Diffusion in tooth

Radmila M. Stevanovic¹, Jelenka Savkovic Stevanovic ²

¹Srbisim“, Beograd, Serbia,
²Faculty of Technology and Metallurgy, Karnegijeva 4, 11000 Belgrade, Serbia,

Corresponding author: J Savkovic Stevanovic

Abstract:- In this paper nutrition and heat transfer mechanism in tooth were examined. Dental ceramic material composition was considered. Those materials should be meet rigid demands for chemical stability, dimensional stability, tissue compatability and thermal stability. Thermal expansion regulation and protection has be provided by heat transfer parameters. Tooth’s nutrition and heat transfer equations have derived and heat materials parameters were analyzed.

Keywords: Tooth, diffusion, mechanism, functionality, parameters.

1. Introduction

Oral temperatures fluctuate from 9 to over 50 °C. The thermal expansion and contraction differences open and close the marginal seal creating these two major problems. The relatively poor bonding properties of the cements are further reduced by the mechanical stresses produced. Ordinarily, metals have a higher coefficient of thermal expansion than glasses, the values of metals used for casting partial dentures are in the range of 130-150 x10⁻⁶ K⁻¹ between 25 and 500 °C. Glasses with sufficient chemical resistance, however, have a significantly lower coefficient of thermal expansion. The required high coefficient is attained through the separation of a finely divided, dendritic form of leucite (K₂O·Al₂O₃·4SiO₂) as a crystalline phase in the glass during firing. Leucite is transformed from the tetragonal to the cubic form in the range from room temperature to 620 °C. This transformation is accompanied by a 5% increase in volume and thus is associated with a high coefficient of thermal expansion. A concentration of 20-30% of leucite suffices to provide an adequate coefficient of thermal expansion to the ceramic. In theory, any frit that will precipitate the required amount of leucite through appropriate temperature handling suffices. In practice, however, several frits of different composition are used, which permit better control of the properties of the ceramic and a broadening of the melting range, this simplifies subsequent firing of the ceramic to the bridge framework.

Ceramic materials quality function were developed in the literature report [1],[2]. Heat effect from oral medium (saliva) to the teeth was derived in the previous paper¹[3].

2. Dental materials composition

Ceramic materials quality depends of raw materials. Feldspar is the most raw material, in ceramic powders. High demands are made on its quality, it should be largely free of foreign phases and low in iron content because of the danger of discoloration[4]–[7].

Feldspar is the most important raw material, in ceramic powders. High demands are made on its quality: it should be largely free of foreign phases and low in iron content because of the danger of discoloration. Norwegian and Swedish feldspar are well suited because they consist largely of orthoclase (K₂O·Al₂O₃·6SiO₂), with the following typical composition, SiO₂ - 65.0%, Al₂O₃ - 18.5%, K₂O - 12.5%, Na₂O - 2.5%, CaO -0.2%, Fe₂O₃ - 0.02%.

The quartz used must have a similar purity. Quartz decreases the melting range of the feldspar-quartz mixture and provides sufficient rigidity to the ceramic mass during firing by increasing its viscosity[8]–[9].

Orthoclase, potassium feldspar, is the most important raw material for a ceramic that is to be fused to metal. To make a frit that easily segregates
leucite, the potassium content must be increased, by adding potassium carbonate \( K_2CO_3 \). Furthermore, the addition of flux powders, such as alkalis, alkaline earths, or boric acid, is necessary to lower the fusion range. The ceramic must be able to be applied at a temperature significantly below the softening temperature of the metal. Firing temperatures between 900 and 980°C are customary. Significantly lower firing temperatures, such as those sometimes desired decrease chemical durability.

