Russian Journal of Biomechanics, N 1-2, 71-80, 1998

PHOTOELASTICITY AND STOMATOLOGY

I.I. Demidova

Institute of Mathematics and Mechanics, Sankt-Petersburg University, 2, Bibliotechnaja Square, 198904, Petrodvoretz, Sankt -Petersburg, Russia

Abstract: Photoelastic investigations were made to study the stress distributions in dental tissues. It is necessary not only for determination of the optimal geometry of the fillings and the nails but also for prediction of the possible fractures in the teeth and for explanation of the etiology and treatment of the different dental diseases.

Key words: photomechanics, stomatology, stress, fracture

Introduction

The nature is very rational in all its manifestations. And all this corresponds fully with the structure of the human oral cavity. The nature has very successfully chosen the building materials of the human tooth: enamel which is a composite material with a very high compressive strength; dentine which is more isotropic material; periodontal tissue which is soft and the bone which also has a very complicated composite structure. The properties of the tooth tissues chang permanently during the lifetime. The physico-mechanical properties of the tooth tissues are shown in the Table 1 [1-9].

Table 1.

The properties of the dental tissue.

Tissue	E, MPa	σ_P, MPa	σ_c, MPa	ν	α, 10^{-6} 1/°C
Enamel	$(0.28\div8)\cdot10^4$	$1.1\div34$	$130\div380$	$0.28\div0.31$	$10\div12$
Dentine	$(1.4\div19)\cdot10^3$	$2\div55$	$230\div310$	0.31	$7\div8$
Dentine (molar) Crown Root	 $2.15\cdot10^3$ $1.56\cdot10^3$		 220 150		
Cement	$23\cdot10^3$		110		7
Jaw bone Cortical	 $(1\div2)\cdot10^4$	 $40\div50$		 0.3	
Spongy	$(1.3\div5)\cdot10^3$	$10\div20$	$10\div20$	0.32	
Periodontal tissue	$5\div6.8$	8		0.45	
Pulp	$3\cdot10^{-3}$			0.45	
Gingiva	19.9			0.4	

Here E is a Young′s modulus, ν is a Poisson′s ratio, α is a coefficient of thermal expansion, σ_c is a compressive strength, σ_p is a tensile strength. From the Table 1 we can conclude that:

1. Enamel has the great diapason of the strength and Young's modulus. And this can be corresponded with the individual features. Due to this we can explain the difference in the tooth

caries of individual patients as the teeth have the thermoforce loads. It is known that the physico-mechanical properties are inhomogeneous [7].

2. The values of the compressive strength σ_c and tensile strength σ_p differ by the orders of value. Thus when we investigate the stress fields we must look for the regions with the tension.

3. For the isotropic materials the A.J. Frenkel relation is known [19]

$$E\alpha = const.$$

We can see from the Table 1, that for enamel and dentine there is no such correlation. Due to this fact it is difficult to choose a proper filling material.

Our dentofacial system is a very stable and perfect technical construction. It can stand the big stress changes and return to its permanent condition. The dentofacial system has some features:
1. It is a composite construction.
2. The different boundary conditions are given on the tooth crown and the root.
3. The fractures of tissues of the tooth are different:
   - the enamel is the brittle material,
   - the dentine and the bone of the jaw are the viscoelastic materials,
   - the periodontal tissue is a nonelastic material with the large deformation under the tension.
4. This construction has the prestressing as a result of the tooth growth and accumulation of the internal stress.
5. This system is opened to surrounding medium.
6. The aggressive mediums influence this construction, surrounding medium and organism, and the strength of the materials in such conditions is reducing.
7. The state of the dentofacial system depends also from the organism state [10].

