Transactions on Engineering Sciences vol 21, © 1998 WIT Press, www.witpress.com, ISSN 1743-3533

Transient and residual thermal stress in porcelain-fused-to-metal dental crowns

J. Lenz*, M. Thies** & K. Schweizerhof**
*Institut für Theoretische Mechanik
**Institut für Mechanik, Universität Karlsruhe, D-76128 Karlsruhe, Germany
Email: Juergen.Lenz@math.uni-karlsruhe.de

Abstract

Rotationally symmetric, premolar porcelain-fused-to-metal (PFM-) crowns were heated in a porcelain furnace to barely above the ceramic's glass transition temperature (~ 600°C). After opening the furnace, local temperatures at the crown's surface were simultaneously measured with thermocouples and recorded during the cooling phase down to ambient temperature. These data were smoothened and used as input to a FE-model to calculate the internal temperature and stress distribution as a function of time. Maximum transient stresses in the veneer occurred at the surface near the crown's cusp shortly (~ 24 seconds) after opening the furnace, whereas maximum residual stresses were found at the bond interface in the transition region from the occlusal to the wall section.

This work was supported by the Deutsche Forshungsgemeinschaft.

1 Introduction

PFM-crowns are fabricated by fusing porcelain at high temperatures (~1000°C) to an alloy frame. As soon as the ceramic's temperature falls below its glass transition temperature during the subsequent cooling phase, it changes from a sluggish, plastic into a brittle, elastic state. Thereafter, thermal stresses build up in the crown during further cooling.

Transactions on Engineering Sciences vol 21, © 1998 WIT Press, www.witpress.com, ISSN 1743-3533

The transient thermal stresses (stresses occurring during the cooling phase between glass and ambient temperature) depend on a large number of parameters: mode of cooling, glass temperature of the porcelain, temperature dependence of the mechanical and thermal coefficients of alloy and ceramic (Young's moduli, Poisson's ratios, coefficients of thermal expansion, thermal conductivities, heat capacities) and, of course, the geometry of the crown.

The residual thermal stresses (stresses in the final configuration at ambient temperature), however, are only a function of Young's moduli and Poisson's ratios at room temperature, the difference of the coefficients of thermal expansion of the two materials between the glass temperature of porcelain and ambient temperature, the glass temperature itself, and the geometry.

Both materials are treated as homogeneous, isotropic and linear-elastic, thus obeying the constitutive relations

$$\sigma(\varepsilon, \theta) = 2G\left[\varepsilon + \left\{ \nu e\,\mathbf{1} - (1+\nu)\,\alpha\,(\theta - \theta_G)\,\mathbf{1} \right\}/(1-2\nu)\right]$$

where σ: (Cauchy's) stress tensor, ε: deformation tensor, $\mathbf{1}$: unit tensor, e: (volume) dilatation, θ : (instantaneous) temperature, θ_G : glass temperature of porcelain, G: shear modulus, ν: Poisson's ratio (Young's modulus is given by $E = 2G(1+\nu)$), α: coefficient of thermal expansion.

In the case of the determination of transient thermal stresses, also the mass densities, ρ_M and ρ_C, thermal conductivities, λ_M and λ_C, and specific heats, c_M and c_C, are involved since they appear in Fourier's equation of heat conduction (M: metal, C: ceramic).

For the analysis of transient thermal stresses the temperature dependence of all material coefficients is needed. Appropriate experimental investigations are only known for Young's modulus and Poisson's ratio of a small number of materials[1,2], whereas the temperature dependence of the coefficients of thermal expansion can often be provided by the manufacturers of the material. Corresponding data for the thermal conductivities and specific heats, however, are not available in the literature. Therefore this analysis is partly based on data obtained for substitute materials[3,4] with compositions corresponding as much as possible to those of the alloy or porcelain in question[5].

Viscoelastic effects which can not be excluded for porcelain, especially at high temperatures close to the glass temperature, have not been taken into consideration, thus exempting stress relaxation effects. The presented stress values are therefore higher than those in real crowns. Viscoelastic behavior could, however, be easily incorporated in the numerical analysis as soon as reliable data are available.

