The effect of bioinert electroexplosive coatings on stress distribution near the dental implant-bone interface

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Abstract

In this study, the first time a 2d finite element models of the titanium dental implant with Ti–Zr or Ti–Nb coating sprayed by electro explosive method and bone tissue located near were constructed. The present models simulate small surface implant section and bone located near. Three models with or without bioinert coating were studied in two configurations with cortical or cancellous bone tissue. All materials used in this study were assumed to be linearly elastic, homogenous, and isotropic to simplify the calculation. The stress distribution in the implant and bone tissue located near is uniform. The largest von Mises stress was obtained near the bone-implant interface in the implant area. It has shown that the stress pattern changed in the models with bioinert coatings. The second stress maximum appeared on the boundary between titanium subtract and the coating layer. The most significant changes in stress distribution were reached in the model with Ti–Zr coating. The electro explosive bioinert coatings help to reduce the stress shielding effect and implant failure probability because of bone strength loss. It also was found shear stress changes in the bone tissue.

1. Introduction

Currently, α-β-titanium-based alloy Ti6Al4V, also known as Grade 5 Ti64, is one of the most commonly used materials for the major part of implants on the medical market [1, 2]. Aluminium and vanadium applying as alloying constituents and high Young’s module are two significant disadvantages of this alloy. Ions release from the implant’s surface because of corrosion can cause pathologic health issues. There are lots of studies [3, 4] supporting cytotoxicity and carcinogenicity of aluminium and vanadium ions. Excessive aluminium intake increases the risk of breast cancer [5] and neurological conditions, such as Alzheimer’s disease [6]. Oral or inhalation vanadium and vanadium compounds intake affect negatively on the respiratory system, blood parameters, liver, neurological system, and other organs, and also increase malignant processes [7, 8]. There are lots of in vivo and in vitro studies supporting high safety qualities, corrosion resistance and biocompatibility of titanium alloys with niobium and zirconium additions [9, 10]. J Ureña and co-authors [11] show the high biocompatibility of niobium coating spread by different methods. It was archived positive cell viability and cell-material interaction of the osteoblast-like cells (MG-63). In the study [12] it has been shown that binary Ti–Zr alloy with different Zr concentrations (5, 10 and 15 mass%) has better electrochemical behaviour in medium simulated body fluid properties.

The high Young’s module of titanium alloy (∼110 GPa [13, 14]) compared to that of human bone (∼10–30 GPa of cortical bone; ∼0.1–2 GPa of cancellous bone [15, 16]) is much higher. It is another disadvantage of Ti6Al4V. The difference between Young’s modulus of bone and implant leads to a change in force distribution.
between metal and bone. According to Wolff’s Law, bone tissue near implant remodels in response to stress. This effect, known as stress shielding, increases the risk of implants failure [17].

The results achieved in the article [18] shown that Ti–Zr coating, sprayed by ionic-plasma deposition and containing 11 mas% and 22% of zirconium, 5 μm thick has Young’s modulus from 77 to 98 GPa instead of titanium substrate Young’s modulus equal 110 GPa. The same results were obtained in the study [19]. Young’s modulus of Ti–Nb coating ranges around 53–64 GPa.

Some studies show low Young’s module coating changing force distribution in bone tissue located near the implant. For example, applying the Poiyactive coating on the implant, described in the article [20], reduces the compressive radial stress at the bone-implant interface around the neck of the implant by a factor by 6.6 times and the tensile radial stress by a factor by 3.6 times.

Electroexplosive method, developing nowadays intensively, is used for spraying different coatings [21, 22] and also can be appeared for Ti–Zr or Ti–Nb coatings development. The result archived by studying electroexplosive Ti–Zr, Ti–Nb coating, shows that Young’s modulus of these coatings is lower as compared to Ti6Al4V titanium alloy or commercially pure titanium Young’s modulus [23]. However, the stress distribution between implant with electro explosive bioinert coatings and the bone study does not exist, because of it, this investigation is important. Finite element analysis (FEA) is one of the most effective and informative methods to studied problems associated with biomechanics. It supposes to avoid problems, occurring of analytical techniques, and also get higher-precision results [24, 25].

The aim of this work is the determinate effect of bioinert electro-explosive coatings on stress distribution near the dental implant-bone interface by means of FEA.

