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OPTIMAL DESIGN OF METAL-CERAMIC DENTAL CROWNS

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Abstract: The causes of the metal-ceramic premolar crown failure in the process of its functional application are investigated. Based on the finite element analysis of stress fields under the masticatory load and the temperature load because of the hot or cold water drinking and the residual stresses field in the made crown it is shown that the residual stresses are the main cause of the crown failure and that the residual stresses and the appearing due to the cold water temperature stresses superposition is the most dangerous combination. To make the maximal principal tensile stress magnitude less than the tensile strength the problem of the crown structure optimal design is solved. The suitable choice of the shape and thickness of the crown metal frame and the substitution of the initial cobalt-chrome alloy frame by the less stiff titanic one allowed to diminish the maximal principal tensile stress in ceramics 2.6 times, so that the magnitude of the latter constituted only 75 percent of the tensile strength.

Key words: metal-ceramic crown, residual stresses, optimal design, titanium alloy

The metal-ceramic tooth crowns show the distinct advantages in comparison with metalloplastic and metal ones [1].

Their serious disadvantage is the low tensile strength of ceramics which less than compressive one approximately 8 times [2].

As a result masticatory load or/and temperature one due to hot or cold liquid drinking sometimes breaks down metal-ceramic construction.

The aim of the paper is to investigate in detail the causes of crown failure and to prevent it with the help of optimal design of the metal-ceramic crown structure. Let us choose a mandible premolar as an object of the research since it is one of the most loaded teeth.

To make the metal-ceramic crown (Fig. 1a) it is necessary to apply and then to fuse by means of high-temperature heating consecutively two or more ceramic coats to a metal frame surface. The premolar preparation consists in grinding of enamel layer and a part of dentine layer approximately 1.3 mm deep (Fig. 1b).

All material layers of crown have different physical properties and first of all different temperature coefficient of thermal expansion. As a result the residual stresses field is already present in the made crown. Denote: σ_1 are residual stresses, σ_2 are occlusional (masticatory) stresses, σ_3 and σ_4 are temperature stresses due to hot or cold liquid, respectively. A priory it is not clear what stress field superposition leads to the failure. Consequently we must research following cases:

$$\sigma_1,\ \sigma_1+\sigma_2,\ \sigma_1+\sigma_3,\ \sigma_1+\sigma_4,\ \sigma_1+\sigma_2+\sigma_3,\ \sigma_1+\sigma_2+\sigma_4.$$

Nevertheless we must solve only three problems of mechanics of solids: (i) define residual stresses; (ii) define stresses caused by masticatory load; (iii) define temperature stresses due to hot or cold liquid drinking.

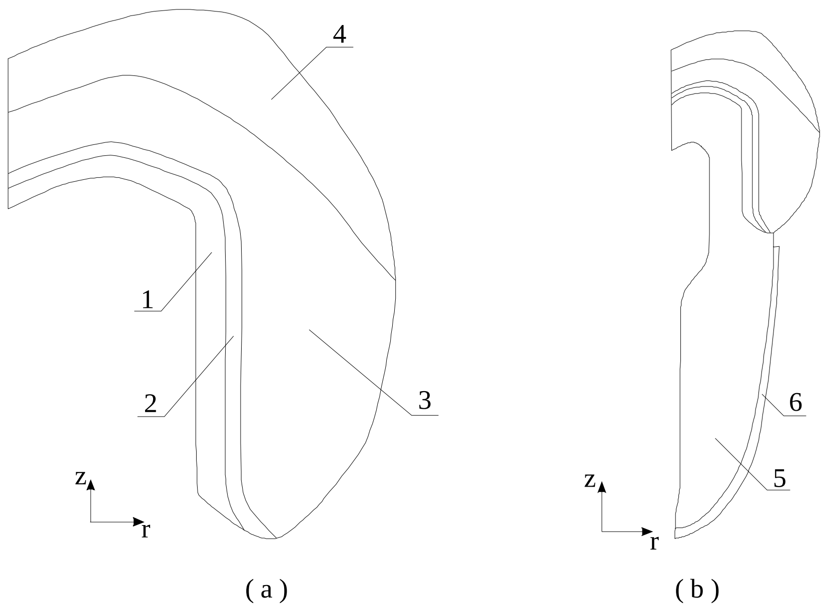

Fig. 1. Traditional structure of crown for premolar: a – crown, b – crown with prepareted premolar; 1 – metal frame, 2 – opacous ceramic coat, 3 – dentine ceramic coat, 4 – incisiale ceramic coat, 5 – tooth dentine, 6 – periodont.

