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Simulation of Crack Propagation in Titanium Mini Dental Implants (MDI)

Developments in mini dental implants (MDI) manufacturing are aimed at making them more biocompatible and, at the same time, lighter, more durable and simultaneously safer than the existing implants. But, occasionally, during installation the failure of MDI may occur or cracks may appear, which could lead to the later failure of MDI. In order to understand and assess crack growth in titanium MDI, Finite Element (FE) software packages ANSYS v13 and FRANC3D v5 have been used. Using FRANC3D software different crack sizes and shapes have been modelled and simulations of crack propagations in three-dimensional model of MDI have been performed. Based on simulation results, the approximate fatigue life of damaged MDI was calculated.

Keywords: *damage, crack growth, titanium implants, MDI, FEM.*

1. INTRODUCTION

In recent years, both the literature and clinical practice showed more interest in finding new ways of treating and taking care of edentulous patients. Factors involved in successful therapy of edentulous patients are: quality bone support, optimal surface stress distribution at the foundation, adequate retention and stability of the prosthesis and muscular and occusal balance. Due to specificity of the lower muco-osseous foundation, construction of the lower complete denture is such a prosthetic problem and in most cases represents a challenge for the therapist [1,2].

During growth and development, the teeth of the permanent dentition are in mandibular and maxillary alveolar extensions. Soon after tooth extraction, the alveolar ridge remains on the spot and over time changes into so called residual alveolar ridge [3]. Residual alveolar ridge (RAR) with surrounding tissues makes the support for the mobile replacement. Numbers of researchers [4,5] agree that in terms of the intensity and direction of bone reduction process, the alveolar ridge of the lower jaw has more unfavourable course than the upper alveolar ridge. Even those patients with suitable and comfortable lower denture, eventually face the problem of the bone resorption [6]. In order to keep the prosthesis stable, its base should be relined from time to time [7]. Sometimes, if the resorption process is severe, neither padding nor complete denture refabricating seems to be effective [8].

Implantology has improved the therapy of edentulous patients within the range of poor to much expressed RAR resorption [9,10]. The oral rehabilitation, which uses two to four implants in supporting complete prosthesis, has been proved rather successful in 96 % of cases. Many authors have reported that patients were pleased with lower complete dentures supported by implants [11]. But, the atrophy of an edentulous jaw could prevent the use of standard implants, especially in the lower jaw area [12]. The anatomic limits, as well as alveolar ridge resorption, may also compromise the number of implants, their length or position in a bone [13,14]. The use of standard diameter implants for supporting complete denture often requires the ridge extension in order to obtain sufficient bone size. On the other hand, older patients with serious medical illnesses or those who use anticoagulant therapy may face the risk of surgical complications. Narrow-diameter titanium implants (2TA11 Titanium [15-17]), which are implanted without lifting the chop, represent a good rehabilitation method for patients suffering from mandibular atrophy. Those implants have the diameter of 2.75 mm to 3.30 mm, and they are placed on a jaw with a reduced bone volume.

Mini dental implants (MDI) are even smaller, with the diameter of 1.8 to 2.4 mm [11,18]. The advantage of MDI usage is minimally invasive surgical procedure which could be completed during one visit to dentist [19]. Compared to MDI (Figs. 1 and 2), conventional implants (of diameters 3.5 mm and above) require aggressive surgical procedure (cutting gingiva, lifting the chop) and osteotomia (bone preparation). Such procedure involves tissue healing process (i.e. tissue regeneration), the recovery of vascular function and implant osseointegration [20].

