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SUBSTANTIATION FOR THE APPLICATION OF THE POROUS INSERTS INTO THE PLATE IMPLANTS ACCORDING TO THE STRENGTH CONDITION

S.G. KONYUCHOVA*, G.I. ROGOZHNIKOV*, Y.I. NYASHIN, S.A. CHERNOPAZOV**, S.V. EREMINA**, K.V. DOZMOROVA****

*Perm State Medical Academy, 39, Kuybishev Street, 614000, Perm, Russia
**Department of Theoretical Mechanics, Perm State Technical University, 29a, Komsomolskii prospect, 614600, Perm, Russia, e-mail: chs@theormech.pstu.ac.ru

Abstract. Calculations of the plate implant constructive parameters with the porous titanium inserts according to the long-time strength conditions under the chewing load were carried out. Porous inserts were simulated with the help of the effective characteristics. To calculate their strength the coefficient of the local stress concentration was calculated. The maximum thickness of the implant frame made of solid titanium was calculated depending on the inserts porosity.

Key words: plate implant, porous insert, effective characteristics, local stresses, strength, finite element method

Introduction

In this work the new design of the plate implant with the porous insert of titanium is investigated from the point of view of the long-time strength. The porous inserts provide reliable adhesion with the bone tissue and as result of this they create conditions for more uniform distribution of stresses in the spongy bone. However, the pores are the stress concentrators, therefore it is required to calculate the implant long-time strength under the repeated chewing efforts. The porous inserts were simulated with the help of the effective characteristics. The quantitative evaluations of the stress state were carried out by the finite element method. Local stresses in the porous inserts were evaluated with the help of the stress concentrator found by calculations. The strength of the adhesion with the bone tissue is increased with the increase of the porous inserts surface lateral area. However, in this case the stresses in the external frame made of solid titanium increase too. To substantiate for the design the following tasks were resolved: the effective characteristics of the porous inserts were calculated depending on the pores percentage contents; the local stresses in the porous structure were investigated; width of the external force frame was determined according to the strength condition depending on the insert porosity. The pores were simulated by the round regulated holes. Calculations of the effective characteristics and local stresses were made with the help of the finite element method.

The present state of the problem

According to the data of the World Health Protection Organization 75% of the Earth population suffer from partial or complete adentia .In our country the frequency of this pathology is met in 40-70 % [1]. The loss of teeth is inevitably connected with the decrease of the chewing efficiency, violating the speech, aesthetics and in some cases with the temporomandibular joint illness. To avoid the undesirable complications in the dentofacial system the replacement of the dental arch defects by the removable and fixed denture structures is carried out. It is stated that 15% of people over 40 need complete removable dentures [2]. According to A.Rybakov data 24.9% of patients do not use the removable dentures. In these and other clinic cases the implants make it possible to find again the “permanent” teeth.

Lately the breakthrough in the sphere of technologies and materials for the implant production was exhibited, the issues of the bone tissue formation and its interaction with the implant are studied in details. We offered a principally new design of the plate intramaxillary implant consisting of head, neck and intramaxillary plate which has a compact and porous structure.

The experiments conducted on the laboratory animals showed that the combination of the compact and porous structures provides a reliable implant function in the jaw due to the bone tissue formation around the implant and its penetration into the intramaxillary plate pores.

Statement of the problem

The plate implant consists of the force titanium frame 2 filled up with the porous titanium 3 (Fig.1). The problem is to choose the constructive parameters providing the maximum area of the porous surface on the lateral surfaces at the given dimensions and strength condition fulfilment. Width of the frame L and material porosity from 30 to 70% refer to the variable parameters. The sizes a = 23 mm, b = 9.5 mm and the implant thickness h = 1.2 mm are fixed, the frame width L varies in the interval 0.3-2 mm. The average vertical chewing load is accepted as 300 MPa. The admissible once-only short-term loads are up to 500 MPa.

The task is to maximize the area of the lateral surface of the porous titanium implant under limitations on dimensions and strength.

In order to check up the strength condition it is required to solve the boundary-value problem of the elasticity theory with the given geometric implant parameters as well as its mechanical and strength characteristics and the chewing load applied to it.