(i) The first problem is the problem of linear thermoelasticity. We know initial uniform temperature field (the burning temperature in the furnace) and final one (the temperature in the oral cavity). The residual stresses are stipulated by nonhomogeneous physical properties and are not dependent on time.

(ii) The second problem is the problem of linear elasticity. In this case the cyclic masticatory load depends on time. But we can consider only the most dangerous case of the maximal masticatory load.

(iii) The third problem is the problem of linear thermoelasticity as the first one. But for this time temperature stresses are caused by both nonhomogeneous physical properties and nonuniform temperature field which is dependent on time. To find this temperature field we must solve nonstationary heat conduction problem. As it is not obvious what the time moment is the most dangerous the entire time interval of temperature change is to be considered.

The finite element method [3,4] was applied to solve all three problems.

The acceptable for mandible premolar assumption of axial symmetry was used. Thus the calculated domain for the problem (i) was a half of the crown section (Fig. 1a), the domain for the problems (ii) and (iii) was a half of the crown – premolar – periodontal ligament section (Fig. 1b).

The failure possibility for the ceramics and the tooth dentine was evaluated with the help of the maximum stress theory which is useful for the brittle materials [5], i. e. the fracture is absent if:

$$\frac{\sigma_p}{\sigma_t} < 1 \bigcap \frac{\sigma_n}{\sigma_c} > -1, \tag{1}$$

where σ_p and σ_n are the maximal positive and minimal negative principal stresses, respectively; σ_t and σ_c are the tensile and compressive strengths, respectively. The failure possibility for the metal was evaluated with the help of the theory of maximum strain energy due to distortion, which is useful for the plastic materials [5], e. the fracture is absent if:

$$\frac{\sigma_e}{\sigma_{-1}} < 1, \tag{2}$$

where σ_e is the equivalent stress and σ_{-1} is the fatigue limit.

To investigate where and why the crown fails the stress state of the traditional structure made from cobalt-chrome alloy KHS and ceramic mass Sinadent-KHS [6] was calculated. The

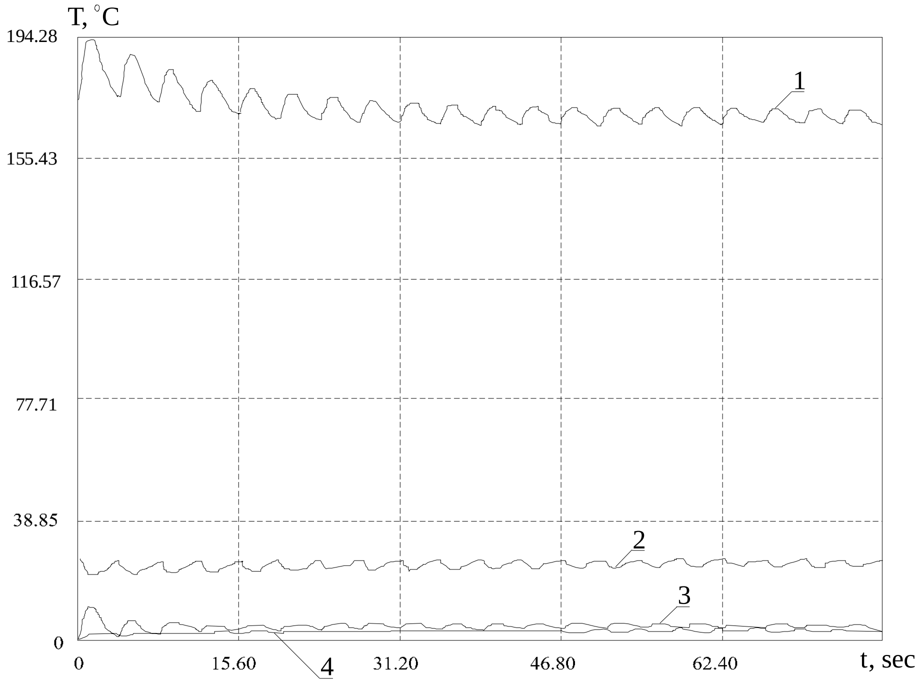

Fig. 2. Maximal over space domain absolute value of dimensionless principal stress (%) in KHS-ceramics of traditional structure crown and in tooth dentine as function of the time for the case of $\sigma_1 + \sigma_4$ superposition:

1 - tensile stress in ceramics,
2 – compressive stress in ceramics,
3 – tensile stress in tooth dentine,
4 – compressive stress in tooth dentine.

elastic, thermal and strength material properties used in calculations are presented in works [6-10]. The heat-transfer coefficients under the hot or cold liquid (water) flow around tooth with crown were calculated with the help of formulae presented in [10].