Figure 1. Mini dental implant (MDI)

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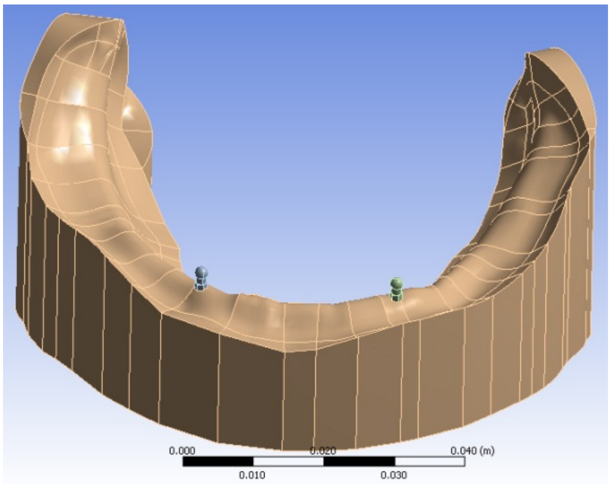

Figure 2. Positions of two MDIs in the mandible (virtual geometry)

The MDI installation is much simpler and consists of screwing the implant into the bone through the initial opening. Mini dental implants could be almost immediately loaded no matter how much time is needed for osseointegration [21]. Moreover, MDI retained overdentures offer higher retention and stability and transfer the occlusal load distributions to supporting tissues much better [22,23].

This is why there were no signs of a damaged bone, nor the areas of bone injury during the implantation. But, occasionally, during MDI installation failure may occur (Fig. 3) or very small internal cracks may appear which could lead, after a certain number of chewing cycles, to fatigue failure of implant. In order to investigate this phenomenon FE model of MDI has been used and crack growth in MDI was analyzed. Results of this investigation are presented in this paper.

Figure 3. MDI broken during installation

2. FINITE ELEMENT MODEL AND ANALYSIS

In order to understand and assess crack growth in MDI, several different Finite Element (FE) tools, capable of performing crack growth analyses in 3D geometry, have been analyzed and finally *ANSYS13* and *Franc3D v5* have been selected. Results presented earlier [22] have been used in order to define boundary conditions for crack growth analysis.

2.1 Determination of the magnitude and direction of load input

During installation of MDI micro cracks may be initiated on the implant's surface and their growth can cause fatigue failure of MDI in cyclic stress environment. In order to simulate fatigue crack growth in MDI, it is necessary to define realistic dynamic loads. There are sufficient data in literature [7,20] on the magnitude and direction of the mastication force, and in the case of edentulous patients the magnitude of force varies from 50 N to 210 N, but many authors take the average value of 100 N. In this study, horizontal and vertical forces of magnitudes 0.005 N were applied on spherical part of MDI during two consecutive time intervals (each interval is 1 second long). Later, these values were multiplied by cyclic load of amplitude 20,000 N in order to simulate fully reversed load with constant amplitude of 100 N. Since load on MDI, caused by changeable mastication force acting on the denture, is mostly much less than 100 N and varies with time, a random load spectrum (maximum amplitude of 20,000 N) was used for crack initiation predictions (Fig. 4). Time period for this spectrum was 94 seconds.

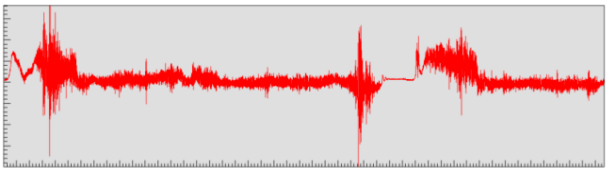

Figure 4. Random load spectrum used for crack initiation analysis

2.2 Static stress analysis results and identification of the critical MDI area

After the horizontal and vertical force had been applied, FE analysis was performed and obtained stress values were only 0.0459 MPa and 0.00639 MPa, respectively. This is due to the fact that small loads (0.005 N) were applied on MDI. But, during the second phase of the simulation these loads were multiplied by previously described random spectrum in order to get realistic dynamic loads. The main idea was to identify critical area of MDI in terms of fatigue crack appearance and to calculate the number of load cycles necessary to initiate the crack. To determine the number of cycles to crack initiation, Strain Life Method was used. Strain Life typically deals with a relatively low number of cycles and therefore addresses Low Cycle Fatigue, which usually refers to fewer than 100,000 cycles. The Strain Life equation is shown below:

$$\frac{\Delta\varepsilon}{2}=\frac{\sigma_{\mathrm{f}}'}{E}(2N_{\mathrm{f}})^{b}+\varepsilon_{\mathrm{f}}'(2N_{\mathrm{f}})^{c} . \qquad (1)$$