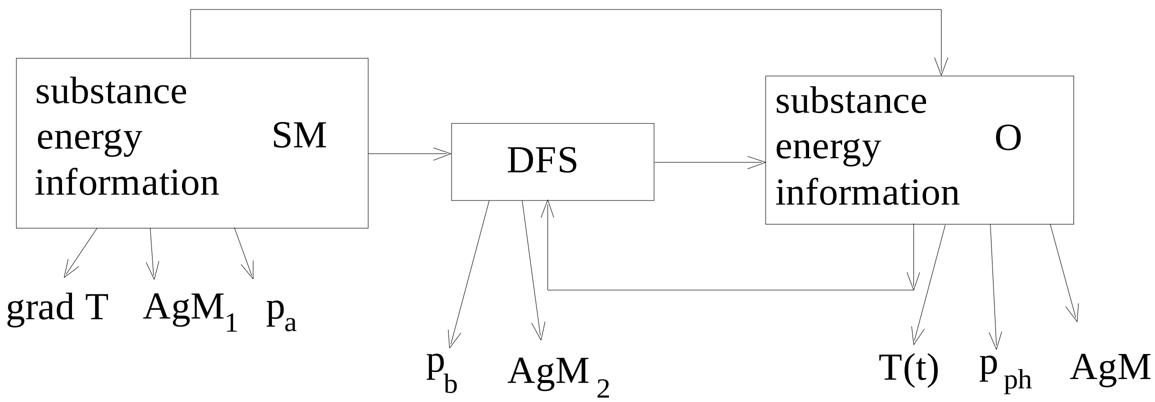


Fig. 1. The scheme of the discussed system.

Here p_a is a the atmospheric pressure, AgM_1 is a aggressive medium acting on surrounding medium (SM), AgM_2 is a aggressive medium acting on dentofacial system (DFS), AgM_3 is a aggressive medium acting on organism (O), grad T is a temperature difference between SM and DFS, T(t) is a organism temperature, p_{ph} is a physiological pressure, p_b is a mastication pressure.

It is difficult to solve this problem of the theory of elasticity in full. The stress state in dentofacial system is usually calculated by the analytical methods, finite element analysis or experimental methods with the models [1-22]. It is necessary to point out that it is impossible to take into consideration all features of the tooth tissues.

One of the first works on this problem was a theoretical work by J.L. Synge [12] who analyzed the pressure in the periodontal tissue under acting of the vertical, horizontal loads and moments considering it as a problem concerning the equilibrium of a thin incompressible elastic membrane. At present the finite element method is more often used to solve dental problems [4, 5]. The experimental tensometric and photoelastic methods are also used.

Applications of photoelasticity

The photoelasticity is a modeling method [14 - 16]. The teeth construction is necessary fulfilled with the geometrical similarity and Young's modulus correlation. For such investigations the materials must be transparent. The properties of some materials are given in the Table 2.

Table 2.

The optical and mechanical properties of some polymer materials.

Materials	E, 10^3 MPa	C ,10^{-6} 1/MPa	ν	α, 10^{-6} $1/^0$C
Epoxy	3	27÷50	0.32	68÷72
PMMA	2.4÷3	-2	0.4	
Polycarbonate	1.5÷2.5	80	0.45	60
Glass	60	2 - 3	0.25	
Hysol -4485	0.04	2350	0.48	0.577

Here C is a stress optical coefficient.

To solve isothermal problems by the photoelasticity it is necessary to measure the optical parameters (the optical path δ and the isocline φ) in the model and calculate the stresses σ_{ij} from the equations.

$$\delta \cos 2\varphi = C\, h\, (\sigma_{11}-\sigma_{22}), \qquad \delta \sin 2\varphi = 2\, C\, h\, \sigma_{12},$$