2. Research materials and methods

A dental implant made of Ti6Al4V titanium alloy was used as the substrate. The explosive spraying of Ti–Zr and Ti–Nb coatings were carried out on the electro electroexplosive installation EVU 60/10M by an electric explosion of zirconium or niobium foils. The power density was 2.0 GW/m². The weight of zirconium or niobium foils were 850 mg. The structure and morphology of sprayed coating and layer located near were analysed by means of scanning electron microscopy (Carl Zeiss EVO50 SEM).

The coatings’ thickness was studied on the cross-sections by digital solutions Leica Application Suite. The thickness of the obtained coating is about 63 μm. The Young’s module investigation of Ti–Zr and Ti–Nb coating was provided at low indenter load 50 mN by NHT-S-AX-000X Nano Indentation Tester. Nanoindentation was carried out on three lines at 5 μm from the surface-coating interface. The distance between indentation is 10 μm. The next indention series consisting of 3 lines starts at 10 μm from the surface-coating interface. Thus, the average distance between indention is 5 μm.

The Young’s module measure was provided by the Oliver–Pharr method by Nano Indentation Tester software. Under this method, the coating’s elastic modulus is obtained from indentation load-displacement data found during one cycle of loading and unloading.

The Young’s module E of the studied material is evaluated as:

\[
S = \int \beta \frac{2}{\sqrt{\pi}} E_v \sqrt{\lambda_c}
\]

where \(\beta\) in the range from 1.02 to 1.08 for different variants of indentation. The founded values \(S\) and \(A_c\) allows to determinate effective Young’s module in contact \(E_v\). This parameter is related to elastic constants as:

\[
\frac{1}{E_r} = \frac{1 - \nu^2}{E} + \frac{1 - \nu_i^2}{E_i}
\]

where E and \(E_i\) are Young’s modulus; \(\nu\) and \(\nu_i\) — Poisson coefficients of studied the material.

Thus, in order to determine the elastic modulus and hardness using the Oliver—Pharr method, it is sufficient to find the contact stiffness \(S\) from the loading diagram.

\[
\frac{P}{S^2} = \frac{\pi}{(2\beta)^2} \frac{H}{E^2}
\]

where \(P\) is indentation loading, and \(H\) is hardness. Equations don’t depend on indentation depth, contact area, presence of the material roughness and allow to obtain elastic module \(E\). Obtained values were shown in table 1.

The Hounsfield values of cancellous and cortical bone density are 1362.94 and 472.21, respectively [27]. The relationship between HA and kg m⁻³ is \(\rho = a + b \cdot H\), where \(a = 527, b = 0.44\) are coefficients, \(H\) is Hounsfield units. All materials properties are shown in table 1.

The three 2d models were created to investigate the effect of the electro-explosive bioinert coating on the stress distribution near the implant-bone interface. In the third model, also known as the reference model, the
intermediate layer, as well as the substrate, is Ti–6Al–4V alloy. This model was used to evaluate the stress distribution near the implant-bone interface without electro-explosive bioinert coating.

The length of studying models is 1000 \( \mu \text{m} \), the thickness is 300 \( \mu \text{m} \), while the titanium surface thickness is 87 \( \mu \text{m} \), the intermediate layer thickness is 63 \( \mu \text{m} \) as shown on figure 1, and bone layer thickness is 150 \( \mu \text{m} \). All dimensions are shown in table 2. The boundary BE is fixed. The compressing force \( F_1 \) parallel to the x-axis and equal 114.6 N. The bending strength \( F_2 \) is parallel to the y-axis and equal 29N. The general force \( F \) is the geometric sum of \( F_1 \) and \( F_2 \), which value is 118.2 N \cite{29}. Two forces are directed to the JF boundary on the other side of the models. The groups of boundaries AB, JC, HD, FE and AJ is free (figure 2). All models were developed and performed in COMSOL Multiphysics® 5.5. Meshing plays a major role in the accuracy of the results. There are 745634 mesh elements. All materials were assumed to be homogenous, isotropic, and linearly elastic. Models specification are shown in table 2.

All calculations were carried out according to the theory of elasticity for the stationary case. Therefore, Newton’s second law, which serves as the equilibrium equation, in tensor form has the form:

\[
0 = \nabla \sigma + F_V
\]

\( \sigma \) is stress, \( F_V \) is force per volume.