Transactions on Engineering Sciences vol 21, © 1998 WIT Press, www.witpress.com, ISSN 1743-3533

2 Materials and Methods

With the help of a jig fabricated in brass on a computer-controlled milling machine, crown frames with constant wall thickness $d_M = 0.45$ mm were cast from the following dental alloys:

gold alloy	Aquarium C (manufacturer: Williams) Au86,Pt11,In2.5,Ir,Ta
palladium alloy	Capricorn Aries (manufacturer: Williams) Pd63.7,Ag26,Sn7,In1.5,Ru,Re
NiCr-alloy	Williams Litecast (manufacturer: Williams) Ni68.5,Cr15.5,Mo14,Al1,Si,Mn
CoCr-alloy	Remanium 2000 (manufacturer: Dentaurum) Co61.5,Cr25,Mo7,W5,Si1.5,Mn,Ce

Values for Young's modulus, E_M, and Poisson's ratio, ν_M, at room temperature and the mean coefficient of thermal expansion, α_M, in the interval 20°C – 600°C are given in the following table[6]:

alloys	E_M [GPa]	ν_M	α_M [10^{-6} K^{-1}]
Aquarius C	75.9	0.42	14.8
Capricorn Aries	97.9	0.39	14.8
Williams Litecast	158.6	0.27	14.4
Remanium 2000	200.0	0.33	14.3

For veneering the porcelain ips-Classic (manufacturer: Ivoclar) was chosen. In order to produce ceramometallic crowns with the most identical dimensions possible a special device was constructed which allowed to rotate the crowns, after porcelain had been applied, against a fixed stripping blade which had the desired external contour of the crown. The height of the crowns amounted to 7.5 mm, the maximum radius to 4.1 mm (the special geometry of the final specimens is given in Fig. 2; here due to axisymmetry only half of the cross section is displayed).

For Young's modulus, E_C, and Poisson's ratio, ν_C, each at room temperature, the values $E_C = 69.4$ GPa and $\nu_C = 0.19$ were used[1]. From measurements of thermal strain as a function of temperature which were carried out by the manufacturer, the mean value $\alpha_M = 12.2 \times 10^{-6}$ K^{-1} was obtained for the porcelain's coefficient of thermal expansion in the temperature interval 20°C – 581.7°C; $\theta_G = 581.7$°C is the glass temperature of the porcelain (as space is limited, the diagrams showing the temperature dependencies of the materials' coefficients which were used to compute the transient thermal stresses, are omitted here).

The temperature distribution inside the crown is determined by the external thermal conditions which define the heat transfer (heat flux) between the crown and its surroundings. The heat flux is given by a combination of radiation (dominant at higher temperatures) and free convection (dominant at lower temperatures). The determination of the relevant parameters for radiation and convection would only be possible upon extremely high experimental effort. Moreover, simulation of convection and radiation for geometrically complex bodies still is a problem in numerical analysis[7]. In order to avoid these difficulties the environmental influence was instead taken into account by measuring directly the surface temperature as a function of time during cooling.

For that reason the crowns were heated in the furnace (Ivoclar Programat P 90) to a temperature of θ_O = 600°C (i.e. just a few degrees above the glass temperature of the ceramic) for about ten minutes to establish a homogeneous temperature distribution inside the crown thus simulating a situation corresponding to the so-called retarded (long-term) cooling. Then the lid of the furnace was lifted off, the firing tray with the crown taken out of the furnace and the system exposed to air (at room temperature) and shielded by a wide cylinder to avoid uncontrollable flow of air.