$$\partial\sigma_{11}/\partial x + \partial\sigma_{12}/\partial y = 0,$$

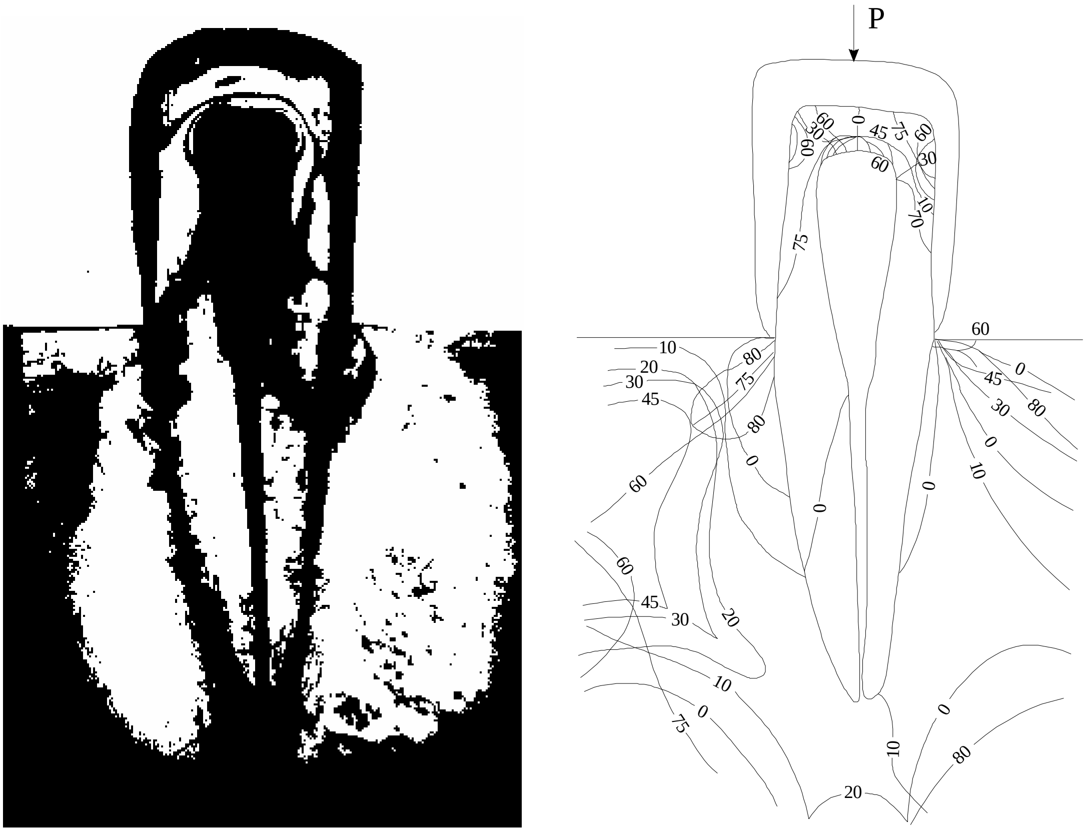
where h is the thickness of the model. Three - dimensional problem is solved by different methods of photoelasticity [15, 16].

It is noticed that according to the Mayer - Volf's law the bone trabeculars arrange along the lines of the principal stress. The last lines can be constructed on the base of the isocline lines obtained easily by photoelasticity.

The photoelasticity was applied to solve the different stomatological problems before the application of the numerical methods. One of the first who used this method was M.A. Noonan [2]. Then many problems were solved by this method [3, 4, 8, 9, 20, 21]. The main target of this works was to determine the stress state of the mandible and the teeth under the mastication and temperature loads in the systems of the "tooth-filling", the "tooth-false teeth set" and the "tooth - implant". As a result of those experiments a lot of interesting information was obtained on the form of the filling cavity and the stress analysis in orthopedics.

Modeling of functional loads. Mastication loading

At the process of the natural mastication the teeth `are loaded by the forces which can be decomposed on the vertical and horizontal components. The action of the vertical force P_y is most studied [2, 3, 8, 20]. E.N. Petrov [3] showed that the most greatly stress concentration appears on the root apex. The lateral pressure is less 10 times than the pressure along the tooth axis. The toughness of the periodontal tissue has influence on the stress state of the surrounding tissue.