The generalised Hooke’s Law equation related stress tensor \( \sigma \) with deformation \( \varepsilon \) is given bellow:

\[
\sigma = E \cdot \varepsilon
\]

The Young’s module and Passion ratio relate to Lame parameters as follows:

\[
\lambda = \frac{\nu E}{(1 + \nu)(1 - 2\nu)}, \quad \mu = \frac{E}{2(1 + \nu)}
\]

The last required equation is the kinematic link between the displacement \( u \) and the deformation \( \varepsilon \) in the tensor form (Cauchy-Green strain tensor).

\[
\varepsilon_{cd} = \frac{1}{2}[(\nabla u)^T + \nabla u]
\]

\( T \) is a transposition operation.

| Material              | Young’s modulus, GPa | Poisson ratio | Density, kg m \(^{-3} \) |
|-----------------------|----------------------|--------------|--------------------------|
| Ti–6Al–4V             | 110 \cite{26}        | 0.35         | 4470.5                   |
| Ti–Zr coating         | 73.8                 | 0.36         | 6520                     |
| Ti–Nb coating         | 84.3                 | 0.35         | 8750                     |
| Cortical bone tissue  | 14.8 \cite{26}       | 0.3 \cite{26} | 1126.28                  |
| Cancellous bone tissue| 1.85 \cite{26}       | 0.3 \cite{26} | 734.77                   |

Figure 1. Electron microscopical cross-sections image of the bioinert coating formed by an electro explosive method: (a)—Ti–Nb coating with Ti–6Al–4V substrate; (b)—Ti–Zr coating with Ti–6Al–4V substrate.
3. Research results and discussion

The obtained result may numerically vary from stress in implants and located near bone tissue, because all materials were assumed to be linear elastic and isotropic to simplify calculations. The difference between isotropic and anisotropic materials was shown in the article [26].

However, as in the articles [30, 31], it was shown the unequal stress distribution between implant and bone. The higher von Mises stress locate in the implant area, rather than in bone tissue layer (figure 3). This difference can be described by higher Ti6Al4V Yong’s module, using as a construction material of implants. Maximum von Mises stress locates on bone-implant interphase (boundary JC) and boundary FE nearly fixed boundary BE. The second region with maximum stress value exists because of the studied model geometry.

In the bone layer, the maximum von Mises stress values were obtained near point B on the fixed boundary BE. Among the models’ variants with cortical tissue, the least von Mises stress in the bone layer was obtained in the reference models, in which the average and the maximum stress values are 0.3691 MPa and the 3.9655 MPa. The von Mises stress is larger in the model with Ti–Nb coating, with average stress value of 0.3942 MPa and the maximum stress value of 4.1995 MPa. The largest interface von Mises stress was obtained in model with Ti–Zr coating, in which the average stress value is 0.4066 MPa, and the maximum stress value is 4.3123 MPa. The least minimum stress value is 1.0727 · 10^{-6} MPa. It was obtained in the reference models. The largest minimum stress value of 1.2183 · 10^{-6} MPa was obtained in the model with Ti–Nb coating. The minimum value of 1.1918 · 10^{-6} MPa was obtained in the model with Ti–Zr coating.

In the models’ variants with cancellous bone tissue, the lowest von Mises stress was obtained in the reference models, in which the minimum stress value is 4.9102 · 10^{-7} MPa, the average stress value is 0.1032 MPa, and the maximum stress value is 1.0927 MPa. The von Mises stress is larger in the model with Ti–Nb coating. The minimum stress value is 5.8782 · 10^{-7} MPa, the average stress value is 0.1198 MPa, and the maximum stress value is 1.0727 · 10^{-6} MPa.
value is 1.2586 MPa. The highest interface von Mises stress was reached in model with Ti–Zr coating. Found minimum, average and maximum stress values are $6.4073 \cdot 10^{-7}$ MPa, the average stress value is 0.1291 MPa, and the maximum stress value is 1.3506 MPa.

The minimum, average and maximum von Mises stress values in models with cancellous tissue are less than in models with the cortical bone. The minimum von Mises stress values differ between variants with tissues in 2.1846 times for the reference model, 2.0726 times for models with Ti–Nb coating and 1.8600 times for models Ti–Zr coating. The differences between average stress values in variants with cortical bone tissue and cancellous bone tissue are 3.5761 times for reference models, 3.2906 times for models with Ti–Nb middleware, and 3.1498 times for models with Ti–Zr middleware. The maximum stress values differ in 3.6292 times, 3.3366 times and 3.1930 times, thoroughly.