The raw materials are first sintered into frits. The composition of ceramic materials varies greatly among manufacturers. This is caused, in part, by the practice of mixing several different frits. The main constituents of most of the relevant ceramic materials are present in these following ranges: \( SiO_2 \ 58-66\% \), \( Al_2O_3 \ 15-17\% \), \( K_2O \ 10-14\% \), \( Na_2O \ 5-8\% \), \( LiO \ 0-1\% \), \( CaO \ 0-2\% \), \( B_2O_3 \ 0-3\% \). Quality of the corresponding ceramic material can be expressed as a function of composition[1]:

\[
Quality = f(SiO_2, Al_2O_3, K_2O, Na_2O, LiO, CaO, B_2O_3, \sigma)
\]

where \( \sigma \) is phase passing parameter.

A ceramic of this sort is made into ready-to-use powders by adding opacifiers and pigments to the frit, so that the final veneer corresponds in color to the shade guides provided. Every veneer corresponds in color three different powders the opaque, dentin, and enamel powders. The opaque ceramic provides adhesion and simultaneously prevents the metal from showing. To meet this function, it contains up to 12% of opacifiers such as \( TiO_2 \), \( SnO_2 \), \( CeO_2 \), \( ZrO_2 \), or \( ZrSiO_4 \). Dentin and enamel powders make a toothlike appearance possible through their coordinated shades and translucence.

The assures that the formed contours of the tooth are not lost during firing. Furthermore, the quartz content affects several important properties of the content of the ceramic material: flexural strength, thermal expansion, resistance to thermal shock, and opacity. These properties depend not only on the proportion of quartz but, significantly, on how much of the quartz passes into the glassy phase and how much remains in the crystalline phase.

### 2.1 Ceramic materials behavior

Occasionally, minor amounts of opacity inducing materials such as kaolin, mullite, or carborundum are added to the mixture. Addition of flux powders, such as soda or calcite, can reduce the melting temperature.

The raw material are crushed first in a jaw crusher or chaser mill and then ground in ball mills before being mixed in accordance with the prescribed formula, maximum particle size 150 \( \mu \)m. After fired between 1200 and 1400 °C until the feldspar has melted completely and the quartz has largely dissolved in the mass. The glass blocks that result from this are again crushed and ground to a fine powder, maximum particle size 100 \( \mu \)m.

The starting material for tooth formation prepared thus prepared must now be given in color. A large number of differently colored ceramic powders are needed, because manufactures offer approximately 20 different shades of teeth. Further more, every tooth is built up of several differently opaque and variously shaded layers. The natural appearance required cannot be attained in any other way. Shading is provided by the pigments ordinarily used in ceramics, red-brown spinels (Fe, Zn, Cr, Al oxides) and yellow vanadium containing ZrO\(_2\). Precise control of the color values and the transparency of the powders is prerequisite to achieve the desired tooth colors. The fluoroscence of natural teeth is initiated by using special fluorescing pigments or by adding lanthanide oxides to the starting frit. The colored powders are converted to plastic masses by use of appropriate organic additives, starch paste or oils.

Shaping teeth requires much manual effort. Two part metal molds are generally used. The labial layers of the tooth are placed in one half of the mold and the lingual layers in the other. Posterior teeth are formed from occlusal and basal halves. To permit retention of the completed teeth in the denture base material, precious-metal shells, largely paladium are mounted on the back of the anterior teeth (Fig.1). After firing, gold plated posts are soldered to these shells. For posterior teeth, retention is provided by dovetailshaped undercuts in the base region.

The filled halves of the form are pressed together for joining. When they are heated to 150-200 °C, the organic components lose their plasticizing effect and serve as binders. The formed teeth are then heated to 800°C, to volatilize the organic components. The tooth is finally fired at 1200-1350 °C for 8-30 min, depending on the producer. Now, the vacuum technique, which introduced 1949, is used primarily. This produces teeth essentially free of pores, which is beneficial in terms of strength and polishability of the teeth and – by increasing the transparency-particularly desirable in terms of aesthetic effects. In this procedure, the furnace is evacuated to approximately 1kPa. When the tooth
surfaces have become firing is continued at atmospheric pressure firing is when the tooth surface complete are smooth while the tooth contours are still unchanged. After soldering of the retentions and the required quality checks, the teeth are collected in sets according to color and shape as shown in Fig. 1.