(a) (b)

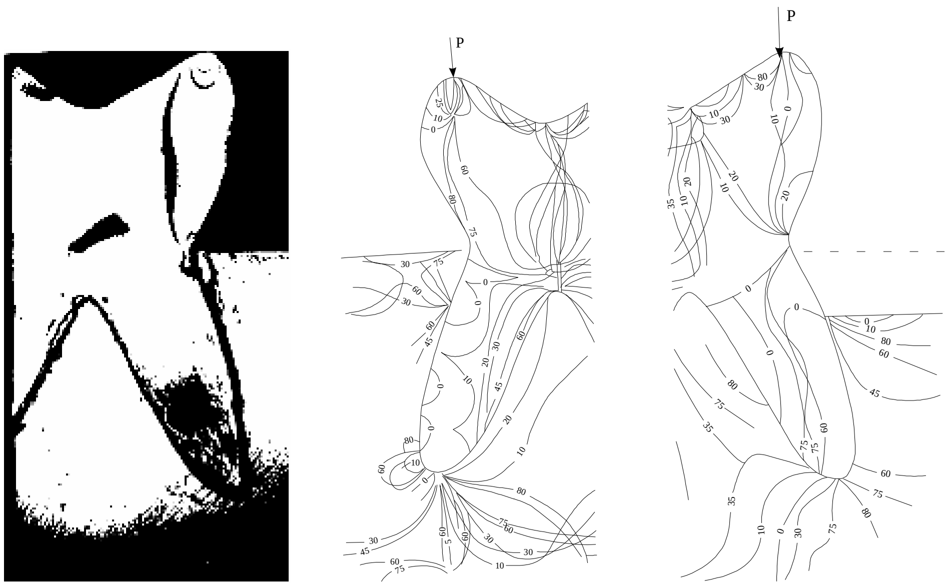
Fig.2 The fringe pattern (a) and isocline in the incisor model (b).

The most dangerous load as underlined J.L. Synge [12] is the horizontal load P_x. This loading exists not only during the mastication but also under the pressure of the neighboring teeth, tooth-grinding, after the orthopedic treatment and especially due of the bridge construction because the load is never uniform in such cases.

The problem of the modeling of the periodontal diseases development is the bone resorption, which causes the degradation of the tooth function. It was analyzed on the models under the vertical and horizontal loadings. That kind of study was undertaken before on the mathematical models of the anterior teeth [16]. According to the theory of elasticity these problems are the problems of the influence of the loads on the body under the changing boundary conditions.

Action of the vertical load

In the Fig.2b, 3 b,c the isocline pictures of the two models of teeth are depicted. The incisor model was composite - the enamel, the metal, the dentine and the bone -the hot-setting epoxy polymer. This picture of the isoclines gives information on the stress state. For the incisor the concentration of isocline lines is observed at the top level of the crown and in the bone near the border, the stress sign in the bone will change several times, because we see two marks "O". In the Fig. 3a the fringe pattern of the molar under the vertical loading is depicted. First, what is interesting to notice, it is the optimal geometry especially the roots; birefringence is near to "O", and stress is very low. In the molar model we can see the concentration of the isocline and the birefringence also near the border in the tooth and in the bone at the upper part of the crown and at the roots apex. The stress concentration is also observed at the areas of loading where the compressive strength of the tooth tissue is very high. The stress concentration was discovered at



(a) (b) (c)

Fig. 3 The fringe pattern (a) and isocline in the molar model (b - *H* = 1, c - *H* = 2/3, *H*-teeth weight).