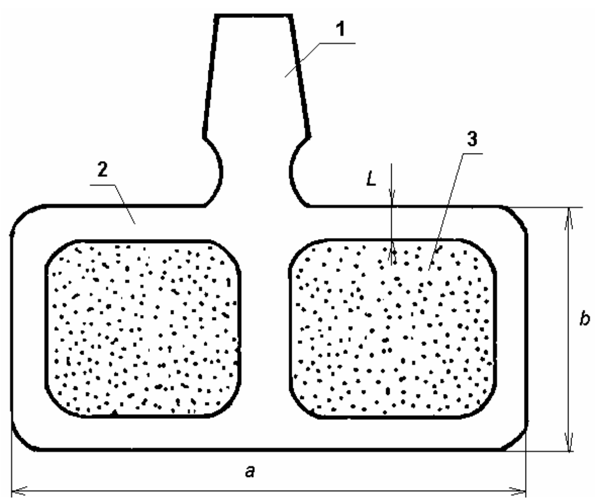

Fig. 1. The plate implant with the application of the titanium porous insert.

The following assumptions are accepted in its solving:

- The force is applied along the implant stem (1 in Fig.1), the lateral components of this force are not taken into account.
- Plane stress state of the investigated area is considered.
- The pores are replaced by the regularly located holes filled up with the spongy bone tissue.
- Elastic behavior of the porous inserts is simulated with the help of the effective modules of elasticity.
- The local stresses in the porous insert are calculated with the help of the stress concentrator coefficient.
- The calculation scheme presents fragment of the jaw with the implant fastened along the edges.

Effective characteristics of the porous inserts

According to the assumption accepted the structure of the porous insert is replaced by the regulated one. Share of the materials (bone and titanium) in the regular structure corresponds to the values of these parameters for the real insert structure when the pores are completely filled up with the bone tissue. For the macroscopically uniform stress and strains fields the local fields of stresses and strains possess the property of periodicity. In this case the effective modules of elasticity may be determined from the local problem solution to the periodicity cell. Macroscopically such material will be the monotrope composite.

One of the spread inclusion schemes (in our case these are holes with the bone tissue) in one-directional composite is the hexagonal packing. Material with such packing has symmetry axis of the 6-th order that is equivalent to the symmetry axis of the infinitely high order [2]. The scheme of the periodicity cell at the hexagonal packing for the round inclusions is shown in Fig.2.

It follows from the properties of the cell geometric symmetry that on the boundaries of the rectangular area shown in Fig. 1 while being stretched (or compressed) in the elastic symmetry axial direction the normal vector components of the displacement are constant while the tangential stress is absent. It allows simplifying the calculation scheme and accepting it in the form shown in Fig. 3.

The ratio of the calculated area typical sizes in Fig.3 depending on the volume content of Ψ inclusion is expressed by the following formula:

$$\frac{R}{a}=\left(\frac{2\Psi}{\sqrt{3}\pi}\right)^{1/2}.$$

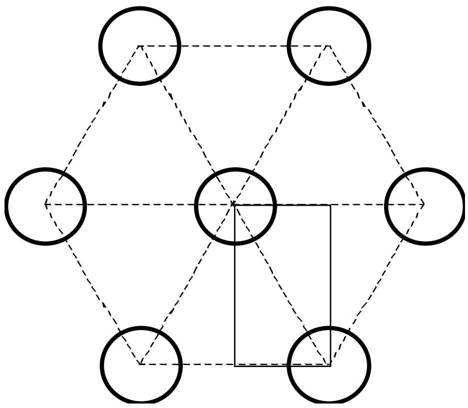

Fig. 2. The periodicity cell, material with the hexagonal packing of fibres.

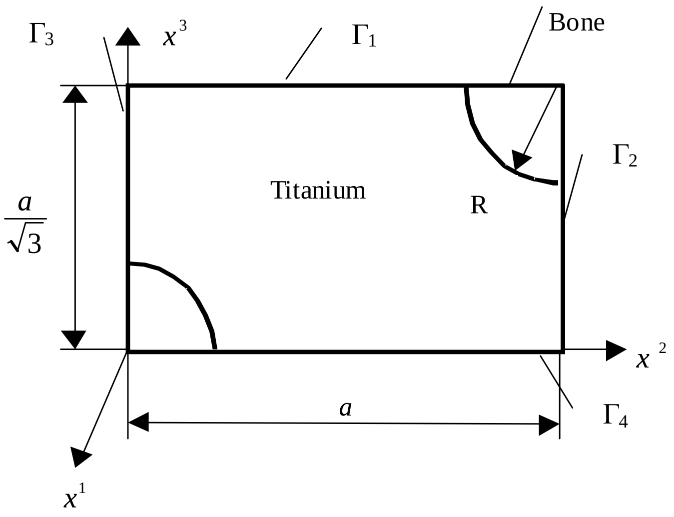

Fig. 3. The periodicity cell.