For Strain Life Method, the total strain (elastic + plastic) is the required input, but a widely accepted approach is to assume a nominally elastic response and then to relate local stress/strain to nominal stress/strain at a stress concentration location. To relate strain to stress Neuber's Rule was used:

$$\varepsilon\sigma = K_t^{2} eS . \qquad (2)$$

This calculation was nonlinear and was solved via iterative methods. The value of 1 for K_t was used, because mesh was refined enough to capture any stress concentration effects.

In Figure 5 the critical area of MDI (in terms of crack appearance) is clearly labelled and the number of blocks of load spectrum which would initiate the crack was found to be between 533 and 20,000. This means that total time before crack would start to grow is between 14 hours (the worst case) and 500 hours (optimal case).

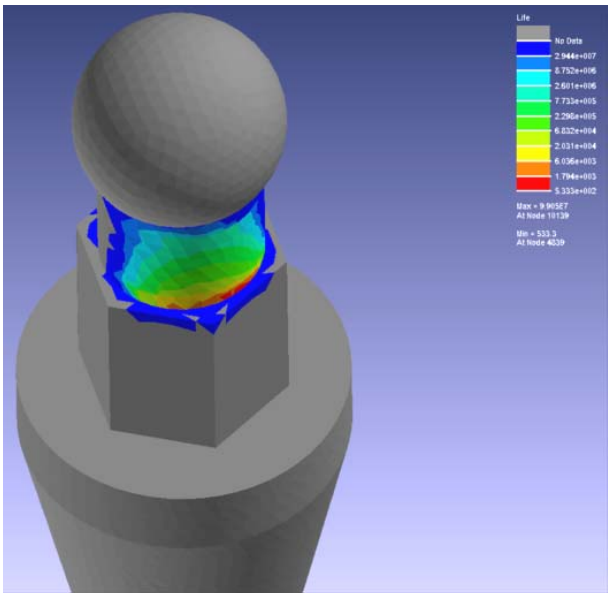

Figure 5. MDI's critical area in terms of fatigue crack appearance

2.3 Simulation of fatigue crack growth in ANSYS v13 and FRANC3d software

The first step in setting the crack growth properties was to define the initial crack length. The value of 0.05 mm was chosen. The second step was to define crack geometry. In our case, it is assumed that the crack in the implant is much like a semi-circular crack in tension.

Once the model is created in ANSYS, the FRANC3D steps necessary to perform crack growth analysis are: read the mesh information, rebuild the mesh around the crack, perform the ANSYS analysis and compute stress intensity factors (SIFs) [24,25]. The program begins the process of inserting the flaw into the original model and then meshes the resulting cracked model (Figs. 6 and 7).

The default crack extension criterion used for simulation was Specified Median Extension. The relative extension at each point along the crack front was computed based on the chosen equation and a user-specified median extension. The median extension occurs at the point along the crack front with the median Mode I SIF value. To simulate crack growth a Paris-like power law was used. The power law equation for determining relative extension is shown here:

$$\Delta a_{\text{node}\,i} = \Delta a_{\text{mean}} \left(\frac{\Delta K_{\text{node}\,i}}{\Delta K_{\text{mean}}} \right)^n . \tag{3}$$