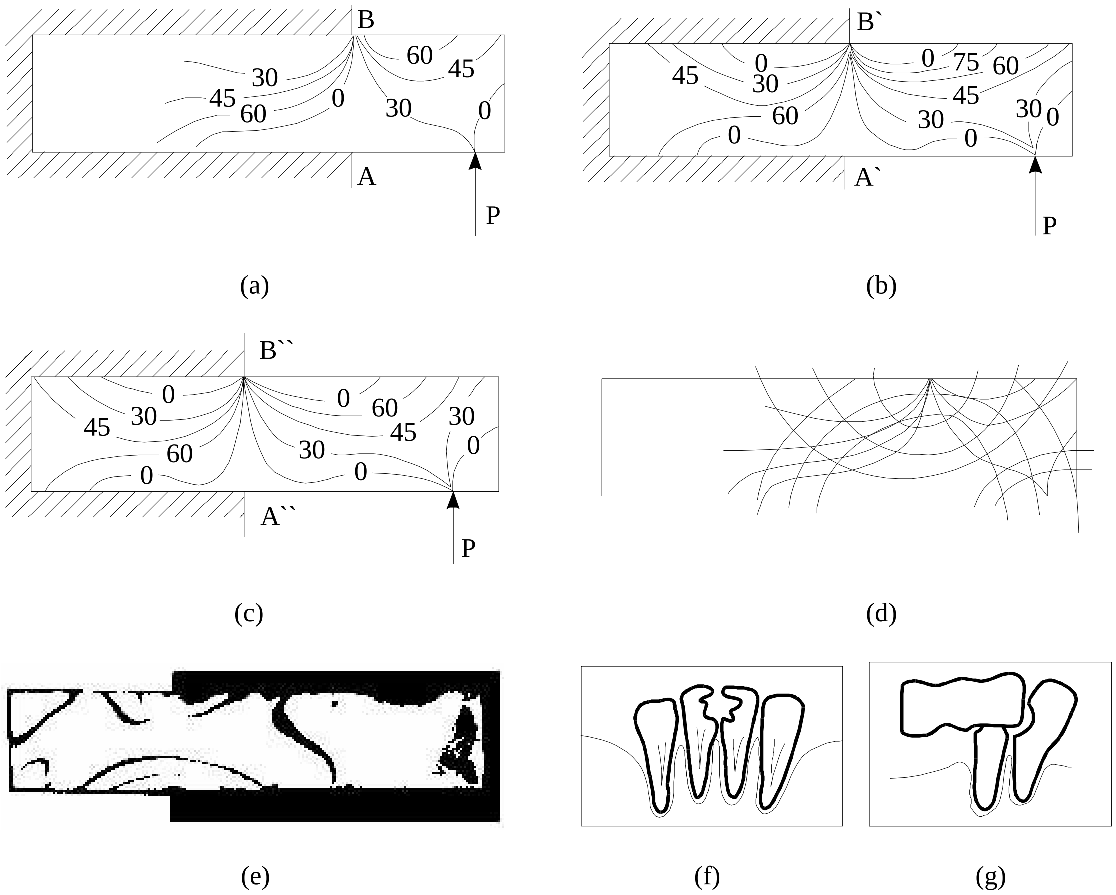


Fig. 4. The isocline (a), isochrome (e), isostate (d) pictures without resorption and with resorption (b - *H*=1/3, c - *H*=1/2). The different X - ray cases of the teeth destruction under the horizontal loading (f,g).

the boundary between of the tooth and the gum. At the level near the applied forces the stress distributions σ_{xx} and σ_{yy} are similar to the stress distributions under the acting the force on the half - plane. The character of stress changes in lower place than loading one and there is no extreme of the compression stress on the curve of the distribution. Due to the geometrical: form of the tooth the stress σ_{xx}, σ_{yy} and τ_{xy} closer to the center become tensile, and this causes the destruction, which dentist call the fissure caries. Also the stress concentration is located in the area near the border with the gum, this area is an area of the geometrical change of the tooth contour. It is known that in such places the stress concentration is located. When modeling the resorption of the bone (H = 2/3) (Fig. 3b) we discovered that the tooth crown is stressed at its upper part same as in the first case (H =1). But the isocline picture is nonsymmetric. The isocline concentration replaced on the level of the resorption border. That means that this area has the highest level of stress. The stress in the root increases by the orders of value and such condition provokes double stress concentration that causes more degradation in the periodontal area. In the area above the area of the resorption the stress is tensile that cause the degradation of this area because it is not protected and is more influenced by the action of the aggressive condition, which causes future degradation of this area. Our research for the H<1 has shown that the area of tensile bending stress is going down and new appearing stress causes the future stress which is higher than its level. The character of the stress distribution on different resorption levels is not equal. But for the incisor the character of the stress distribution on different resorption levels is equal. They are increasing together with the increasing of the bone atrophy. These results for the molar was confirmed by the finite element method [18].

The horizontal loading

For the horizontal loading we have used the model of cantilever beam (Fig. 4a). The solution for this model is known from the theory of the strength of materials. In this case the correlation between the free and fixed parts corresponds to the sizes of the crown and the root. The material for models was polymethylmetacrilat (PMMA). It is the best material for this purpose.