In the intermediate layer, the maximum von Mises stress values were obtained near point C on the fixed boundary BE. Among the variants with cortical bone tissue, the largest intermediate layer von Mises stress was obtained in the reference models, in which the minimum stress value is 0.2814 MPa, the average stress value is 1.0698 MPa, and the maximum stress value is 5.9249 MPa. The von Mises stress is less in the model with Ti–Nb coating. The average and stress values reduce to 0.9326 MPa and 4.6427 MPa, thoroughly. However, the minimum stress value grows to 0.2832 MPa. The lowest interface von Mises stress was achieved in model with Ti–Zr coating. The minimum stress value is 0.2675 MPa, the average stress value is 0.8658 MPa, and the maximum stress value is 4.0112 MPa.

Among the variants with cancellous bone tissue, the highest intermediate layer von Mises stress was obtained in the reference models. The minimum stress value is 0.3323 MPa, the average stress value is 2.2102 MPa, and the maximum stress value is 19.5352 MPa. The von Mises stress is lower in the model with Ti–Nb coating. The minimum and average stress values reduce to 0.2627 MPa, 2.0689 MPa and 18.2784 MPa. The lowest interface von Mises stress was achieved in model with Ti–Zr coating. The minimum stress value is 0.2432 MPa, the average stress value is 1.9912 MPa, and the maximum stress value is 17.3587 MPa.

The minimum von Mises stress values in the reference model are larger in the variant cancellous tissue. It differs in 0.8467 times from the variant with the cortical bone. The minimum stress values in the models with bioinert coatings are larger in the variants with cortical bone tissue. The difference between variants with

![Von Mises stress distribution.](image-url)
different bone tissues is 1.0782 times for models with Ti–Nb coating and 1.0998 times for models Ti–Zr coating. The average and maximum von Mises stress values in models with bone cancellous tissue are larger than in models with the cortical bone. The differences between average stress values in variants with cortical bone tissue and cancellous bone tissue are 0.4840 times for reference models, 0.4508 times for models with Ti–Nb middleware, and 0.4348 times for models with Ti–Zr middleware. The maximum stress values in variants with various bone tissues differ in 0.3033 times, 0.2545 times and 0.2311 times, thoroughly.

In the substrate layer, the maximum von Mises stress values were obtained near point E on the fixed boundary BE. Among the variants with cortical bone tissue, the largest maximum von Mises stress value was obtained in the reference model. It is 8.4059 MPa. In the model with Ti–Nb coating, the maximum stress values decrease to 8.1253 MPa. The least maximum stress value of 8.0011 MPa was achieved in the model with Ti–Zr coating. At the same time, the largest average value of 0.6101 MPa was obtained in the reference model. The average stress value decreases to 0.6077 MPa in the model with Ti–Nb coating. The largest average value of 0.6084 MPa was obtained in the model with Ti–Zr coating. The largest minimum von Mises stress was reached in the model with Ti–Nb coating. It is 2.7396 · 10⁻⁴ MPa. The less minimum value of 1.7650 · 10⁻⁴ MPa was obtained in the reference model. In the model with Ti–Zr coating, the minimum stress decreases to the least value of 1.1007 · 10⁻⁴ MPa.

The bioinert coatings have a reverse effect on stress distribution in the models’ variants with cancellous bone tissue. The maximum von Mises stress values grow, whereas the intermediate layer Young’s module reduces. Instead of the variants with cortical bone tissue, the maximum von Mises stress value of 16.6668 MPa was obtained in the model with Ti–Zr coating. In the model with Ti–Nb coating, the maximum stress values decrease to 16.4231 MPa. The largest maximum stress value of 16.0305 MPa was obtained in the reference model. The largest average value of 1.2377 MPa also was found in model with Ti–Zr coating. The less average value of 1.1971 MPa in the model with Ti–Nb coating. The least average value of 1.1333 MPa was achieved in the model with Ti–Nb coating. The minimum von Mises stress values reduce with intermediate layer Young’s module decreasing. However, the largest minimum von Mises stress was reached in the reference model. It is 3.0457 · 10⁻⁴ MPa. The minimum value reduces to 2.4720 · 10⁻⁴ MPa in the model with Ti–Nb coating. The least minimum stress value of 1.0682 · 10⁻⁴ MPa was obtained in the model with Ti–Zr coating.