Porosity, color matching with the shade guide, and dimensional stability are particularly stressed. Additional requirements are tissue compatibility of the material, and observance of laws and regulations relating to protection from radiation. Tissue compatibility and excellent service of porcelain inspired considerable work directed toward the use of porcelain and porcelain’s processing techniques, not only for artificial teeth, but for in days, crowns, bridges, and full-denture bases. The desirable attributes more than offset the severity of several problems, such as rigid manufacturing control, time consuming and rigid processing techniques, excessive shrinkage during processing, and brittleness in the finished restoration. This last characteristic, brittleness, limits the use of porcelain in many restorative uses, or requires that adequate metallic reinforcement and proper restoration design be carefully worked out.

The introduction of the transparent enamels was significant esthetic advancement toward the duplication of natural tooth appearance. The stain free porcelain to gold bonded appliances, with matched of thermal expansion coefficients for porcelain and gold, have provided a basis for strong, durable, esthetically fine fixed-bridge restorations.

Porcelain at this time finds its greatest application in dentistry as artificial teeth, jacket crowns, inlays, and as a veneer over metallic restorations for esthetic purposes.

Clinically, porcelain teeth are slightly more wear- and abrasion-resistant than natural teeth and outwear plastic teeth by a factor in the range of 10-20 times. Porcelain is the most chemically inert and stain-resistant, and hast the best tissue acceptance of any restorative material.

2.2 Interaction effects

Today, standard practice involves casting the framework in metal and veneering this with a ceramic layer.

Partial dental restoration such as crowns and bridges were fabricated entirely of precious metal. After insertion, such as a prosthesis can hardly be distinguished from natural teeth.

![Diagram of a ceramic tooth](image)

**Fig.1 A ceramic tooth**

The first attempts of this sort were made to enamel a gold denture base. Later, frit was developed that achieved sufficient adhesion between metal and ceramic. The bonding material produced is related to enamel. The metal provides sufficient tensile strength, while the ceramic, glaze-like veneer affords great abrasion resistance, good tissue compatibility, and an esthetic appearance.

In the past, mechanical retention of the ceramic layer on the rough metal surface was thought to be prerequisite for good adhesion between the two components. Today, more significance is attributed to adhesion through chemical bonding between the materials[6]. Bond formation generally is described to the presence of easily oxidized components, such as tin and indium, in the alloy. Presumably, the metal oxide layer between the metal and the ceramic is enriched through a so-called oxide firing step.
The durability of the bond between the metal and the ceramic depends particularly on the thermal expansion of the components. If the difference in this parameter is too great, the ceramic inevitably will split away from the metal during cooling. Under optimal condition, the ceramic shrinks a little less than the metal during cooling, the ceramic has a smaller coefficient of thermal expansion than the metal. It is then under slight compressive strain, which avoids tensile strain that is absorbed less well by the ceramic.

The dental workers mixes the ceramic powders to a creamy mass using water or a special modeling liquid. Each of the three ceramic layers is applied and fired separately. Appropriate distribution of grain size of the ceramic powders assures sufficient contour stability and condensability of the ceramic pastes.

The grain size is in the range of 2-80 μm, with a maximum between 20 and 30μm. Each firing lasts about 5 min. The vacuum firing procedure, described for tooth firing, has been widely adopted. If the veneer must be ground later for adjustment, glazing and refining provide the necessary shiny appearance. Unpigmented, finely ground glass are used as glazes.

They contain sufficient flux and can be fired at lower temperatures than those required for veneering. Strongly, pigmented glazes are used to provide specific colors. For example, tooth necks can be accentuated with color, and superficial anomalies, such as enamel tears and white spots, can be copied.