In calculations, the following data taken from our experiments were used: the temperature of a ‘hot’ water (the maximal temperature without sense of mouth burnt) is 65°C; the temperature of a ‘cold’ water (the temperature of water, taken from refrigerator) is 7°C; a man drinks the glass (200 g) of hot or cold water during 100 sec, taking 20 sips. One sip lasts 1.5 sec, a pause between two sips does 2.5 sec.

In all calculations we analyzed the relative stress, that is the principal stress relating to the tensile or compressive strength in accordance with (1) for ceramic and tooth dentine or equivalent stress relating to the fatigue limit in accordance with (2) for metal.

The calculations show:

- the most dangerous case is the $\sigma_1 + \sigma_4$ (residual stresses plus temperature stresses of cold water) superposition (1-st column, Table 1);
- the residual stresses give the main contribution in superposition $\sigma_1 + \sigma_4$ (1st column, Table 1);
- for the $\sigma_1 + \sigma_4$ case the dimensionless stress reaches the maximal level at the beginning (time t=1.5 sec) of the drinking process (Fig. 2);
- the dimensionless compressive principal stress in ceramics less than tensile one approximately 10 times (Fig. 2, 3);
- the dimensionless stresses in tooth dentine less than dimensionless tensile principal stress in ceramics more than 10 times (Fig. 2, 3);
- the dimensionless stress in metal less than dimensionless tensile principal stress in ceramics approximately 4 times (Fig. 3);

- for the $\sigma_1 + \sigma_4$ case at the time moment t=1.5 sec the tensile principal stress reaches the maximal magnitude at the point A of ceramics (Fig. 3a), exceeding the tensile strength approximately 1.9 times (according to the clinical tests the crowns sometimes fail namely in a region of the point A);
- the tensile principal stress exceeds the tensile strength 1.3 times also at the point B of ceramics (Fig. 3a).

Founding on this results let us choice maximal in ceramic part of crown dimensionless tensile principal stress of residual stress field as the criterion of optimality, i. e. the optimization problem is:

$$\max_{\Omega_{ceram}} \frac{\sigma_p}{\sigma_t} \to \min. \tag{3}$$

Table 1.

Maximal over space domain and time interval absolute value of dimensionless principal stress (%).

Variant of superposition	Traditional structure, KHS	Optimal structure, KHS	Traditional structure, VT-00	Optimal structure, VT-00
σ_1	173.6	94.9	107.5	48.5
$\sigma_1 + \sigma_2$	156.5	83.9	102.1	45.8
$\sigma_1 + \sigma_3$	185.5	101.9	109.4	42.3
$\sigma_1 + \sigma_4$	194.3	112.9	135.0	71.6
$\sigma_1 + \sigma_2 + \sigma_3$	181.6	108.4	95.0	45.2
$\sigma_1 + \sigma_2 + \sigma_4$	159.7	91.5	134.9	67.7