The problem is solved in two stages. At the first stage the following boundary-value problem is solved

$$\sigma_{ij,j} = 0,\ \sigma_{ij} = A_{ijkl}\varepsilon_{kl},\ \varepsilon_{ij} = (u_{i,j} + u_{j,i})/2,$$

$$A_{ijkl} = \begin{cases} A^f{}_{ijkl} \ \ in\ the\ \ fiber, \\ A^M{}_{ijkl} \ \ in\ the\ matrix, \end{cases} \qquad (1)$$

with the boundary conditions

$$u_1 = 0,\ \ \sigma_\tau = 0\ \ at\ \Gamma_1,\ u_2 = a/\sqrt{3},\ \ \sigma_\tau = 0\ \ at\ \Gamma_2,$$

$$u_1 = 0,\ \sigma_\tau = 0\ \ at\ \Gamma_3,\ u_2 = 0,\ \sigma_\tau = 0\ \ at\ \Gamma_4.$$

The given conditions correspond to the cell stretching along the axis x^3 by unit average strain $\langle \varepsilon_{33} \rangle$. In this solution the plane strain condition is accepted where the average value of the strain component $\langle \varepsilon_{11} \rangle = 0$.

The received local stress fields are averaged over the cell volume:

$$\langle \sigma_{\kappa\kappa} \rangle = \frac{1}{V}\int \sigma_{kk} dV \qquad (\ not\ sum\ over\ k) \qquad (2)$$

According to the problem conditions of the first stage $\langle \varepsilon_{33} \rangle = 1,\ \langle \varepsilon_{22} \rangle = \langle \varepsilon_{11} \rangle = 0$.

The macroscopic dependences between the stresses and strains take the following form (the upper index in parentheses indicate the stage number):

$$\left\langle \sigma_{11}{}^{(1)} \right\rangle = \left\langle A_{1133}{}^{(1)} \right\rangle \langle \varepsilon_{33} \rangle = \left\langle A_{1133}{}^{(1)} \right\rangle,$$

$$\left\langle \sigma_{22}{}^{(1)} \right\rangle = \left\langle A_{2233}{}^{(1)} \right\rangle \langle \varepsilon_{33} \rangle = \left\langle A_{2233}{}^{(1)} \right\rangle, \qquad (3)$$

$$\left\langle \sigma_{33}{}^{(1)} \right\rangle = \left\langle A_{3333}{}^{(1)} \right\rangle \langle \varepsilon_{33} \rangle = \left\langle A_{3333}{}^{(1)} \right\rangle.$$

With the help of relations (3) one may find three effective components of the tensor of elasticity. They are at the right hand side of equations. Determining the missing components is carried out at the second stage by means of the problem (1) solution with the boundary conditions

$$u_n = 0,\ \ \sigma_\tau = 0\ \ at\ \ \Gamma_i,\ \ i = 1,2,3,4,$$

where u_n being the normal displacements at the area boundaries. The strain in the axial direction x^1 is accepted as equal to one: $\varepsilon_{11} = \langle \varepsilon_{11} \rangle = 1$.

After the problem solving according to formula (2) the average values of the normal stresses are calculated and the following effective components of the rigidity tensor are determined:

$$\left\langle \sigma_{11}{}^{(2)} \right\rangle = \left\langle A_{1111}{}^{(2)} \right\rangle \langle \varepsilon_{11} \rangle = \left\langle A_{1111}{}^{(2)} \right\rangle,$$

$$\left\langle \sigma_{22}{}^{(2)} \right\rangle = \left\langle A_{2211}{}^{(2)} \right\rangle \langle \varepsilon_{11} \rangle = \left\langle A_{2211}{}^{(2)} \right\rangle,$$

$$\left\langle \sigma_{33}{}^{(2)} \right\rangle = \left\langle A_{3311}{}^{(2)} \right\rangle \langle \varepsilon_{11} \rangle = \left\langle A_{3311}{}^{(2)} \right\rangle.$$

Mechanical properties of titanium and spongy bone tissue used at the calculation of the effective characteristics are given in Table 1.