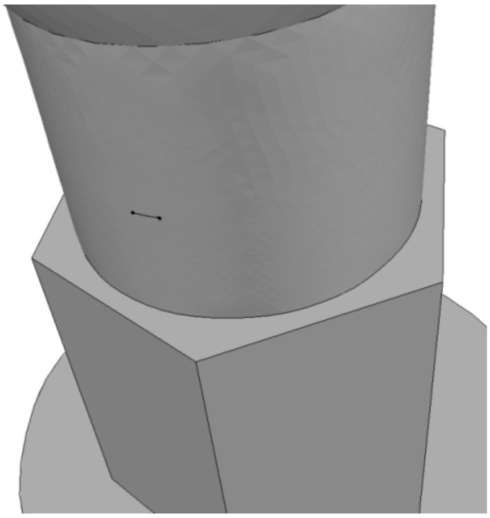

Figure 6. MDI model with initial crack length 0.05 mm

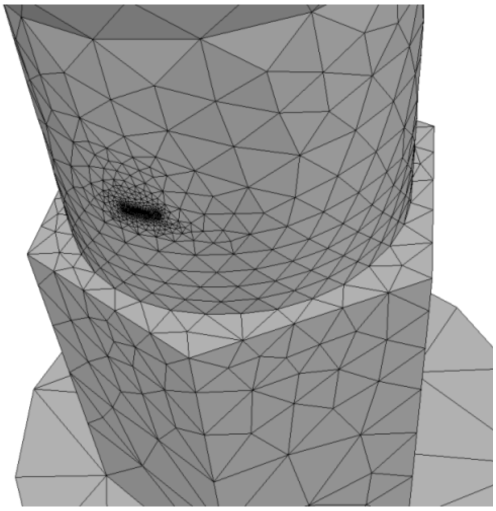

Figure 7. FE mesh of the crack

The next figures (Figs. 8, 9, 10 and 11) display the computed crack front in the model after five and ten steps of calculation. After each step the extension was scaled, polynomial was adjusted to fit through the new crack front points and the polynomial extrapolation was adjusted to ensure intersection with the model surface.