The crowns were equipped with NiCr/Ni-thermocouples at a number of points on the outer veneer and the inner alloy frame (Fig. 1) situated on the contour of an intersection through the crown containing its axis. The electronic outfit (National Instruments SCXI-1000, 1100, 1300) allowed a simultaneous measurement of temperature at these contact points as a function of cooling time, whereby the start of each experiment was trig-

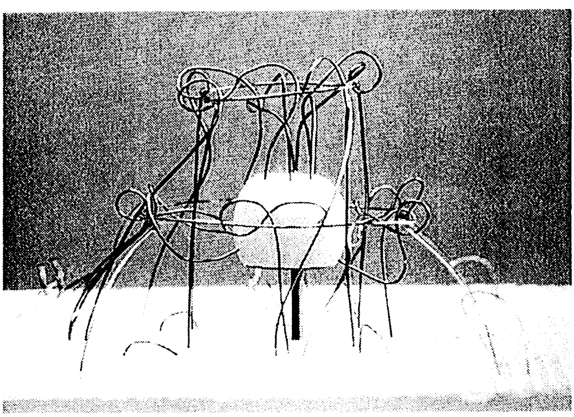
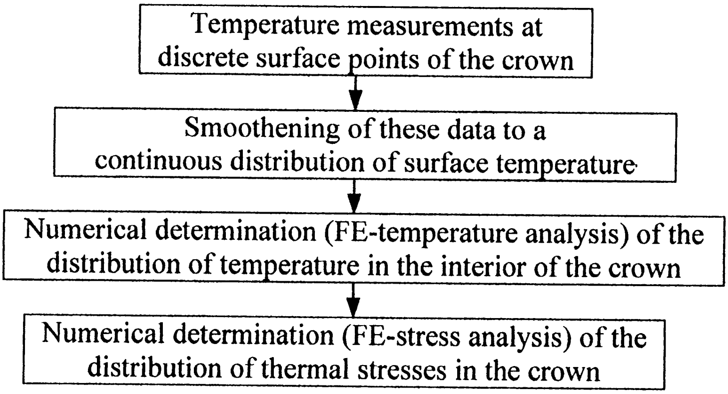


Figure 1: Crown specimen equipped with thermocouples.

Transactions on Engineering Sciences vol 21, © 1998 WIT Press, www.witpress.com, ISSN 1743-3533

gered with the instant of lifting the lid of the furnace. The measurements were repeated ten times for statistical reasons. Afterwards the crowns were rotated by 90° with again ten measurements carried out at this position in order to take into account possible deviations from axi-symmetry of the system. At last the mean value of the instantaneous temperature was determined from all these measurements.

The discrete temperature information was smoothened to a continuous, time-dependent temperature distribution which was then used as loading of a finite element (FE) model to compute the temperature distribution in the interior of the crown and finally the distribution of thermal stresses in the system. The following flow chart comprises this computational procedure:



The numerical simulations were carried out using the FE-program ANSYS. In Fig. 2 the final mesh consisting of 2384 axisymmetric four-node elements is displayed. Appropriate investigations prior to the final computations proved that a further refinement of the mesh leads only to negligible deviations in the stress values.

3 Results

For the combination Williams Litecast/ips-Classic three characteristic situations of the distribution of maximum principal stress in the veneer are shown in Figs. 3-5 (the stress distribution in the alloy frame is left out thus concentrating on that part of the crown which is endangered to failure). After opening the furnace the stresses increase continuously with time until after approximately 24 seconds (Fig. 3) the highest stress occurring during the complete cooling phase is reached (in the following the locus of highest thermal stress is indicated by an arrow). This

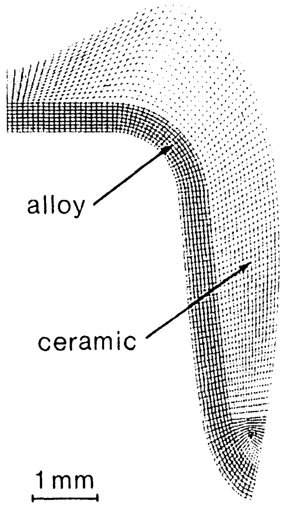


Figure 2: Mesh used in the FE-analysis and dimensions of the crown. The thickness of the alloy frame amounts to d_M = 0.45 mm.