Table 1. Mechanical properties of materials.

Material	Module of elasticity *E*, MPa	Poisson's ratio
Spongy bone	5000	0.3
Titanium	110000	0.35

Application of finite element method (FEM) to the calculation of the effective modules of elasticity yields the results given in Table 2.

Table 2. Effective coefficient of rigidity of the porous titanium filled up with the spongy bone, calculated with FEM help.

Pores, %	$\langle A_{1111} \rangle$	$\langle A_{1122} \rangle$	$\langle A_{1212} \rangle$	$\langle A_{2222} \rangle$	$\langle A_{2233} \rangle$	$\langle A_{2323} \rangle$
30	104511	37544	41891	74725	33400	20662
50	72379	21750	15409	43322	19940	11691
70	44472	11834	8922	22919	12121	5399

Then according to the found components of the tensor of elasticity the effective compliance tensor components were calculated. With their help the values of the elastic technical constants were calculated. They are given in Tables 3-5. Comparison of the received results with the calculations by Voigt formula is also performed there.

Table 3. Module of elasticity in the plane of isotropy.

Pores, %	*E* in the plane of isotropy, MPa		Error, %
	Voigt	FEM	
30	78514	54761	43.3
50	57523	31907	80.3
70	36531	15698	132.7

Table 4. Module of elasticity in the direction perpendicular to the plane of isotropy.

Pores, %	*E* in the direction perpendicular to the plane of isotropy, MPa		Error, %
	Voigt	FEM	
30	78514	78461	0.06
50	57523	57447	0.13
70	36531	36479	0.14

Table 5. Poisson's ratio in the plane of isotropy.

Pores, %	Poisson ratio in the plane of isotropy		Error, %
	Voigt	FEM	
30	0.35	0.347	0.8
50	0.35	0.343	2
70	0.35	0.338	3.4

Application of the simplest approach to the evaluation of the considered composite technical elastic constants with the use of Voigt hypotheses gives a considerable error in the module of elasticity in the plane of isotropy that is increased with the growth of the void volume and runs to 132%. Therefore in further calculations the material technical elastic characteristics were used which are received by averaging with the help of FEM and given in Tables 3-5.

Strength criteria

As a strength criterion at the momentary maximum chewing load on the implant the criterion of the specific potential energy of deformation is accepted (the forth strength theory) [5]. The experiments confirm well the forth theory of the plastic materials working in the same way for stretching and compression. In accordance with this theory the dangerous condition (yielding) in three-dimensional stress state comes at a time when the specific potential energy of deformation u_{ϕ} achieves its limiting value. Strength condition according to this theory will be as follows:

$$\sqrt{\frac{1}{2}\left[(\sigma_1-\sigma_2)^2+(\sigma_2-\sigma_3)^2+(\sigma_3-\sigma_1)^2\right]}\le\frac{\sigma_y}{n}=[\sigma],$$

where σ_y – the yield limit (defines the material resistance to the rise of plastic deformations in compression), n- denotes a safety coefficient, σ_1, σ_2, σ_3 stand for principal stresses. Normally, yield limits comprise 0.5-0.9 of the strength limit σ_s , with major values referring to the strength limit for alloyed steels and titanium alloys. According to the condition of the static strength the low-cyclic fatigue is excluded. An endurance limit σ_r is the maximum value of periodically alternating stress which the material can withstand practically infinitely long without the fatigue cracks emergence. The condition of strength in this case may be written as

$$\sigma_{\max}\le\frac{\sigma_r}{n_r},$$

where n_r is a safety coefficient.

Research into the stress- strain state of the plate implant has shown that hazardous areas are characterized by a predominant absolute value for one of the principal stresses, whereas its change in chewing corresponds to an asymmetric loading cycle. Generally, it is the stress intensity [5] that is taken for an equivalent stress.