Important properties that must be checked constantly by the producer include thermal expansion, adhesion to the metal, bending strength, firing shrinkage, chemical durability, and transparency and color of the fired ceramic materials.

Damaged crowns of single vital teeth continue in part to be restored with jacket crowns. The jacket crown consists only of ceramic and is therefore aesthetically superior to the metal -ceramic crown. The opaque metal framework of the latter precludes imitation of the diffuse transparency of the natural tooth. Because metal ceramic crowns have better mechanical properties and more readily attainable exactness of fit, they have largely replaced jacket crowns.

The following technique is used today to fabricate a jacket crowns (Fig.1). A model made of a die of the prepared tooth. The model is covered with platinum foil, the foil serves as a base for the layers of ceramic to be placed on it. The foil is removed after the crown has been completed. As with ceramic-fused to-metal restorations several layers of ceramic, each with a specific transparency and shade, are fired. The core material is covered with a dentin layer and then with an enamel layer.

3. Diffusion to a tooth

Taking into account nutrition and thermal diffusion, microscopic description in the liquid-solid phases shown in Fig.1, can be described by equations (1) and (2). In this case interphase change can be neglected[10].

![Diagram of Diffusion to a Tooth](image)

**Fig.2 Diffusion to a Tooth**

Nutrition component transfer,

\[
\frac{\partial c_i}{\partial t} + v_x \frac{\partial c_i}{\partial x} + v_y \frac{\partial c_i}{\partial y} + v_z \frac{\partial c_i}{\partial z} = D_i \left( \frac{\partial^2 c_i}{\partial x^2} + \frac{\partial^2 c_i}{\partial y^2} + \frac{\partial^2 c_i}{\partial z^2} \right) \tag{1}
\]

Heat transfer,

\[
c_p \rho \left( \frac{\partial T}{\partial t} + v_x \frac{\partial T}{\partial x} + v_y \frac{\partial T}{\partial y} + v_z \frac{\partial T}{\partial z} \right) = \lambda \left( \frac{\partial^2 T}{\partial x^2} + \frac{\partial^2 T}{\partial y^2} + \frac{\partial^2 T}{\partial z^2} \right) \tag{2}
\]

where \(c_i\) nutrition, \(T\) the temperature, \(x, y, z\) are space coordinates and \(t\) is time, \(v\) is geometrical velocity, \(\rho\) density, \(c_p\) specific heat of material, \(D_i\) diffusion coefficient and \(\lambda\) the thermal diffusivity or heat conductivity. If mixing effects can be neglected equation (2) can be transformed[2-4]:

\[
\frac{\partial T}{\partial t} + v_x \frac{\partial T}{\partial x} = \lambda \left( \frac{\partial^2 T}{\partial x^2} \right) \tag{3}
\]

If diffusion can be neglected in \(y\) and \(z\) direction equation (2) can be restarted in the form:
Jelenka Savkovic Stevanovic et al / Diffusion in tooth

\[
\frac{\partial T}{\partial t} + v_x \frac{\partial T}{\partial x} = \lambda \left( \frac{\partial^2 T}{\partial x^2} \right) \quad (4)
\]

where \( \left( \frac{\partial T}{\partial t} \right) \) means speed of temperature change into the tooth, \( \left( \frac{\partial T}{\partial x} \right) \) is heat transfer rate in direction, and \( \left( \frac{\partial^2 T}{\partial x^2} \right) \) heat transfer acceleration in \( x \) direction which can regulating by parameter \( \lambda \). For the steady state condition and when velocity in the \( x \) direction can be neglected, equation (3) becomes:

\[
\lambda \left( \frac{d^2 T}{dz^2} \right) = 0 \quad (4)
\]

The demand made on the ceramic’s physical properties are different from those required of ceramic powders for application to metal. Because no metal base is present, the thermal expansion of the ceramic does not have to be increased, and the firing temperature does not have to be reduced below 1000°C. Nor need the core material be extremely opaque. However, the absence of a support for the crown, otherwise provided by the metal framework, must be compensated by increased strength, at least of the core material. The bending strength of this material should be at least 100 N/mm², whereas 50 N/mm² is sufficient for the opaque material in the metal -- ceramic technique.