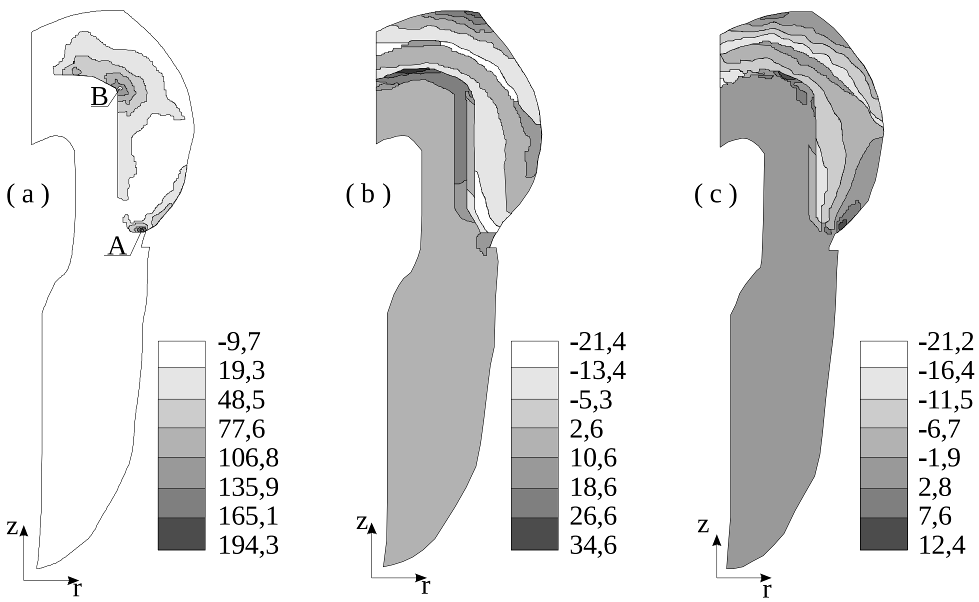

Fig. 3. Dimensionless principal stress (%) in traditional structure KHS-crown and in premolar for the case of $\sigma_1 + \sigma_4$ superposition in the most dangerous time moment t=1.5 sec: a, b, c – first, second and third principal stresses, respectively.

Such choice permits to reduce significantly calculations to solve the optimization problem.

The high level of stresses in local regions of points A and B denotes the existence of the stress concentration. For this reason the problem (3) of crown structure optimal design was solved at two stages.

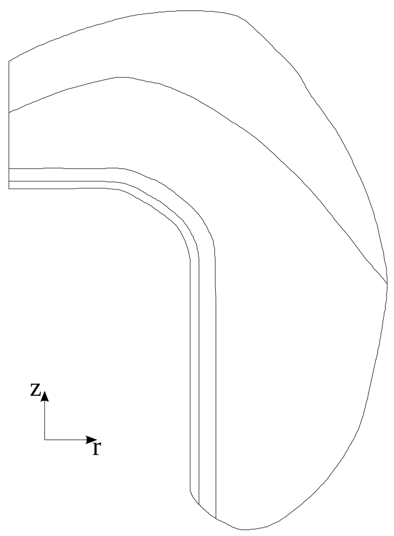

Fig. 4. Optimal structure of crown for premolar.

First we fixed the thickness of the metal frame and varied its shape to decrease the stress magnitude in places of its concentration on account of more uniform stress distribution.

Then we fixed the shape and reduced the thickness of the metal frame to decrease the general level of stresses. Figure 5 shows the crown structure, which is the result of the optimal search. As follows from Table 1 (see 2nd column) the optimal design of the metal frame shape and the optimal thickness provided the maximal tensile stress decreasing 1.7 – 1.8 times both for residual stresses field and for the most dangerous case of $\sigma_1 + \sigma_4$ – residual stresses and temperature stresses of cold water superposition.

It is evident that application of less stiff metal to make frame also permits to decrease a general level of stresses. As such material we considered titanic alloy VT-00, which Young’s modulus is approximately a half of the one for KHS alloy. The ceramic composition for VT-00 alloy was developed by authors [11]. In calculations there were used the elastic, thermal and strength properties for VT-00 alloy and new ceramic compositions from this work and works [8, 12]. As follows from calculations results (see Table 1, 4th column and Fig. 5) for optimal structure crown made from VT-00 alloy and new ceramics the maximal tensile stress magnitude decreased 1.5 times and constituted only 72% of the tensile strength of ceramics for the most dangerous $\sigma_1 + \sigma_4$ case.