The isocline picture from the model is shown in the Fig. 4a-c. Under the normal conditions (Fig. 4a) the roots are practically unloaded, but under the resorption increasing the isoclines reach the root apex (Fig. 4c). The character of the isostate distribution (Fig. 4d) in all cases is practically similar, and is similar to the X-ray picture destruction. The scheme is shown in Fig. 4f,g. According to the "O" isocline on the isocline picture it is possible to find the compression and tension areas. The isocline concentration (Fig. 4a-c) is seen under the load point and at the B point.

Root load modeling

The tooth roots are surrounded by the periodontal tissue. The pressure in this tissue is changed under the mastication and also depends on the organism state (Fig. 1). It is known that the physiological pressure is not the monotone time function. If the pressure impulse is very high even a short time then the addition force acts on the root. As a result the stress concentration is appearing in the tooth.

The geometry of the molar is similar to the curve beam for which a connection between the load and the appearing stress is known [19]. This phenomenon was opened by accident under the photoelastic investigation of the teeth [20].

Due to the photoelasticity it was found that the addition stress concentrations are appearing in the tooth fissure and near the boundary with the gum. On the outer surface the stress is tensile and this causes the fracture of the molar. In turn the residual stress and cracks will force the beginning

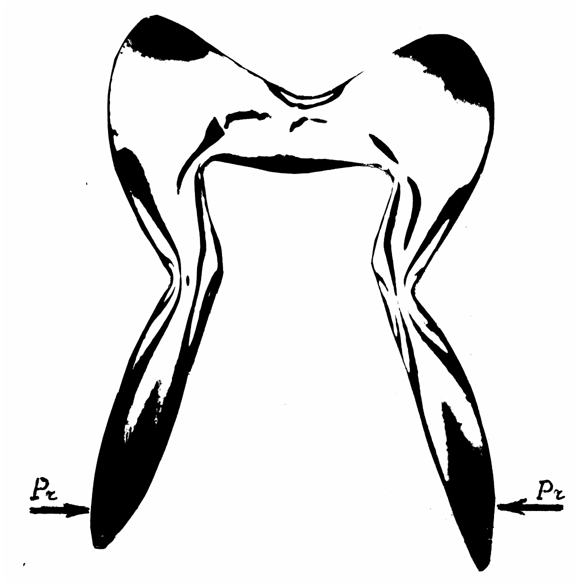


Fig. 5 The fringe pattern on the molar model under the action of the root load.

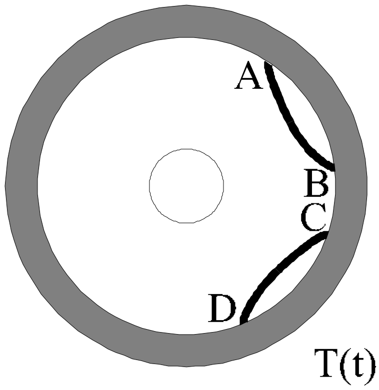


Fig. 6. Cracks in composite model after cooling.

and progressive development of the different non-caries diseases of the enamel, the dentine and the periodontal tissue. These conditions can provoke the inflammation at the root apex region. (Fig. 5). Such stress distribution can explain the etiology of different dental diseases: pathological enamel loss, enamel erosion, the wedge defect.

Temperature stress

With the help of photoelasticity it is difficult to solve the nonisothermal problem because it is necessary to consider the absence of the adequation between the thermal properties of the polymer materials and the teeth (see Tables 1 and 2).

Homogeneous temperature fields. The numerical and experimental investigations of the stress state of the composite body under the nonstationary temperature fields showed that the residual stress will be accumulate in this construction. Even homogeneous nonstationary temperature field in composite body stimulates the residual stress. On the metal-polymer ring by the method of photothermoviscoelasticity [21] the crack in the form of crater-like holes was discovered [22]. For the teeth this experiment is equal to the heating of the teeth.