maximum stress is found at the surface of the veneer close to the cusp and has a value of $\sigma \approx 68$ MPa. The figure reveals a large stress gradient at the surface of the porcelain whereas a wide section of the interior of the veneer (adjacent to the alloy frame) is under compression or at most moderate tension. Subsequently the porcelain stresses at the surface decrease and later stresses build up along the material interface in the transition region from the occlusal to the wall section of the crown. Fig. 4 shows the stress distribution after 100 seconds: the maximum principal stress now occurs near the crown's margin, but the stresses at the material interface have already reached the almost identical value $\sigma \approx 15$ MPa. Upon continued cooling a further stress relief at the veneer's surface is observed while the stresses at the material interface are constantly growing. In Fig. 5 the stress distribution is given when the crown has practically cooled down to ambient temperature (20°C $\leq \theta \leq$ 20,3°C) thus corresponding to the distribution of residual thermal stresses. The maximum principal stress of $\sigma \approx 39.6$ MPa is located at the material interface in the curved section where also the highest stress gradients appear. The exterior part of the veneer is loaded either by compressive stresses (near the symmetry axis of the crown) or at most by small tensile stresses $\sigma \leq 6$ MPa (around the cusp and in the wall region).

Fig. 6 finally shows the stress distribution in the complete crown. It is clear that the alloy frame is subject to rather high tensile stresses.

Concerning possible failure modes of the crown due to critical stresses, the following conclusions can be drawn:

1. The highest stresses in the veneer during the complete cooling process are found at the surface near the cusp about 24 seconds after

Transactions on Engineering Sciences vol 21, © 1998 WIT Press, www.witpress.com, ISSN 1743-3533

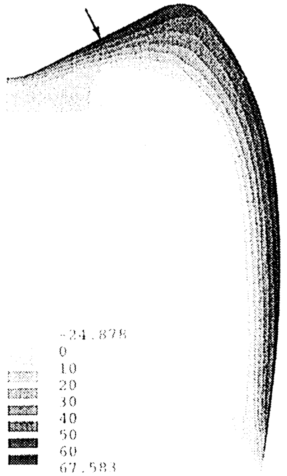


Figure 3: Thermal stresses in the veneer 24 seconds after opening the furnace.

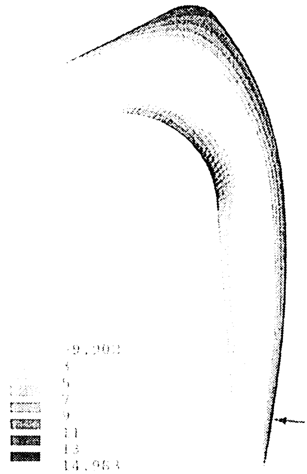


Figure 4: Thermal stresses in the veneer 100 seconds after opening the furnace.

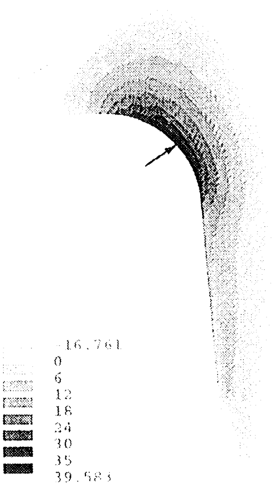


Figure 5: Residual thermal stresses in the veneer (650 seconds after opening the furnace).

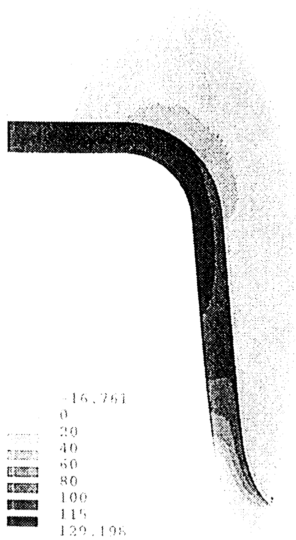


Figure 6: Residual thermal stresses in the complete crown (alloy frame and veneer).

opening the lid of the furnace. As shown in Fig. 3, however, the stresses in the upper wall section are of the same magnitude. If these stresses

Transactions on Engineering Sciences vol 21, © 1998 WIT Press, www.witpress.com, ISSN 1743-3533

become critical, cracks and/or spallations will most likely occur in these regions of the ceramic veneer.