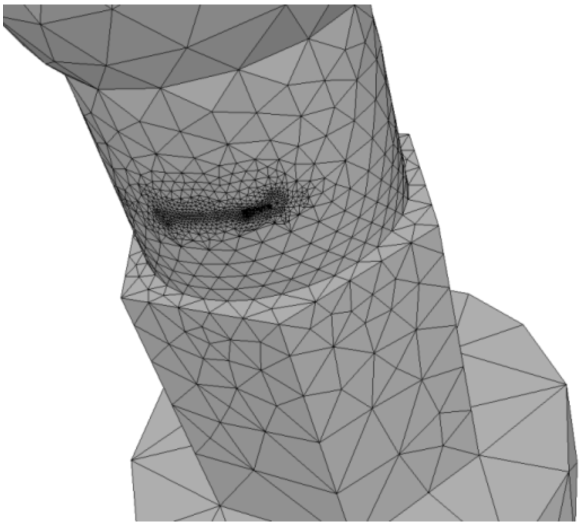

Figure 8. The computed crack shape in MDI after five steps of calculation

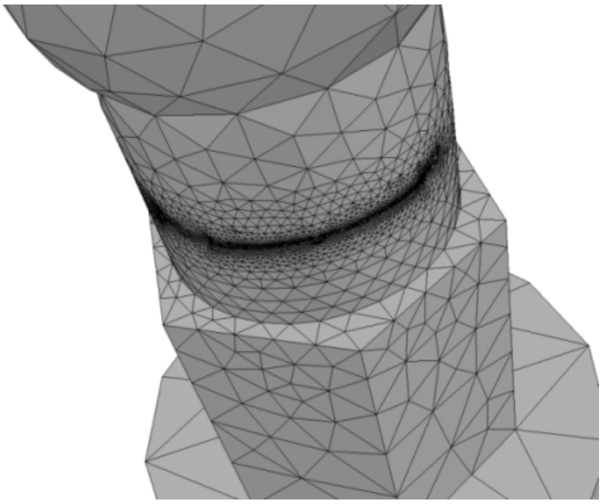

Figure 9. The computed crack shape in MDI after ten steps of calculation

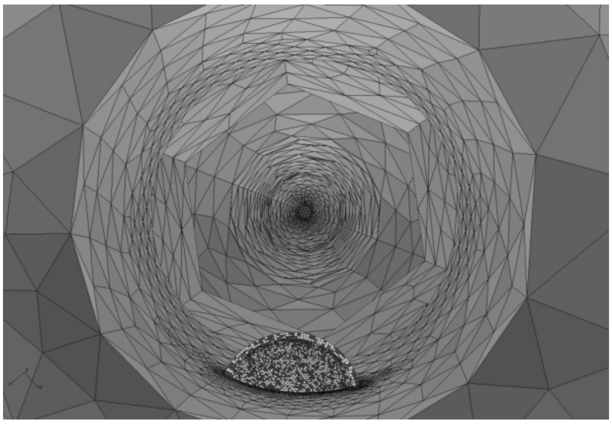

Figure 10. Interior view of crack front in the model after five steps of calculation

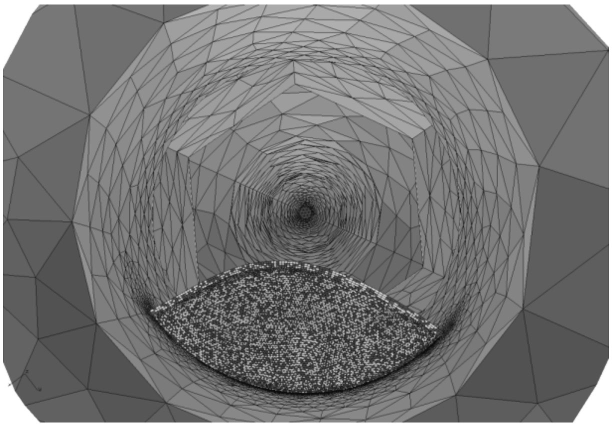

Figure 11. Interior view of crack front in the model after ten steps of calculation

Crack growth can be slow or even stop under certain loading conditions. This effect can be assessed using the crack retardation models. Here, the standard retardation algorithm was used. At the same time, the number of cycles which can lead to critical crack length was calculated in ANSYS. The plot in Figure 12 shows crack length versus cycle number. It must be noted that the initial crack length was 0.05 mm and the final crack length was found to be just over 1 mm after 500,000 cycles. This is why the calculation in FRANC3D continued until the crack reached the length of 1 mm. It turned out to be after the tenth step of calculation.

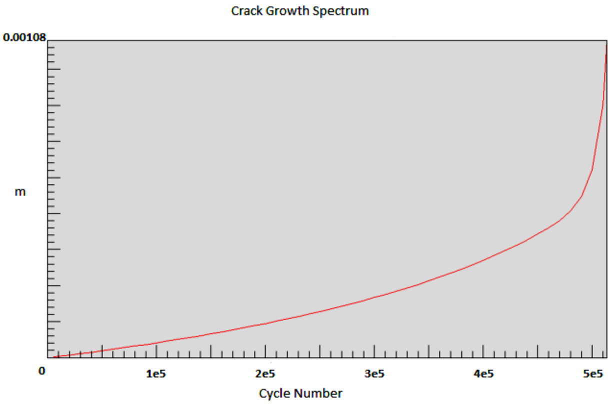

Figure 12. Crack length versus cycle number

3. DISCUSSION

The objective of the analysis carried out was to establish the methodology of investigation of fatigue phenomena, which, in most cases, cause the failure of the supporting structures. As the supporting MDIs are of vital importance for the toothless patients and because *in vivo* analysis of the fatigue phenomena is very difficult, the FEM calculations of the number of cycles that will lead to fatigue crack failure must be used in order to predict fatigue life of the implants.