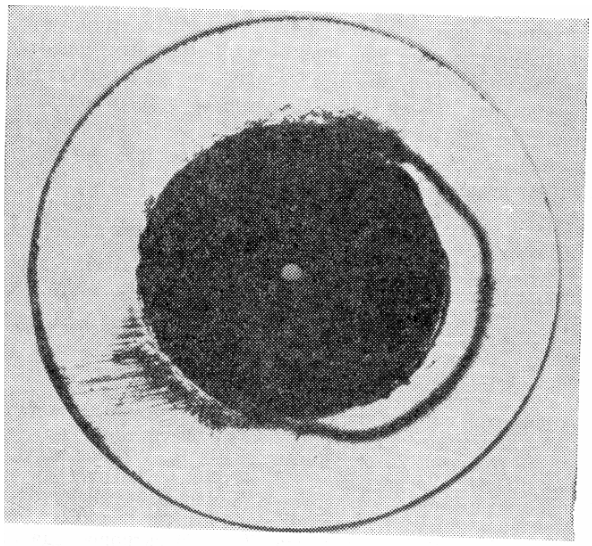


Fig. 7 The crack in the composite model after the curing.

This experiment is the model of the caries appearing after fluctuations of the organism temperature. The example of the temperature stress kinetics is given in the monograph [21]. The calculations are fulfilled for the epoxy polymer ring surrounded by the metallic ring. The temperature T_{max} was lower than the glass state temperature of polymer.

These inner cracks grow under the influence of the aggressive surrounding medium in the oral cavity. In such condition due to the fracture (caries) in the tooth crown the dentist will remove a big part of the tooth tissue (ABCD in Fig. 6) [20].

Action of the temperature gradient. Another reason of the tooth fracture is a temperature changes, especially local, for example the cycle changes: ice-cream-hot coffee - ice-cream - hot coffee, temperature outside 80^0C, inside-37^0C. In the monograph [15] the isochrome fringes under non homogeneous cooling are depicted. The geometry of the isochromes corresponds with the caries in the stage of white spot. The heat conduction of the tooth tissues is very low but the pulp reacts on the temperature gradients of the 5^0C and dies. Hence the temperature gradient is small but the crown is a composite body and the temperature equalizing in the oral cavity brings to the concentration of the accumulated stress. By the photothermoviscoelasticity method the kinetics of temperature stress in the polymer ring was determined [22].

Modeling of dentofacial system treatment

Tooth - filling system. It is a basic problem of stomatology and the most popular one under the investigation by the photoelasticity. The different questions were discussed, namely [2, 3, 5, 23]:
- the form of the filling cavity;
- the influence of the filling size and the material sort on the stress state;
- the stress state of this system under vertical force and temperature field;
- quality of the filling material preparing.

Besides several authors model the process of the influence of the temperature fields on the teeth during the preparing of the cavity and also the curing process of the filling material in the teeth cavity. Because under the curing the filling polymer material has the decreasing dimension the crack may appear by analogy with the crack in the metallic - polymer ring (Fig. 7).

The tooth extraction. In the papers [9, 22] authors described tooth extraction from the biomechanical point of view and used the photoelasticity for the description and demonstration this

Fig 8 The fringe pattern in the teeth-jaw model under luxation.

operation. For first stage - the fixation of the dental forceps the investigations was done on the model disk and ring loaded by the forces applied along the diameter. It is a very known problem of the photoelasticity. For the second stage - the swing (the luxation) the model of the teeth - jaw segment was fulfilled from the different polymer materials. In the Fig. 8 the image of the fringe patterns is shown.

We can see the stress concentrations between the forceps, in the tooth from the bending, in the jaw under the contact with the tooth in two places. For the third stage - the traction the model was completed by the model of the periodontal ligament.

Demonstration

The interference images are attractive and may be used for the education. It is necessary to have the models from the transparent materials and two Polaroid.

The information about the stress distribution in the teeth gives us the necessary knowledge about the optimal form of the caries cavity, the nails, unknown defects. Also it helps to find the correlation between the tooth degradation and the surrounding tissue. In the intact tooth the inner degradation processes can appear

- in dentine on the enamel - dentine boundary due to the temperature change;
- in the enamel under the upper layer due to the temperature stress or because of the inflammation around the tooth root;
- in the molar in the fissure region under the influence of the vertical loading.