The endurance limit for an asymmetric cycle may be calculated by the formula [5]:

$$\sigma_r=\frac{2q_1}{1-r+(1+r)q_1}\sigma_s,\quad q_1=\sigma_{-1}/\sigma_s,\quad r=\sigma_{\min}/\sigma_{\max},$$

where σ_{-1} is the endurance limit for a symmetric cycle, σ_{max} - the ultimate cycle stress by an absolute value, $\sigma_{\min}$ - the least cycle stress by an absolute value, r - a cycle characteristics (asymmetry coefficient), calculated with regard to actual stress signs.

To evaluate a force frame strength there have been used the following experimental cast titanium data:

ultimate strength σ_s……………………………………..410 Mpa,
yield limit σ_y=0.7σ_s …………………………………287 MPa,
symmetric cycle endurance limit σ_{-1} = 0.28σ_s………114 MPa,
asymmetry coefficient r…………………………..….0,
asymmetric cycle endurance limit σ_0………………...178.4 MPa.

The calculation with the use of effective characteristics makes it possible to find macroscopic (averaged by a composite) stresses. Local stresses in a titanium matrix can considerably exceed the averaged ones. That results in the necessity to investigate local stresses for determining a porous titanium safety coefficient. Local and macroscopic stress fields were compared according to the stress intensity value received from the periodicity cell problem solution (Fig. 2) for a plane- stress state. The maximum stress concentrator $k = \dfrac{\max \sigma_i}{\langle \sigma_i \rangle}$ ($\langle \sigma_i \rangle$ - an average stress intensity over the titanium matrix σ_i) was determined within various combinations for average assigned strains from the following ranges: $-1 \le \langle \varepsilon_2 \rangle \le 1,\ -1 \le \langle \varepsilon_3 \rangle \le 1$. The concentration coefficient k calculated values are given in Table 6.

Table 6. The stress concentrator in the porous titanium.

Pores, %	30	50	70
$k = \max \sigma_i / \langle \sigma_i \rangle$	2.64	2.7	2.6

Figure 4 shows an example of the stress concentrator calculation.

The stress concentrator coefficient in the porous titanium may be viewed as independent of porosity and as initially equal to 2.7. The ultimate strength with regard to the stress concentrator discovered is equal to 151.8 MPa which satisfactorily meets the experimental data: σ_s=129-291 MPa. The following values of the porous titanium strength parameters have been used in the calculation:

ultimate strength σ_s ………………………………..……151.8 MPa
yield limit σ_y=0.7σ_s ………………………………...….106.3 MPa
symmetric cycle endurance limit σ_{-1} = 0.28σ_s ………..…42.5 MPa
asymmetry coefficient r………………………………….0
asymmetric cycle endurance limit σ_0……………………66.4 MPa

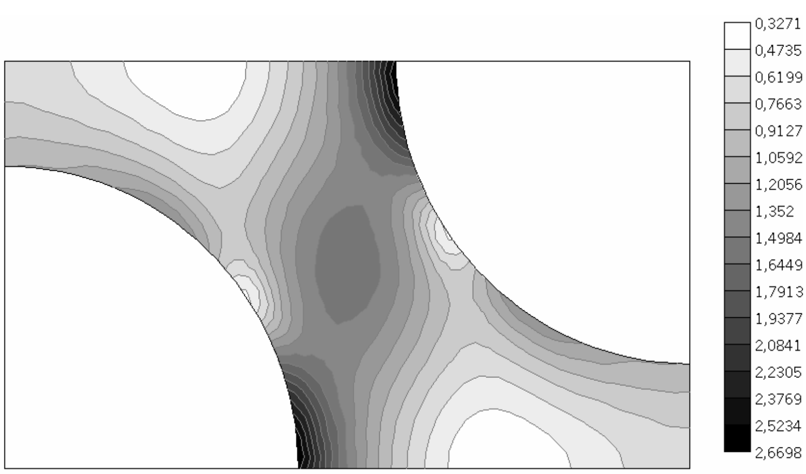

Fig. 4. The stress concentrator in the titanium matrix. The pores are filled with the spongy bone tissue. $\langle\varepsilon_x\rangle$= -1, $\langle\varepsilon_y\rangle$= +1.

Stress state features

This section contains the analysis of the implant stress state. The analysis has been done for finding out strength hazardous areas. The drawings feature some of resulting calculations for the implant with the frame width *L*=1.2 mm and with insert porosity be equal to 50%. A stress state under the vertical loading is characterized by a stress concentrator in the place of fastening the neck to the implant intrabone section (Fig. 5), with the concentrator of the first order being conditioned by longitudinal compressive stresses. The partition width increase under the stem slightly (up to 7 %) reduces the stress intensity value.

