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Influence of thermal gradients on stress state of veneered restorations

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ABSTRACT

Objectives. To assess transient and residual stresses within the porcelain of veneered restorations (zirconia and metal) as a result of cooling rate and porcelain thickness.

Methods. Porcelain-on-zirconia (PZ) and porcelain-fused-to-metal (PFM) crowns were fabricated with 1 or 2 mm of porcelain. Thermocouples were attached both internally and externally to the crowns to record transient temperatures. For fast cooling, the furnace was opened after the holding time and switched off. Slow cooling was accomplished by opening the furnace at 50 °C below the glass transition temperature (T_g) of the material. An axially symmetric FEA model simulated thermal stresses. Time-dependent temperature equations from thermocouple readings were set as boundary conditions. Framework materials and the porcelain below T_g were considered to behave elastically. Visco-elastic behavior was assumed for porcelain above the T_g modeling properties as dependent on cooling rate.

Results. Differences in residual stress were found for fast and slow cooled PZ and PFM crowns. Significant transient stress waves were observed within the porcelain when fast cooling through T_g. They are believed to be related to non-uniform volumetric changes originated from thermal gradients. Results were confirmed by modeling and physical testing of crowns containing a defect.

Significance. Residual stresses do not distinguish PZ from PFM. High magnitude transient stresses observed within the porcelain during fast cooling may explain clinical fractures involving internal defects. Stress waves may also originate internal micro-cracking which could grow under function. Therefore, slow cooling, especially for all-ceramic crowns with thick porcelain, is important to prevent thermal gradients and high-magnitude transient stresses.

1. Introduction

Porcelain–zirconia systems are used in dentistry due to zirconia's high strength and the esthetics of porcelain veneers. The

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zirconia framework has some translucency and allows light transmission through the restoration conferring more natural appearance than metal copings [1].

Clinical studies on zirconia-based restorations reported survival rates of 81–100% in 3 years [2] and 74% in 5 years [3]. An especial concern has been raised regarding the potential susceptibility of porcelain on zirconia to premature chipping and fracture [1]. The percentage of porcelain fractures (chipping, cracking, delaminations and large fractures) are high when compared to the same modes of porcelain fractures observed for metal–ceramic restorations [1–5].

Regarding this particular porcelain issue (early fracture) with zirconia restorations, some main practical questions arise, such as: can veneered-zirconia restorations be handled as it has been successfully done for metal–ceramic systems? Which differences in material's properties or processing techniques contribute to stresses development and distribution through the porcelain? How can this problem be fixed?

Possible causes of porcelain early fracture were raised in previous studies, such as: lower elastic modulus and fracture toughness of the porcelain material [6]; inhomogeneous or thick layers of porcelain [7,8]; thermal incompatibility [9–11]; poor bond strength (wetting) of porcelain on zirconia [11–13]; inadequate design of framework or insufficient support of porcelain [14–16]; inadequate porcelain processing (firing) [17]; inadequate cooling rate [18–20].

Internal and subsurface origin are frequently related to the porcelain fracture as described by Swain [7] and illustrated in Fig. 1, which shows a clinical porcelain–zirconia crown fractured by porcelain chipping. The electronic microscopy analysis showed that the fracture origin was within the porcelain bulk and not related to its external surface. In addition, cracks were observed at the subsurface area (approximately 0.5 mm below the surface) following the direction of (parallel to) the occlusal surface. The internal origin of the fracture and the subsurface cracks suggest an association of the fracture related to a thermal response.

As demonstrated in previous studies [20,21], thermal gradients are frequently related to fast cooling of porcelain–zirconia and metal–porcelain crowns. Thus, the potential association of temperature gradients to the development of residual and transient stresses within the porcelain should be investigated.

The temperature-dependence of the thermo-mechanical properties (especially close to the glass transition temperature) of dental porcelains may play an important role in the stress state of porcelain on veneered-zirconia restorations. Asaoka and Tesk [22] highlighted important factors that have been studied by a number of investigations and should be considered for determination of the transient and residual stresses and their importance to the final state of the porcelain: (1) geometric shape [7]; (2) elastic modulus dependency on temperature [23]; (3) coefficient of thermal expansion dependency on temperature [7,22]; (4) temperature distribution during cooling process [20,21]; (5) temperature-dependent viscosity [23–25]; and (6) cooling rate-dependency of the glass transition temperature (T_g) [26]. These factors were incorporated to the analyses performed in the present study.

Dental porcelains are silicate glasses containing modifying cations, such as aluminum, potassium and sodium, to adapt its properties (basically viscosity and the glass transition temperature) to a specific function [27]. Above the glass transition temperature (T_g generally between 400 and 600 °C for dental porcelains), porcelains behave as a viscous liquid and any force applied to the structure results in creep or plastic deformation; and therefore no residual stress is accumulated [7]. Below the T_g, the porcelain behaves closely to an ideal elastic solid and any stress applied to the porcelain results in a proportional instantaneous (more exactly, at the speed of sound) strain [28]. It does not creep under continuous load and, when the stress is removed the deformation is instantaneously recovered. The porcelain change from viscous-liquid to solid during cooling is followed by a change in volume and, consequently, in its density. Changes in length/volume usually depend on temperature and heating/cooling rate.

Cooling viscous-liquid porcelain to temperatures below the glass transition not only reduces the quantity of energy available for structural rearrangements, increasing viscosity and decreasing density, but also has an effect on thermal-dynamic properties, such as heat capacity (C_p) and thermal conductivity (k). In this work the terms heat capacity and specific heat are used interchangeably.

Glass transition temperature (T_g) is also strongly influenced by cooling rate: the faster the cooling, the higher the transition temperature [26,29]. Higher cooling rates usually result in development of thermal gradients within the ceramic body. Non-uniform thermal contraction (volume and density changes) and solidification (viscosity change) are likely generated by the temperature gradients, and result in the development of stresses.

Understanding the cooling-rate dependence of T_g [26] and the solidification process are important for the investigation of potential development of transient and residual stresses in the porcelain. Whether these so-called "transient" stresses influence the porcelain cracking or early fracture is a subject to be explored in the present work.

Therefore, the present study investigates possible reasons for fracture of porcelain–zirconia restorations originated from cracks and defects localized inside or at the subsurface of the porcelain. The study analyzed the development of transient and residual stresses in porcelain–zirconia and porcelain-fused-to-metal (PFM) restorations as a result of slow and fast cooling. Finite element analysis was used to simulate cooling from temperatures above the glass transition temperature to room temperature.

The study tested the following hypotheses: (1) residual stresses generated after fast cooling are greater than for slow cooling; (2) magnitude and distribution of residual stresses in the porcelain on zirconia and on metal are similar; (3) thermal gradients originated during fast cooling contribute to the development of transient stresses; (4) transient stresses allows nucleation and propagation of cracks from defects in porcelain.

2. Materials and methods

2.1. *Thermal analyses*

Porcelain-on-zirconia (PZ) and porcelain-fused-to-metal (PFM) crowns were fabricated with 1 or 2 mm of compatible