Transient and Residual Stress in Porcelain/ Alloy Strip for Dental Use as Affected by Tempering*

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Porcelain-fused-to-metal (PFM) restorations may develop cracks during processing or in-mouth service if the relative physico-mechanical properties of the porcelain and alloy are highly mismatched. The precise conditions when it might occur are not known. Many processing and property variations can affect the stresses developed throughout a porcelain-alloy system. To understand this, a computer simulation of stress in a PFM strip was conducted. The simulation considers cooling from temperatures higher than the porcelain sag point. The following temperature-dependent factors were incorporated: the elastic modulus, shear viscosity (porcelain), and coefficient of thermal expansion. Cooling rates during tempering of porcelain were measured. The cooling rate dependencies of the glass transition temperature and temperature distribution during cooling were also included in the simulation. The results suggest that tempering with a high cooling rate make up for compressive residual stress in body porcelain and the high curvature of the composite beam.

Key Words: Biomaterials, Laminated Construction, Residual Stress, Thermal Stress, Viscoelasticity, Transient Stress

1. Introduction

Porcelain-fused-to-metal (PFM) restorations were presented to the dental profession about three decades ago. This technological advance precipitated a change to the era of full-coverage restorations that serve both the functional and cosmetic requirements of patients with carious, disfigured, or missing teeth. PFM restorations consist of a cast metal coping onto which a porcelain veneer is fired. With this technique, opaque porcelain is fused against the casting to mask the metal. The opaque is heavily loaded with metallic oxide opacifiers and may be applied with a thickness of 0.1 to 0.2 mm. Since the opaque porcelain is reflective, it must be covered with at least 1 mm of body porcelain if reasonable esthetics are to be achieved.

Currently, the use of PFM restorations represents a significant component of dental restorative practice. However, the dental practitioner has been faced with

the clinical problem of occasional failure of the porcelain-alloy system during function; a problem of small magnitude in terms of the frequency of occurrence, but of serious consequence when it does occur. Failures can be attributed to a variety of clinical, processing and material system deficiencies. With the continuous presentation of more and different types of alloys and porcelains for use by the dental profession, it becomes of increasing clinical importance to assess their compatibility with existing problems.

For this study, a computer simulation using a viscoelastic stress analysis was developed to clarify the effect of tempering and thermal expansion of alloy on transient and residual stresses in the PFM strip.

2. Materials and Methods

2.1 Cooling rate

The powder of the porcelain was formed into a cylindrical shape (5.0 mm in diameter and 10.0 mm in length) in a steel die by dry-pressing. Thermocouples of 0.13 mm in diameter were embedded in the porcelain compacts. The porcelain was fired according to the manufacturer's recommended procedure. After firing once in a furnace, the porcelain was reheated to

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950°C and kept there for 5 min. Cooling rates were measured under the following three conditions : (F) cooled in the furnace with no heat generation : (R) removed from the furnace and cooled in air at room temperature : (B) removed from the furnace and cooled in air by blasting with compressed air at 0.6 MPa from a distance of 30 cm.

2.2 Thermal expansion

Temperature dependencies of thermal expansions of the porcelains and alloy were measured by a push rod dilatometer. The coefficient of thermal expansion for a material in a temperature range which has no transformation has been found to fit the following equation to a high degree :

$$\alpha = C_1 + C_2 \cdot T, \quad (1)$$

where α is the thermal coefficient of expansion/contraction at temperature $T^\circ\text{C}$, C_1 and C_2 are constants characteristic of each material. The glass transition temperature, T_g , of the porcelain has a cooling rate dependency as shown in the next equation⁽¹⁾:

$$d(\ln|q|)/d(1/T_g) = -Q/R, \quad (2)$$

where q is the cooling rate, and Q and R are the activation enthalpy of shear viscosity and the gas law constant, respectively.