Jacket crowns were fabricated in the past from ceramic powders quite similar to those used for teeth. This required that they had to be fired at temperatures no lower than 1250 °C. Today, ceramics are available which, through the addition boric acid and other fluxes, can be fired at temperatures below 1100 °C. The necessary increase in bending strength of the core material is achieved by adding as much as 50% alumina, usually in the form of carborundum. Prerequisites to the increased flexural strength elicited by the carborundum are good binding with the surrounding glass matrix and a controlled difference in thermal expansion between the carborundum and the glass phase. Miniature aluminum oxide plates are available for firing into the lingual region of the crown to increase bending strength. Even three-membered bridges can be made when alumina rods are used for stabilization.

Efforts underway to develop a fixed dental prosthesis that does not require a metal framework. In principle, this is fulfilled by the jacket crown which, unfortunately, does not meet all the demands posed by aesthetics, exactness of fit, and durability. Two other systems have recently been developed.

4. Heat transfer

Let consider various layers shown in Fig.3. In different hot medium each layer has its own expansion. Mechanism of heat transport in the compact layer is conductivity.

Fig.3 A ceramic- fused- to- metal crown

Overall heat transport:

\[
\alpha S(T_{saliva} - T_{tooth}) = \lambda_{tooth} \left( \frac{\partial^2 T_{tooth}}{\partial x^2} \right) + \rho_{tooth} C_{pe} \frac{T_{tooth}}{\partial t} \quad (5)
\]

Heat transfer function for enamel can be derived,

\[
\alpha S(T_{saliva} - T_{e}) - \lambda_e \left( \frac{\partial^2 T_{e}}{\partial x^2} \right) = \rho_e C_{pe} \frac{T_{e}}{\partial t} \quad (6)
\]

for dentin,

\[
\lambda_d \left( \frac{\partial^2 T_d}{\partial x^2} \right) - \lambda_e \left( \frac{\partial^2 T_e}{\partial x^2} \right) = \rho_d C_{pe} \frac{T_d}{\partial t} \quad (7)
\]

for opaque layer,

\[
\lambda_d \left( \frac{\partial^2 T_d}{\partial x^2} \right) - \lambda_o \left( \frac{\partial^2 T_o}{\partial x^2} \right) = \rho_o C_{pe} \frac{T_o}{\partial t} \quad (8)
\]

and, for metal layer,

\[
\lambda_m \left( \frac{\partial^2 T_m}{\partial x^2} \right) - \lambda_o \left( \frac{\partial^2 T_o}{\partial x^2} \right) = \rho_m C_{pm} \frac{T_m}{\partial t} \quad (9)
\]

Dentists try to control term \( \frac{\partial T}{\partial t} \), which describes temperature increasing with time inside a tooth. Practical experiences were illustrated in the previous...
papers [2],[8],[9]. One of the alternatives to control heat transfer parameters, is changing component materials.

5. Conclusion
The nutrition and heat transfer mechanism through biomaterials for teeth substituting were studied. Diffusion and mixing phenomena were included in consideration. Nutrition and heat transfer functions by thermal diffusion were derived. Raw materials determine thermal stability of ceramic powder. The ceramic powders are transformed to plastic masses adding organic additives such as starch pasta or oils. Thermal behavior of ceramic powders depend not only from component composition, already of way to phase passing.

Notation

\( C_p \) – material’s heat capacity
S-tooth surface
T-temperature, °C

Greek Symbols

\( \lambda \) -heat conductivity coefficient
\( \rho \) -enamel density
\( \sigma \) -phase passing parameter

Subscript

e - enamel
d - dentin
m - metal
o - opaque

Reference