Another feature of the stress state is a large value of tensile stresses in the titanium frame lower section. However, the value of these stresses is approximately twice less than the value of compressive stresses at the neck's footing. Under of action of maximum loading equal to 500 N, the maximum value in the present version of the calculation is found to be equal to 1.08. The minimum static safety coefficient in this case is equal to 0.93. Thus, when rare momentary loads of the above-mentioned value are occasionally applied in the concentrator area there will appear plastic deformations, and the material will deform in a low-cyclic fatigue mode.

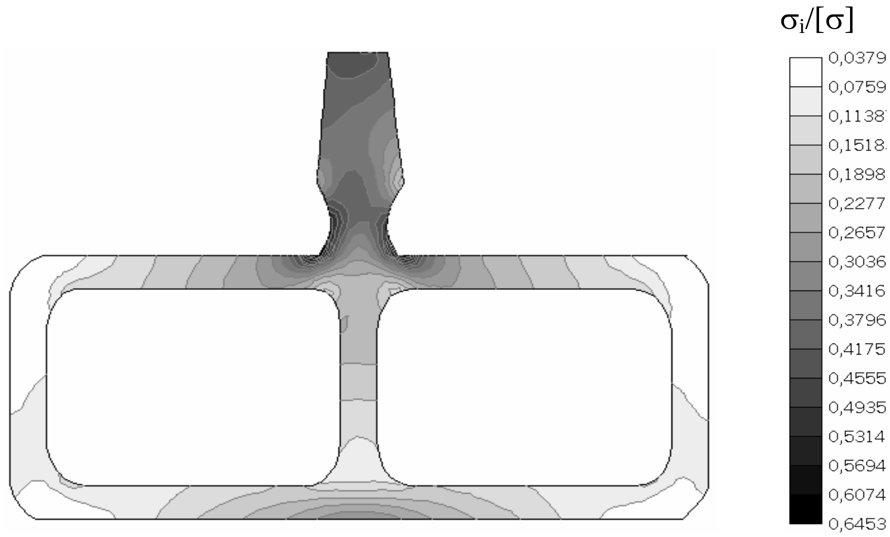

Fig. 5. The force frame static strength under the action of force 300 N and a 1.55 safety factor.

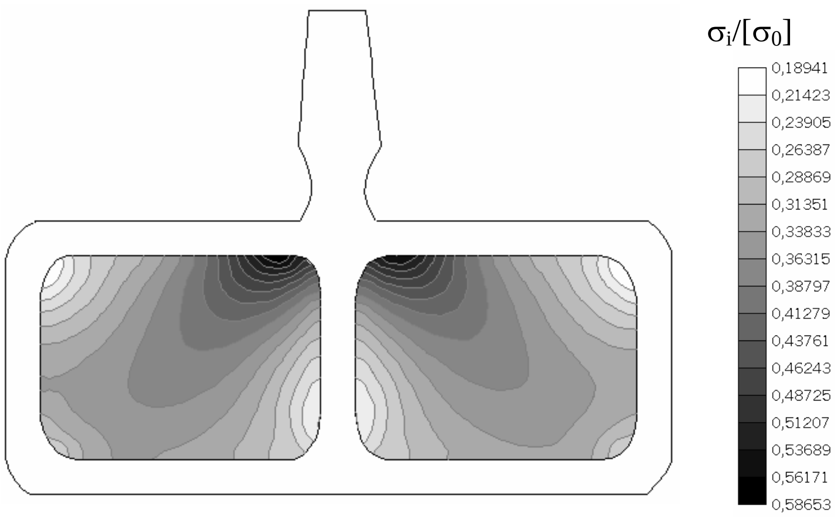

Fig. 6. Porous titanium insert long-time strength with recurrent loads of 300 N being applied. A safety coefficient is 1.7.

Calculations for long-time strength (with the effect of recurrent loads of 300 N) show that in this design version the safety coefficient in so far as stress concentration areas are concerned is less than a unity and makes up 0.96 %. It is suggestive of the possibility to give (in the course of time) rise to the production of fatigue cracks.

Calculation for the long-time strength of porous inserts is presented in Fig. 6.