2.3 Viscosity

The deformation temperatures of the porcelain, which was the same material as used for thermal expansion measurements, were determined for three different heating rates⁽²⁾. The viscosity was calculated from the relation between the deformation temperatures and heating rates using Eq. (2). Here, the deformation point is defined by the temperature where the increase in the length of the specimen due to thermal expansion is balanced by the negative deformation (viscous flow) due to the applied stress.

2.4 Stress analysis

For the modeling simulation, a composite beam having 50 thin, equal layers of porcelain and one layer of alloy, as shown in Fig. 1, was chosen. A flow chart of the simulation procedure is shown in Fig. 2.

When the surface is kept at temperature $A \exp(-mt)$ for $t > 0$, the temperature distribution in the

Fig. 1 Schematic diagram of porcelain/alloy model used for stress analysis

slab which has zero initial temperature has an exact solution as follows⁽³⁾:

$$T = A \exp(-mt) \frac{\cos x(m/x)^{1/2}}{\cos l(m/x)^{1/2}} + \frac{16mA l^2}{\pi} \times \sum_{n=0}^{\infty} \frac{(-1)^n e^{-x(2n+1)^2 \pi^2 l^2 / 4l^2}}{(2n+1)(4ml^2 - x\pi^2(2n+1)^2)} \times \cos \frac{(2n+1)\pi x}{2l}, \quad (3)$$

where x is the thermal diffusivity, l is the half-thickness of the slab, and x is the distance from the midplane of the slab, $-l < x < l$. The thermal diffusivity of the porcelain⁽⁴⁾ was assumed to be 0.66 mm²/s. The temperature in the alloy was assumed to be uniform during cooling because the thermal diffusivity of the alloy is sufficiently higher than that of the porcelain.

Creep relaxation was assumed to follow a Voigt model⁽⁵⁾. The incremental time step, Δt , was determined from the cooling rate at the surface for 1°C

Fig. 2 Procedure for calculation of the transient and residual stresses in the composite beam

temperature decrements. The activation enthalpy of shear viscosity was taken to be equal to the activation energy in the Andrade equation for viscosity.

Each layer has a unique elastic modulus, thermal expansion coefficient, and viscosity, as determined by its temperature. The T_g onset in each layer was determined by its cooling rate by the use of Eq. (2) and T_g from a reference cooling rate. Internal stresses and curvatures of the slab were calculated by the equilibrium of internal moments and by strain continuity being required at the interfaces, with external forces set equal to zero. The net strain in any layer is equal to the sum of the strains due to thermal contraction, normal internal stress, bending, and viscous relaxation. Transient stresses were calculated by an incremental time step method, as shown in Fig. 2, and with the temperatures from heat-soaked temperature T_s to T_0 (30°C) divided into stages 1°C apart. Stresses were computed for every stage⁽⁶⁾.

3. Results

3.1 Data used in simulation

Cooling rates of the porcelain were measured for three conditions. The measured temperature, T , was represented by the following equation :

$$T = T_0 + A \exp(-mt). \quad (4)$$

Here, A is a constant related to heat-soaked temperature, t is the elapsed time, and m can be represented as $SU/(V\rho C_p)$, where S is the surface area, U is the coefficient of heat transfer, V is the volume of the porcelain, ρ is the density and C_p is the heat capacity. The m 's for porcelain with 1 mm thickness were

calculated to 0.005, 0.045 and 0.17 s⁻¹ for tempering (F), (R), and (B), respectively.

The true coefficient of thermal contraction for the porcelains* and alloy** is shown in Fig. 3. Here, the cooling rate was 5°C/min and the calculated temperature interval was 20°C. Measurement of thermal expansion/contraction of porcelain at high temperatures is difficult because of the viscous deformation of porcelain near the softening temperature. A reasonable assumption is then needed for the porcelain in this temperature range. In this case, a constant expansion was assumed, as shown in Fig. 3 by the solid line, for the porcelain. Reference data of T_g onset for the body and opaque porcelains were measured at 354 and 327°C for the cooling rate of 5°C/min.