Many different FEM based tools can identify critical areas in terms of fatigue crack appearance, but only FRANC3D can simulate crack growth through solid (i.e. through 3D geometry) and, at the same time, can be used to predict fatigue life. However, the FRANC3D uses ANSYS solver for the stress and strain analysis, so it cannot be used independently and the geometry must be imported from other CAD softwares. Regardless of these limitations, FRANC3D has excellent algorithms for automatic (or user defined) crack propagation simulations.

4. CONCLUSION

1. The main goal of this paper was to show that it is possible to simulate complex phenomenon such as fatigue crack failure, as well as micro crack growth in small supporting structures, such as MDIs.
2. It is well-known from the clinical practice that the MDIs are very reliable and that the crack failure at MDI rarely occurs during the exploitation. However, the crack failure at MDI occurs during the installation process. So, it is assumed that micro cracks in MDI can also occur during that process. In that sense, a critical area of the initial crack that could grow in the future was identified. The initial crack length was set to be just 0.05 mm.
3. After the crack was initiated, the number of cycles of randomly generated load spectrum of horizontal and vertical forces required to initiate crack growth, was determined. It was shown that the number of cycles, when expressed in hours, varies between 14 and 500 hours of exploitation (depending on where the crack would appear).

4. Further calculations showed that the critical crack length that would lead to fatigue failure of MDI was slightly greater than 1mm and that more than 500,000 cycles caused fatigue failure of MDI. This result confirmed the expectation that even damaged implant would work well for a long period of time. This also concurs with clinical practice experiences, which show that the fatigue failure of MDI rarely occurs during the exploitation.
5. Given that the worst load case scenario was used (load spectrum was very abrupt and rather long), it can be concluded that the minimal designed life of slightly damaged MDI of 520,000 cycles is absolutely acceptable, considering the fact that MDI is used mostly by elderly patients.
6. This study is the basis for further analyses that should include the variation of MDI geometry, i.e. further diminish of its dimensions. This will enable the installation of MDIs in significantly reabsorbed RARs, which is impossible today.
7. Finally, fatigue life prediction method presented in this paper can be used not only for MDIs, but for a wide range of damaged structures in aerospace industry, marine industry or automotive industry, where fatigue failures are not allowed, therefore must be prevented and minimized.

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NOMENCLATURE

$\Delta\varepsilon/2$	total strain amplitude
E	modulus of elasticity
N_f	number of reversals to failure
K_t	elastic stress concentration factor
e	nominal elastic strain
S	nominal elastic stress
ΔK	stress intensity factor range
Δa	relative extension of crack

Greek symbols

σ_f'	fatigue strength coefficient
ε_f'	fatigue ductility coefficient
ε	local (total) strain
σ	local stress

Superscripts

b	fatigue strength exponent (Basquin's exponent)
c	fatigue ductility exponent

СИМУЛАЦИЈА ШИРЕЊА ПРСЛИНЕ У ТИТАНИЈУМСКИМ МИНИ ДЕНТАЛНИМ ИМПЛАНТИМА (МДИ)

Александар М. Грбовић, Бошко П. Рашуо, Ненад Д. Видановић, Мирјана М. Перић

Унапређења у производњи мини денталних имплантата (МДИ) су углавном усмерена ка повећању њихове биокомпатибилности и, у исто време, издржљивости и безбедности, али и ка смањењу њихових димензија у односу на постојеће имплантате. Међутим, током уградње МДИ-а може доћи до његовог лома или настанка прслине која касније може проузроковати лом. Да би се анализирало ширење прслине у титанијумском МДИ-у, коришћени су софтвери за примену методе коначних елемената (МКЕ) *ANSYS v13* и *FRANC3D v5*. Коришћењем *FRANC3D* програма измоделиране су прслине различитих величина и облика на 3Д геометрији МДИ-а и извршено је симулирање њиховог ширења. На основу резултата симулације израчунат је приближан заморни век оштећеног МДИ-а.