According to the results of the calculations made one may draw the following conclusions. The titanium frame safety coefficient of the construction under study is insufficient for a guaranteed durable service life because of the failure to meet the static strength criterion with maximum loading being 500 N as well as the long-time strength criterion with recurrent loadings of 300 N being applied in the stress concentrator areas. In the titanium insert the conditions of long-time strength are implemented. The reasons for the given situation are the stress concentrator, titanium high porosity (because of which the implant frame is liable to overloading) and also the insufficient frame thickness. In terms of long-time strength the conjugation of the neck with the implant intrabone part is also a weak spot. The construction may be strengthened through enhancing the neck thickness and the thickness of the conjugate area using for instance the neck of a cylinder form.

The frame width calculation

To substantiate the selection of the frame width *L* depending on the insert porosity there have been done calculations of the problem versions in which the insert porosity and the frame width were taken as variables. The porosity was estimated according to the long-time strength criterion with the help of the designed value of the safety coefficient. The results of these calculations are diagrammed in Fig.7-9.

Conclusions

Strength calculations done in this paper enabled to ground a minimum admissible force frame wall width for the implant design in accordance with the condition of long-time strength. With this point taken into account the porous surface tends to have a maximum area due to which the adhesion of the implant with the bone tissue has considerably strengthened. A minimally admissible force frame wa0ll width significantly depends on the insert porosity. In case of high porosity (70 %) and, as a result of it, with the force frame rigidity having been lessened, the force frame comes to be loaded in a greater degree. The calculated minimal wall width in this case made up 2 mm. With the insert porosity being 50 % a minimum wall width is equal to 1.8 mm. The 30 % porous insert makes it possible to apply a 0.6 mm-walled force frame.

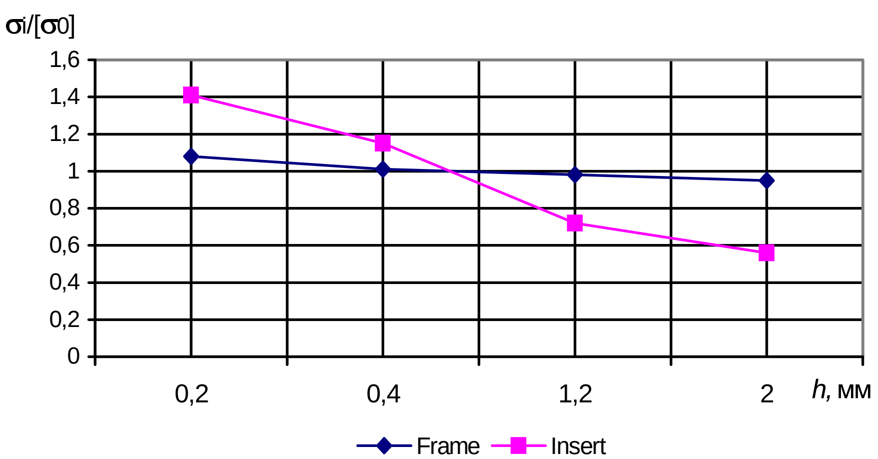

Fig. 7. The influence of the frame width on the implant long-time strength. The insert porosity is 30 %.