2. The residual stresses have a maximum at the material interface in the transition region from the occlusal to the wall section of the crown. It must therefore be expected that the final configuration is rather endangered to debonding than to cracking.

In additional experiments the crowns were kept in the furnace until its temperature had dropped to θ_O = 450°C. At this temperature the stress distribution in the veneer shows a pattern which is similar to that of the residual stress distribution given in Fig. 5. The maximum stress at the material interface, however, possesses the value $\sigma \approx 25$ MPa.. The following cooling process leads to a decrease of the stresses at the material interface and an increase at the surface of the veneer, until after about 18 seconds the stress (again near the cusp and in the upper wall section) reaches the largest value $\sigma \approx 49$ MPa. Further cooling, of course, finally leads again to the residual stress distribution shown in Figs. 5 and 6.

Comparing the maximum stresses found in these cooling processes ($\sigma \approx 68$ MPa for $\theta_O = 600$°C and $\sigma \approx 49$ MPa for $\theta_O = 450$°C), it is clear that a reduction of the critical transient thermal stress of about 30 % can be achieved by lowering the opening temperature. The residual stress distribution, however, can not be manipulated by changing the cooling

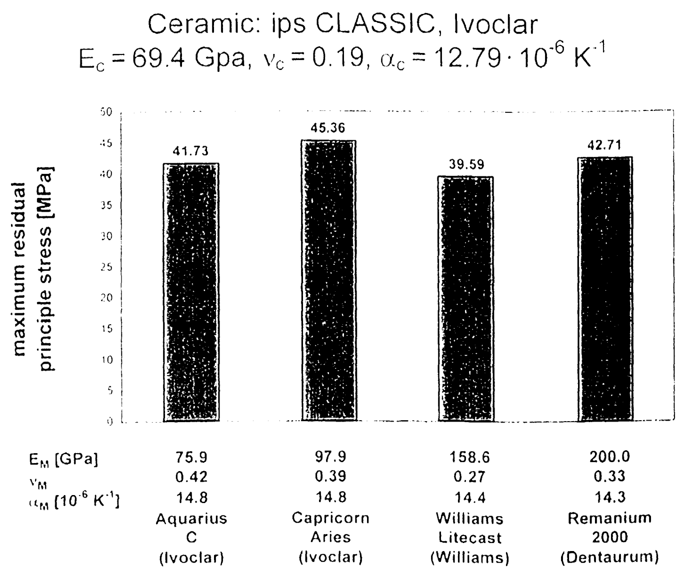


Figure 7: Maximum residual principal stress if ips-Classic porcelain is fused to the four alloys.

Transactions on Engineering Sciences vol 21, © 1998 WIT Press, www.witpress.com, ISSN 1743-3533

process but is completely determined by Young's modulus, Poisson's ratio and the coefficient of thermal expansion of the materials, the glass temperature of porcelain, and the chosen geometry.

Fig. 7 presents the maximum residual thermal stresses in the veneer if ips-Classic ceramic is fused to the four considered alloys. For all material combinations the stress patterns are identical and the locus of highest thermal stress coincides with that shown in Fig. 5 for the NiCr-alloy. The given values differ only by ≤ 7 % from the mean value. Note, however, that the difference in the coefficients of thermal expansion of metal and ceramic is larger for the Au- and Pd- than for the NiCr- and CoCr-alloy.

In order to take into account the influence of Young's modulus E_M of the alloy on the magnitude of the maximum residual stress, numerical simulations were performed for the case that for each alloy/porcelain combination the difference in the coefficients of thermal expansion would amount to the value $(\alpha_M - \alpha_C) = 1 \times 10^{-6}\ K^{-1}$. It is evident from Fig. 8 that the maximum residual principal stress increases with growing Young's modulus E_M (deviations of Poisson's ratio ν_M from the actual value lead to negligible changes in stress as proven by further simulations).