Viscosities of the porcelains in the glass transition range were measured⁽²⁾ and represented by the following Andrade equations : $\eta = 4.0 \times 10^{-2} \exp(25500/T)$ Pa · s for opaque porcelain and $\eta = 6.0 \times 10^{-5} \exp(30800/T)$ Pa · s for body porcelain.

The temperature dependence of elastic moduli of the porcelains and alloy used was from the measured data of the same materials by Kåse et.al.⁽⁷⁾ and Kåse and Tesk⁽⁸⁾.

3.2 Results of simulation

Transient stress developed in a three-layered composite beam during cooling from heat-soaked temperature to room temperature, and residual stresses were calculated. In these calculations, the slabs were assumed as consisting of the laminated body, opaque and Ni-based cast alloy with thicknesses of 0.8, 0.2 and 0.5 mm, respectively.

Fig. 3 True thermal contraction coefficients at temperature, T , for the body porcelain (left) and opaque porcelain (right). That of the alloy used is shown in both figures

* Body porcelain : SiO₂ 66.7% - Al₂O₃ 14.2% - K₂O 9.9% - Na₂O 5.8% - CaO 1.2% - In₂O₃ 1.1% - etc.

Opaque porcelain : SiO₂ 51.3% - SnO₂ 23.8% - Al₂O₃ 12.4% - K₂O 7.9% - Na₂O 3.7% - etc.

** Alloy : Ni 71.5% - Cr 19.0% - Mo 4.0% - etc.

Transient stresses in the surface of the body porcelain and in the interface to the opaque porcelain during tempering are shown in Fig. 4. Figure 5 is the transient stress in the opaque porcelain. Here, the tempering conditions were chosen for two cases; that is, cooled in a furnace for slow cooling and cooled by blasting air for rapid cooling. Above the T_g , the coefficient of thermal contraction of the porcelain was higher than that of the alloy, and below the T_g , it was less. When the porcelain had low viscosity, the strain relaxation of each layer compensated for the thermal contraction mismatch between the porcelain and the alloy. In this temperature range, the porcelains and

alloy were almost stress free. When the temperature reached the deformation point of the porcelain, the transient stress developed depended highly on the thermal contraction mismatch. The progressively increasing stresses reached a peak at the temperature at which the coefficient of thermal contraction of the alloy met that of the porcelain, as shown in Fig. 3. A high tensile stress developed in the porcelain at the porcelain-alloy interface. This transient stress may result in fracture of the porcelain if interfacial flaking occurs during tempering. For the low-temperature range, strain relaxation was negligible. Transient stress was then due to the thermal contraction mis-

Fig. 4 Transient stress developed in the body porcelain during cooling. Temperings are (F) for slow cooling (left) and (B) for rapid cooling (right)

Fig. 5 Transient stress developed in the opaque porcelain during cooling. Temperings are (F) for slow cooling (left) and (B) for rapid cooling (right)

match of the materials and their elastic moduli.

Figure 6 shows the thermal deflection behavior of the porcelainized strip during tempering. Insufficient stress relaxation of the porcelain produced initial bending of the composite beam. After that, thermal contraction mismatch of the materials also became an important factor in determining the curvature. The general behavior as calculated by simulations agreed

closely with the experimental results from the strip model of Tuccillo and Nielsen⁽⁹⁾ and from the split model of Bertolotti and Fukui⁽¹⁰⁾. Here, tempering with rapid cooling produced a large curvature.

Figure 7 shows the residual stress at room temperature. The body porcelain contained stress over a wide range of -20 MPa (compression) to 12 MPa (tension) for specimens cooled in a furnace (F), and

Fig. 6 Curvature of the composite beam during cooling. Temperings are (F) for slow cooling (left) and (B) for rapid cooling (right)

Fig. 7 Residual stress distributions in composite beam after tempering of (F) for slow cooling (left) and (B) for rapid cooling (right)

from -19 MPa to 8 MPa for specimens with tempering by blasting air (B). The stress distribution was almost linear in each material for slow cooling and parabolic in the body porcelain for rapid cooling.