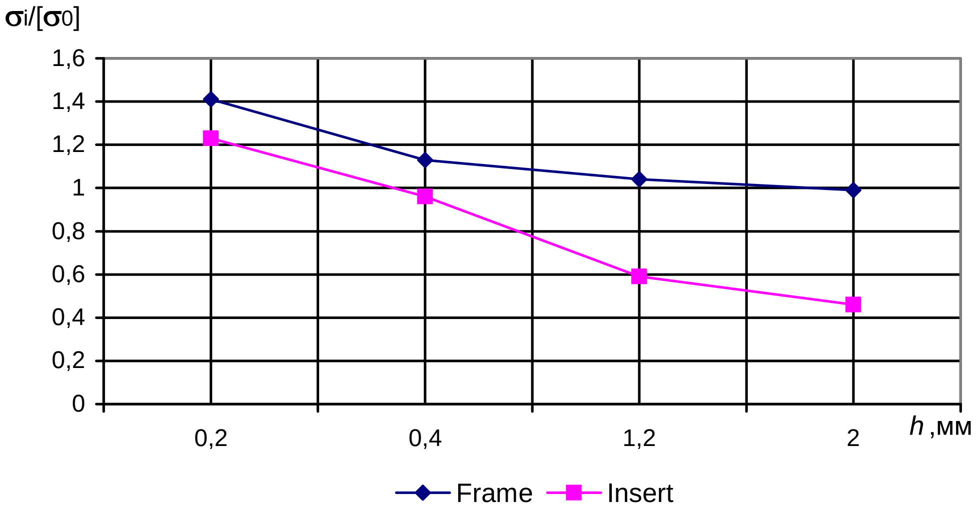

Fig. 8. The influence of the frame width on the implant long-time strength. The insert porosity is 50 %.

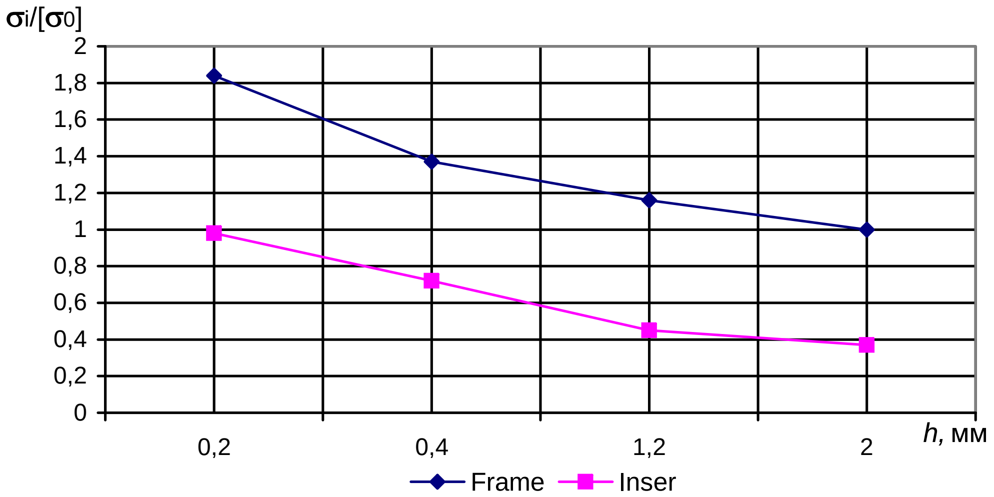

Fig. 9. The influence of the frame width on the implant long-time strength. The insert porosity is 70 %.

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ОБОСНОВАНИЕ ПРИМЕНЕНИЯ ПОРИСТЫХ ВСТАВОК В ПЛАСТИНЧАТЫЕ ИМПЛАНТАТЫ ПО УСЛОВИЮ ПРОЧНОСТИ

С.Г. Конюхова, Г.И. Рогожников, Ю.И. Няшин, С.А. Чернопазов, С.В. Еремина, К.В. Дозморова (Пермь, Россия)

В настоящей работе исследуется новая конструкция пластинчатого имплантата с пористой вставкой из титана с точки зрения длительной прочности. Пористые вставки обеспечивают надежное сцепление с костной тканью и как следствие этого создают условия более равномерного распределения напряжений в губчатой кости. Однако поры являются концентратором напряжений, поэтому возникает необходимость расчета имплантата на длительную прочность при действии повторяющихся жевательных усилий. Пористые вставки моделировались с помощью эффективных характеристик. Количественные оценки напряженного состояния выполнены методом конечных элементов. Локальные напряжения в пористых вставках оценивались с помощью концентратора напряжений, найденного расчетным путем. Прочность сцепления с костной тканью возрастает с увеличением боковой площади поверхности пористых вставок, однако при этом увеличиваются напряжения во внешнем каркасе из сплошного титана. Для обоснования конструкции решены следующие задачи: рассчитаны эффективные характеристики пористых вставок в зависимости от процентного содержания пор; исследованы локальные напряжения в пористой структуре; определена ширина внешнего силового каркаса по условию прочности в зависимости от пористости вставки. Поры моделировались круглыми упорядоченными отверстиями. Расчеты эффективных характеристик и локальных напряжений выполнены с помощью метода конечных элементов. Библ. 7.

Ключевые слова**:** пластинчатый имплантат, пористая вставка, эффективные характеристики, локальные напряжения, прочность, метод конечных элементов

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