The minimum von Mises stress values in the reference model are larger in the variant cancellous bone tissue. It differs in 0.5795 times. For the models with bioinert coatings, the minimum stress values are larger in the variants with cortical bone tissue. The difference between variants with various bone tissues is 1.1082 times in models with Ti–Nb coating and 1.0304 times in models Ti–Zr coating. The average and maximum von Mises stress values in models with bone cancellous tissue layer are larger than in models with the cortical bone. The average stress values differ in 0.5384 times in reference models, 0.5077 times in models with Ti–Nb middleware, and 0.4915 times in models with Ti–Zr middleware. The differences between maximum stress values are 0.5244 times, 0.4947 times and 0.4801 times, thoroughly.

It also was found that stress in cortical bone tissue is higher than in cancellous tissue, as it was shown in the articles [32, 33]. Instead of it, the interface stress is higher in the models with cancellous bone tissue. It can be described by higher cortical tissue Young’s module.

By FEA, it was shown, that the von Mises stress on the cortical bone—intermediate layer interface (boundary JC) decrease along with the intermediate layer Young’s module, as shown on figure 4. Among the variants with cortical bone tissue, the largest von Mises stress was obtained in the reference models, in which the maximum and average stress values are 3.4144 MPa and 0.9156 MPa. The von Mises stress is less in the model with Ti–Nb coating. The maximum value decreases to 2.7899 MPa, and the average stress value reduces to 0.8097 MPa. The least ‘cortical bone—intermediate layer’ interface von Mises stress was achieved in model with Ti–Zr coating, in which the maximum stress value is 2.4606 MPa is, and the average stress value is 0.7606 MPa. Nevertheless, the minimum von Mises stress values grow, whereas the intermediate layer Young’s modules reduce. Therefore, the least ‘cortical bone—intermediate layer’ interface minimum stress value (0.3468 MPa) was achieved in the reference model. The minimum interface stress value increases to the 0.3626 MPa in the model with Ti–Nb coating. The largest minimum stress value of 0.3734 MPa is observed in the model with Ti–Zr coating.

Stress distributes in the variants with cancellous tissue in general similar as in models’ variants with cortical tissue. The largest ‘cancellous bone—intermediate layer’ interface von Mises stress was obtained in the reference models. The minimum stress value is 0.3032 MPa, the average stress value is 1.7176 MPa, and the maximum stress value is 9.9578 MPa. The von Mises stress is less in the model with Ti–Nb coating. The maximum stress value is 9.3731 MPa, and the average stress value is 1.5833 MPa. The least ‘cancellous bone—intermediate layer’ interface von Mises stress was obtained in model with Ti–Zr coating. The maximum stress value is 8.9331 MPa, and the average stress value is 1.5154 MPa. Nevertheless, the lowest minimum stress value of 0.2964 MPa was achieved in the model with Ti–Nb coating. The minimum interface stress value increases to the 0.2992 MPa in the model with Ti–Zr coating.

The minimum von Mises stress values in models with cancellous bone tissue layer are less than in models with the cortical bone. The differences in minimum von Mises stress values between variants with cancellous and bones tissues are 1.2481 times in the models Ti–Zr coating, 1.2234 times in the models with Ti–Nb coating and
1.1439 times in the reference model. The average and maximum values of the same stress in models with cancellous bone tissue layer are higher in models with the cancellous bone. The differences between average stress values in variants with cortical bone tissue and cancellous bone tissue are 0.5331 times in the reference models, 0.5114 times in the models with Ti–Nb coating, and 0.5019 times in the models with Ti–Zr middleware. The maximum stress values in variants with various bone tissues differ in 0.3429 times, 0.2976 times and 0.2755 times, thoroughly.

The studying of the model with electroexploive bioinert coating was shown that Von Mises stress increase in the bone tissue and decrease in the implant in models’ variants with cortical tissue. This overview indicates that electroexplosive coating transfer stress into the bone tissue. The most significant effect was shown in the model with Ti–Zr coating.

So, the electroexplosive coating supposed to decreasing stress shielding effect and possibility of implant failure because of bone loss. As Ti alloys [34] with low Young’s module, this coating decrease interface stress between bone and implant.

However, it is too early to state categorically, that the electroexploive coating decrease stress shielding. It needs to create more complex models taking into account bone and implant geometry and anisotropic properties of bone tissue.