4. Discussion

The factors considered in determining the transient and residual stress in the composite beam are the coefficient of thermal expansion for alloy and porcelains, elastic moduli, cooling rate of tempering, thermal diffusivities, viscosities of porcelains, and dimensions of the composite. From a practical sense, isolation of the effects of all of these factors is difficult.

The two factors that affect the incompatibility of PFM restorations are considered: (1) the difference of the coefficient of thermal expansion for the alloy and porcelains, and (2) the cooling rate. The relationship of these factors was calculated; that is, the transient and residual stresses were simulated when alloys with different coefficients of thermal contraction were used. Figure 8 shows the transient stresses in the body porcelain for the different coefficients of thermal expansion of the alloy used. The designation B is an alloy system in current use. Higher transient stresses developed in the glass transition range of the porcelain when an alloy with a low thermal contraction coefficient is used. In these cases, processing cracks may occur easily in the opaque porcelain. On the other hand, higher tensile residual stress is caused in the surface of body porcelain when an alloy with a

Fig. 8 Transient stresses developed in the body porcelain related to the coefficient of thermal contraction of the alloy. The designations A, B and C correspond to 12.0 , 11.0 and $10.0 \times 10^{-6}/^{\circ}\text{C}$, respectively, for the constant C_1 in Eq. (1). Tempering (R) in the text was used

high thermal contraction coefficient is used.

Figure 9 shows the maximum tensile transient stress in the opaque porcelain, the residual compressive stress at the surface of the porcelain, and the curvature of the composite beam at room temperature. Here, the abscissa represents the C_1 in Eq. (1) for an alloy. In these simulations, the same C_2 value for an alloy was assumed. Results indicate less distortion of a PFM restoration after firing when an alloy with high thermal contraction or slow cooling is used. The simulated results show that the cooling rate of tempering makes up for tensile interfacial stress and curvature of the composite beam for up to $\sim 0.5 \times 10^{-6}/^{\circ}\text{C}$ of the thermal contraction mismatch between the alloy and the porcelain. For the surface residual stress of the porcelain, tempering makes up for the mismatch of up to $\sim 2.0 \times 10^{-6}/^{\circ}\text{C}$. The tensile strength of the porcelain used in this study was estimated to be about 70 MPa by the thermal shock test⁽¹¹⁾. The average coefficient of thermal contraction, $\bar{\alpha}$, from 30 to 500°C of the alloy which is currently used in dental laboratories, ranges from about 14 to $15 \times 10^{-6}/^{\circ}\text{C}$. The PFM restoration with these alloys has compressive or low tensile residual stress at the surface of the porcelain and transient interfacial tensile stress as about two-thirds of its flaking strength.

Fig. 9 Maximum tensile transient stress at the opaque-alloy interface, residual stress at the surface of the porcelain, and curvature of the composite beam at room temperature related to the coefficient of thermal expansion of the alloy. C_1 is the constant shown in Eq. (1), and $\bar{\alpha}$ is the average thermal contraction coefficient, ranging from 30 to 500°C . The designations (F), (R), and (B) represent temperings detailed in the text

5. Conclusions

The calculations of the residual stress and the transient stress in the PFM strip during tempering were conducted considering the temperature dependence of the elastic moduli, the thermal contraction coefficient, and the shear viscosity (porcelains), and the cooling rate dependence of the glass transition temperature of the porcelain.

The results of the simulation help to clarify the relative roles of thermal contraction mismatch between the alloy and the porcelain and cooling rate on the transient and residual stresses in a PFM strip. A high transient tensile stress develops at the opaque alloy interface when an alloy with a low thermal expansion coefficient is used. The surface of the porcelain has a tensile stress when slow cooling or an alloy with a high thermal expansion coefficient is used. These results suggest that cracks in PFM restorations can be prevented by choosing the proper tempering for a given porcelain-alloy system.

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