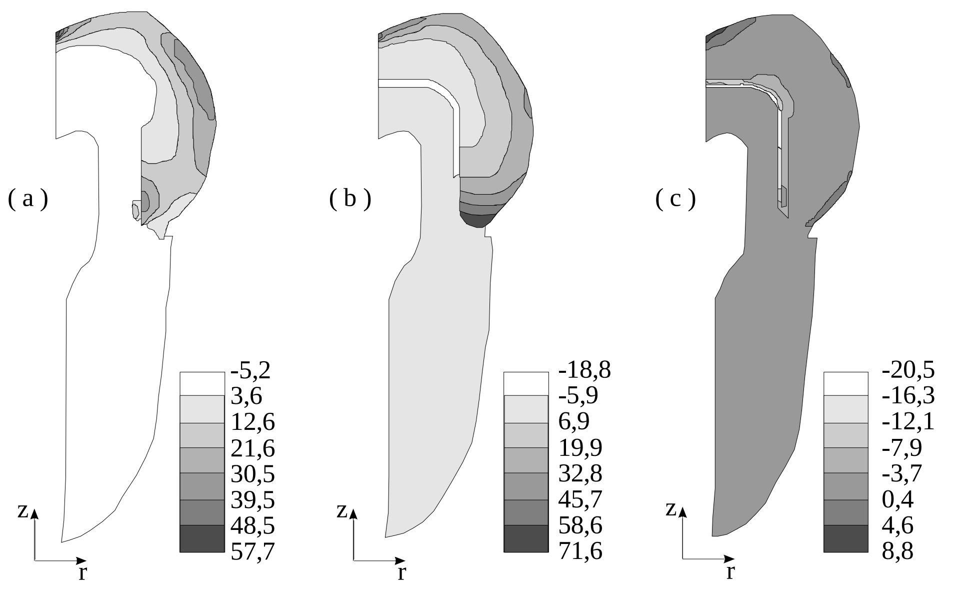

Fig. 5. Dimensionless principal stress (%) in optimal structure VT-00-crown and in premolar for the case of $\sigma_1 + \sigma_4$ superposition in the most dangerous time moment t=1.5 sec: a, b, c – first, second and third principal stresses, respectively.

Conclusions

Thus in the present work we showed with the help of the finite element analysis two following facts. First, the residual stress field arising after the burning in the cooled crown because of various physical material properties is the main cause of the crown ceramics failure. Secondly, the residual stresses and temperature stresses due to the cold water drinking are the most dangerous combination.

Having solved the problem of the crown structure optimal design we found the ways to decrease the maximal principal tensile stress magnitude. These ways are: the suitable choice of the shape and thickness of the crown metal frame and the substitution of the initial cobalt-chrome alloy frame by the less stiff titanic one.

As a result the maximal principal tensile stress in the ceramics of the final crown structure seemed to be 2.6 times less than one of the initial structure so that the magnitude of this stress constituted only 75 percents of the tensile strength.

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Оптимальное проектирование металлокерамических зубных коронок

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В работе исследовались причины разрушения металлокерамической коронки премоляра под действием жевательной и температурной нагрузок. Последняя возникает при употреблении горячей или холодной жидкости.

Были найдены поля напряжений для этих трех случаев, а также поле остаточных технологических напряжений, появляющееся в коронке при охлаждении расплавленной керамической массы на металлическом каркасе вследствие разных физических свойств материалов коронки и, в первую очередь, вследствие разных коэффициентов температурного расширения.

Поля напряжений определялись из решения задач линейной теории упругости и термоупругости, а также нестационарной задачи теплопроводности с помощью метода конечных элементов.

Исследовалась возможность разрушения коронки для различных вариантов суперпозиций полей напряжений с использованием критерия максимального нормального напряжения для керамики и критерия максимальной интенсивности напряжений для металла.

Оказалось, что главную роль в процессе разрушения играют остаточные растягивающие напряжения в керамике, а наиболее опасным является сочетание остаточных напряжений с температурными напряжениями от холодной жидкости. Причем в последнем случае максимальное растягивающее напряжение в керамике превысило предел прочности на растяжение в 1,9 раза.

На основе анализа результатов был сформулирован критерий оптимальности в задаче оптимального проектирования коронки – максимальное по пространственной области и по временному интервалу растягивающее главное напряжение для поля остаточных напряжений в керамике. Такой выбор критерия оптимальности обеспечил значительное сокращение временных затрат на решение задачи оптимизации.

Варьирование толщины и формы металлического каркаса коронки позволило уменьшить значение критерия оптимальности в 1,8 раза. При замене исходного материала каркаса коронки- кобальт-хромового сплава КХС на менее жесткий титановый сплав ВТ-00 величина критерия оптимальности уменьшилась еще в 1,9 раза. При этом максимальное растягивающее напряжение в керамике для наиболее опасной суперпозиции напряжений уменьшилось соответственно в 1,7 раза и в 1,5 раза и составило уже только 0,75 величины предела прочности на растяжение. Библ. 12.

Ключевые слова: металлокерамическая коронка, остаточные напряжения, оптимальное проектирование, титановый сплав

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