It is noticed that the method of investigation depends from the dental problem. For the solution there are the analytical, numerical and many experimental methods. It is better to choose more simple and informative method.

References

1. Black G.V. **Physical properties of teeth**, Dental Cosmos 1895.
2. Noonan M.A. The use of photoelasticity in a study of cavity preparations. **J Dent Child,** 16: 24-28, 1949.
3. Petrov E.N. Experimental investigation of temperature strain properties of polymer materials used by stomatology. Diss. Report. (Leningrad), 1970 (in Russian).
4. Tresher R.W. The stress analysis of human teeth. **J Biomechanics**, 6: 443 -449, 1973.
5. Farah J.W., Craig R.G., Sikarskie D.L. Photoelastic and finite element stress analysis of a restored axisymmetric first molar. **J Biomechanics,** 6: 511-520, 1973.
6. Makarov K.A., Steingart M.Z. **Copolymers in the dentistry**. Moscow,1982 (in Russian).
7. Saulgosis U.G., Iansons A.I. **The elastic properties and the composite structure of the human teeth tissue.** In book: "Mechanics of the biological solid body", Kazan, 32-67,1986 (in Russian).
8. Taptunova G.G., Poluhina S.P., Schelkanov I.V. **The research of the stress state of the maxilla by the photoelasticity.** In book: "Theory and practice of the dentistry". Moscow, 1975 (in Russian).
9. Solovijev M.M., Demidova I.I., Lisenkov V.V., Sakovich A.A. Fracture investigation of teeth under ficsation of forceps. ГЦНМБ № Д - 25.458 1997 (in Russian).
10. Frenkel A. I. **Introduction to physics of the metals**. Moscow, 1948 (in Russian).
11. Demidova I.I. Role of system analysis for biomechanics. Abstract of III Russian biomechanics conference. (N. Novgorod) v.1 1996. (inRussian).
12. Synge J. The tightness of the teeth, considered as a problem concerning the equilibrium of the incompressible elastic membrane. **Phil Trans of the al Society of London**, A 231: 435-470, 1933.
13. Hesin G.L., Curlandsky V.U. The study of the stress state of the jaw by the photoelasticity. **Stomatology,** 2: 1962 (in Russian).
14. Frocht M. **Photoelasticity**. Moscow, 1948 (in Russian).
15. Durelli A.J., Rilly W.F. **Introduction to Photomechanics**. (N. Y.), 1965, Moscow, 1970 (in Russian).
16. Aleksandrov A.J., Achmetzianov M.Ch. **Optical methods**. Moscow,1973 (in Russian).
17. Sosnin G.P. **Protes,** Minsk, 1981 (in Russian).
18. Demidova I.I., Dudnikov V.A., Zimin B.A., Ulitovskji S.B .**Biophysika** 39, 6 1004 - 1009, 1994 (in Russian).
19. Timoshenko S. **Strength of materials**. Princeton, New Jersey, T-N.Y.-L., 1955.
20. Demidova I.I., Ulitovskiy S.B. Inner cracks of teeth S - Pb Vestnik, 1991 (in Russian).
21. Bugakov I.I., Demidova I.I. **Photothermoviscoelasticity**, (S - P b),1993 (in Russian).
22. Lisenkov V.V., Demidova I.I., Solovijev M.M. Biomechanics of teeth extraction. ГЦНМБ № Д - 25.618, 39с,1997 (in Russian).

Фотоупругость и стоматология

И.И.Демидова

Дается анализ биомеханических особенностей поведения зубочелюстной системы человека под нагрузкой. Описано применение метода фотоупругости для определения напряжений в элементах зубочелюстной системы. Рассмотрена картина напряжений в зубах при действии вертикальной и горизонтальной нагрузки на резец и моляр. Приведены картины интерференционных полос и расположение изоклиналей. Обсуждается задача о влиянии неоднородных и нестационарных полей на прочность зуба. В заключение рассматривается задача о вырывании зуба. Библ. 22.

Ключевые слова: фотомеханика, стоматология, напряжения, разрушение

Received 15 June 1998