Al6-4V hip implant models using extended finite element method. Based on the previous simulations, a total of 9 models were made, with different input data, i.e. yield stress and tensile stress. This data was obtained from tensile testing of specimens which were subjected to different aggressive environments (humid and salty), as well as from specimens which were kept in regular conditions. The goal was to determine if the observed differences in mechanical properties would affect fatigue crack growth resistance in any meaningful way, with the main focus being on number of cycles until critical crack length was reached.

Due to the fact that titanium alloys like the one used for this analysis are generally known for their exceptional resistance to corrosion, differences in mechanical properties between different groups of specimens were somewhat small, and as the result, most models had shown almost identical behaviour. The fact that four out of nine were ultimately selected as relevant suggests that the initial assumption about potential differences in fatigue behaviour was only partially correct. This was further confirmed by difference in number of cycles, stress intensity factor values and, especially, crack lengths, which were expressed in a couple of percents in the most “extreme” cases. Still, it can be seen that the specimen subjected to humid conditions had noticeably lower critical crack length and number of cycles, suggesting that, in this case, the humid environment was the one most detrimental to the structural integrity of the hip implant aluminium alloy in question.

While the biggest contribution of this research was the conclusion that there actually was no need for a detailed analysis of a larger number of specimens, since the differences between most models were negligible, some questions still remain - how would longer initial and overall crack lengths affect these differences, what would happen in the case of different implant neck geometries, e.g., with increased thickness, and there is also the possibility of simulating load cases (running, tripping, falling) other than the most common one which was used here. Answering these questions will be the main goal of future research regarding this particular titanium alloy and its resistance to fatigue and corrosion, as two main factors that compromise the structural integrity of hip implants.

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