It is well-known that a small radius of curvature may cause stress concentrations. We therefore also analyzed the effect of the radius of curvature, r, of the outer contour of the alloy frame on the maximum normal

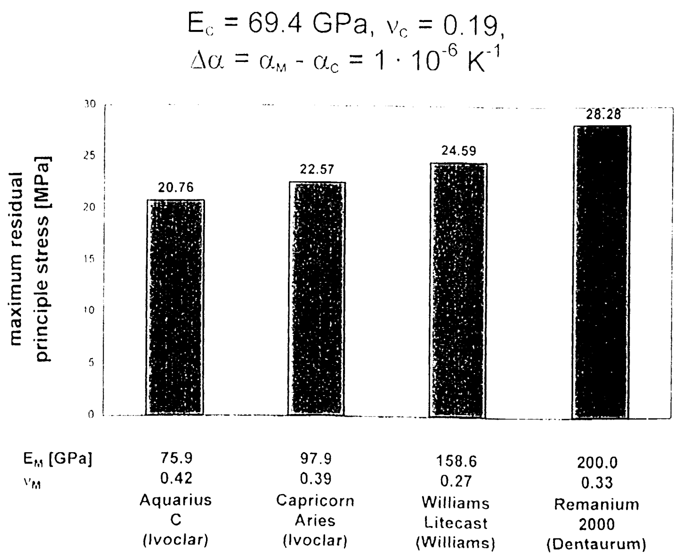


Figure 8: Maximum residual principal stress if porcelain is fused to the four alloys in the case $(\alpha_M - \alpha_C) = 1 \times 10^{-6}\ K^{-1}$.

Transactions on Engineering Sciences vol 21, © 1998 WIT Press, www.witpress.com, ISSN 1743-3533

stress in the veneer at the material interface. For the combination Williams Litecast/ips-Classic these results are shown in the following table:

r [mm]	normal stress [MPa]
0.65	60.50
0.95	50.32
1.45	39.58
1.95	34.12

where the value r = 1.45 mm was chosen in the analyses described above. As expected a decrease of the radius of curvature from r = 1.95 mm to r = 0.65 mm causes a rise of normal stress by 77 %.

4 Conclusions

The analysis of thermal stresses in a premolar ceramometallic crown shows that cracks and/or spallations in the veneer are most likely brought about by high transient stresses which occur shortly after opening the lid of the porcelain furnace, whereas critical residual stresses may rather lead to debonding. Transient stresses can be reduced by gradually cooling the crown inside the furnace down to lower opening temperatures. In order to reduce the danger of failure by debonding, a reasonably large radius of curvature of the bond surface is preferable.

References

[1] Käse, H.R. & Tesk, J.A. Elastic constants of two dental porcelains, *J. Material Science*, **20**, pp. 524-531, 1985.

[2] Käse, H.R. & Tesk, J.A. Elastic constants of three Ni-Cr dental alloys at room and elevated temperatures, *Dental Materials*, **5**, pp. 289-293, 1989.

[3] *Landolt-Börnstein, Zahlenwerte und Funktionen, vol. IV/4a*, Springer, Berlin, 1967.

[4] *Landolt-Börnstein, Zahlenwerte und Funktionen, vol. IV/4b*, Springer, Berlin, 1972.

[5] Thies, M., *Beanspruchung metallkeramischer Kronen durch Wärmeeinwirkung bei der Herstellung und durch Kaubelastung,* Ph.D. thesis, Universität Karlsruhe, 1994.

[6] *Das Dental Vademekum,* Deutscher Ärzte-Verlag, Köln, 1995.

[7] Verein Deutscher Ingenieure (ed.), *VDI-Wärmeatlas,* VDI Verlag, Düsseldorf, 1991.