It should be noted that, because of the different coating and subtract Young’s module, the second stress maximum was found at the coating-subtract interface (figure 5).

Among the variants with cortical bone tissue, the least average ‘intermediate layer—substrate’ interface von Mises stress of 0.6034 MPa was obtained in the reference models. In the model with Ti–Nb coating, the reviewed parameter goes up to 0.6209 MPa. The highest ‘cortical bone—intermediate layer’ interface von Mises stress was achieved in model with Ti–Zr coating. The value is 0.6292 MPa. However, the maximum von Mises stress reduce, with the intermediate layer decreasing Young’s modules. Therefore, the highest maximum stress of 0.7082 MPa was achieved in the reference model. The maximum interface stress value decreases to 0.7008 MPa in the model with Ti–Nb coating, and the least maximum stress of 0.7004 MPa is observed in the model with Ti–Zr coating. The highest minimum stress value is 0.3589 MPa. It was obtained in the model with Ti–Nb.
coating. The lowest minimum stress value is 0.3100 MPa and was achieved in the reference models. The minimum value of 0.3141 MPa was obtained in the model with Ti–Zr coating (figure 6).

The stress distributes in the intermediate layer—substrate interface in general similar as in variants with cortical bone tissue. However, maximum stress values grow with intermediate layer Young’s module decreasing. The highest maximum stress (1.8748 MPa) was achieved in the model with Ti–Zr coating. The maximum interface stress value decreases to the 1.7331 MPa in the model with Ti–Nb coating, and the least maximum stress value of 1.4559 MPa is observed in the reference model. The least average von Mises stress value of 1.1044 was obtained in Figure 5. Cross-section of Von Mises stress distribution.

Figure 6. Von Mises stress in the bone—intermediate layer interface (boundary HD) in the model with: (a)—cortical bone tissue (b)—cancellous bone tissue.
the reference models. The average stress is larger in the model with Ti–Nb coating. The highest average stress of is 1.3089 was achieved in model with Ti–Zr coating. Therefore, the highest minimum stress value in modulus is 0.7435 MPa. It was obtained in the reference model. The lowest minimum stress value of 0.7178 MPa was obtained in the models with Ti–Nb coating. The minimum value grows to 0.7222 MPa in the model with Ti–Zr coating.

The minimum von Mises stress values in models with cortical bone tissue layer are less than in the models with cancellous bone. The differences in minimum von Mises stress values are 0.4365 times in the models Ti–Zr coating, 0.5001 times in the models with Ti–Nb coating and 0.4170 times in the reference model. The average and maximum values of the same stress in models with cancellous bone tissue layer are higher in models with the cancellous bone. The differences between average stress values in variants with cortical bone tissue and cancellous bone tissue are 0.5463 times in the reference models, 0.5018 times in the models with Ti–Nb coating, and 0.4807 times for models with Ti–Zr coating. The maximum stress values in variants with various bone tissues differ 0.4865 times, 0.4044 times and 0.3736 times, thoroughly.

However, the second stress maximum cannot cause coating lamination or cracking formation on the interface, since the Ti–Nb and Ti–Zr coatings possess high adhesion to Ti substrate because of the coating particle penetration into the substrate material during electroexplosive straying [35].

Using of bioinert coating have a direct impact on the shear stress on the interface between bone and implant, that is key to the mechanical transduction mechanism of osteoblast proliferation and differentiation [36, 37].

In the studied model, on the major part of the interface between implant and bone, except the micrometres near the fixed board, shear stress is higher in variants with bioinert coating. However, near the fixed boundary, it was found that shear stress rapidly increases and the greatest values were found in the reference variant without bioinert coating (figure 7).

For the variants with cortical bone tissue maximum shear stress value reduce with intermediate layer Young’s module decreasing. The largest maximum stress value of 1.1336 MPa was found in the reference model. This parameter decreases to 0.9846 MPa in the model with Ti–Nb coating. The least maximum stress value of 0.8843 MPa was obtained in the model with Ti–Zr coating. However, the least minimum and average shear

Figure 7. Shear stress in the bone—intermediate layer interface (boundary JC) in the model with: (a)—cortical bone tissue (b)—cancellous bone tissue.
stress are 0.0704 MPa and 0.1101 MPa, respectively. These values were found in the reference model. The minimum stress value increases to 0.0868 MPa, and the average stress value grows to 0.1165 MPa in the model with Ti–Nb coating. The largest minimum stress value of 0.0887 MPa and the average stress value of 0.1195 MPa was reached in the model with Ti–Zr model.

For the variants with cancellous bone tissue, the maximum and average shear stress values change in the same way as in the variants with cancellous bone tissue. The largest maximum stress value of 2.8872 MPa was obtained in the reference model. The largest minimum stress value of 0.0887 MPa was found in the model with Ti–Nb coating. The least minimum stress value of 0.0868 MPa, and the average stress value of 0.1165 MPa was reached in the model with Ti–Zr model.

The least minimum and average shear stress values equal 0.0320 MPa was found in the reference model. The average stress value increases to 0.0368 in the model with Ti–Nb coating. The largest average stress value of 0.0394 MPa was reached in the model with Ti–Zr model. The largest minimum stress value of 0.0237 MPa was found in the reference model. In the model with Ti–Nb coating, the minimum stress decreases to the lowest value of 0.0204 MPa. The minimum stress value is 0.0204 MPa in the model with Ti–Zr coating.

The minimum shear stress values are larger in the variants with cortical bone tissue layer. In the reference models, the difference of the values between variants with cortical and cancellous bone layer is 2.9755 times. Values reached in models with electro explosive Ti–Nb, and Ti–Zr coatings differ in 23.5158 times and 4.3436 times, thoroughly. The average results are also larger in variants with a cortical bone layer. The average stress values differ in 3.4385 times for reference models, 3.1650 times in models with Ti–Nb coating, and 3.0313 times in models with Ti–Zr coating. The maximum values are higher in variants with cancellous bone tissue and differ in 0.3926 times 0.3498 times and 0.3283 times in the reference models, in the model with Ti–Nb and Ti–Zr coating, thoroughly.

The shear stress values decrease from the implant-bone boundary. At the same time, in the bone layer, the maximum shear stress is higher in models with bioinert coating. In the model’s variants with cortical bone tissue, the largest maximum stress values were obtained in the model with Ti–Nb model. At the distance of 1 μm from the implant-bone boundary, for the variants with cortical the largest maximum shear stress is 0.2894 MPa (figure 8). In the model with Ti–Zr coating, maximum shear stress decrease to 0.2861 MPa at the same distance. The least value of 0.2739 MPa was reached in the reference model.
However, in the model’s variants with cancellous bone tissue, the largest shear stress value of 0.1525 MPa was found in the model with Ti–Zr coating. This parameter decreases to 0.1402 MPa in the model with Ti–Nb coating. The least maximum value was reached in the reference model. It is 0.1121 MPa.

Regardless of the bone tissue, the largest minimum and the average values were obtained in the models with Ti–Zr coating. For the variant with cortical bone tissue, the minimum and average values are 4.2465 × 10⁻⁴ MPa and 0.1186 MPa. For the variants with cancellous tissue, these parameters are equal 1.5564 × 10⁻⁴ MPa and 0.0381 MPa, thoroughly. In the model with Ti–Nb coating, the minimum and average shear stress values decrease from 4.0809 × 10⁻⁴ MPa and 0.1155 MPa in the variant with cortical tissue to 1.4192 × 10⁻⁴ MPa and 0.0355 MPa in the cancellous bone. The lowest minimum and average shear stress values were found in the reference model. For the variant with cortical bone tissue, these parameters are 3.7869 × 10⁻⁴ MPa and 0.1091 MPa. For the variants with cancellous tissue, the minimum and average values are equal 1.1780 × 10⁻⁴ MPa and 0.0307 MPa, thoroughly.

In view of the foregoing, it can be affirmed, that studied bioinert coating can supposed osseointegration mechanism by shear stress increasing.

4. Conclusion

In this study was found that the von Mises stress distributes in studied model unequal. The maximum values located in the implant area near the bone-implant interface (JC) and the boundary FE. The layer of bioinert Ti–Zr or Ti–Nb coating changes the stress distribution in the model. The Stress values decrease in implant area grow in bone tissue. These changes contribute to reducing stress shielding. It should be noted that vale increase near the coating-substrate interface. Ti–Zr coating has the most significant impact on stress distribution because of its lower Yong’s module. The average shear stress values are higher in variants with bioinert coating. However, maximum stress values are higher in the reference model. These results were achieved for both bone tissue types. Despite the simplicity of the studied model, it possible to conclude, that studied coating can favourably change the life cycle of the implant.

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