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Influence of thermal expansion mismatch on residual stress profile in veneering ceramic layered on zirconia: Measurement by hole-drilling

Amélie K. Mainjot[a,b,*], *Achref Najjar*[b], *Boris D. Jakubowicz-Kohen*[b], *Michaël J. Sadoun*[b]

[a] *Dental Biomaterials Research Unit (d-BRU), Department of Fixed Prosthodontics, Institute of Dentistry, University of Liège (ULg, CHU), 45 Quai G. Kurth, Liège, 4020, Belgium*
[b] *Unité de Recherches Biomatériaux Innovants et Interfaces (URB2I-EA4462), Université Paris Descartes, Sorbonne Paris Cité, Faculté de Chirurgie Dentaire, Paris, France*

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ABSTRACT

Objectives. Mismatch in thermal expansion coefficient between core and veneering ceramic ($\Delta\alpha = \alpha_{\text{core}} - \alpha_{\text{veneer}}$, ppm/°C) is reported as a crucial parameter influencing veneer fractures with Yttria-tetragonal-zirconia-polycrystal (Y-TZP) prostheses, which still constitutes a misunderstood problem. However, the common positive $\Delta\alpha$ concept remains empirical. The objective of this study is to investigate the $\Delta\alpha$ dependence of residual stress profiles in veneering ceramic layered on Y-TZP frameworks.

Methods. The stress profile was measured with the hole-drilling method in bilayered disc samples of 20 mm diameter with a 0.7 mm thick Y-TZP framework and a 1.5 mm thick veneer layer. 3 commercial and 4 experimental veneering ceramics ($n = 3$ per group) were used to obtain different $\Delta\alpha$ varying from −1.3 ppm/°C to +3.2 ppm/°C, which were determined by dilatometric analyses.

Results. Veneer fractures were observed in samples with $\Delta\alpha \geq +2.3$ or ≤ -0.3 ppm/°C. Residual stress profiles measured in other groups showed compressive stresses in the surface, these stresses decreasing with depth and then becoming more compressive again near the interface. Small $\Delta\alpha$ variations were shown to induce significant changes in residual stress profiles. Compressive stress near the framework was found to decrease inversely to $\Delta\alpha$.

Significance. Veneer CTE close to Y-TZP (+0.2 ppm/°C $\Delta\alpha$) gived the most favorable stress profile. Yet, near the framework, $\Delta\alpha$-induced residual stress varied inversely to predictions. This could be explained by the hypothesis of structural changes occurrence within the Y-TZP surface. Consequently, the optimum $\Delta\alpha$ value cannot be determined before understanding Y-TZP's particular behavior when veneered.

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[*] *Corresponding author at*: Dental Biomaterials Research Unit (d-BRU), Department of Fixed Prosthodontics, Institute of Dentistry, University of Liège (ULg, CHU), 45 Quai G. Kurth, Liège, 4020, Belgium. Tel.: +32 4 270 31 31.
E-mail address: a.mainjot@chu.ulg.ac.be (A.K. Mainjot).

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1. Introduction

Yttria-tetragonal-zirconia-polycrystal (Y-TZP) was introduced as a framework material for dental crowns and fixed partial dentures (FPDs) in the early 2000s. Because of its high strength and fracture toughness associated with favorable optical and biocomptability properties, it was considered to be a good alternative to metal for fixed prostheses on teeth and implants. Nevertheless, if clinical studies on Y-TZP based restorations have reported low rates of framework fractures, they have highlighted a significant number of failures related to veneering ceramic cohesive fractures (chipping). Chipping constitutes the first cause of failure of those restorations and has been shown to be more frequent than with metal-based prostheses [1–3].

The chipping mechanism is complex and not well understood. Yet it is known that cracks form and propagate in the presence of tensile stress [4]. The tensile stress results from the application of an external load but also from the presence of residual stresses, which are "locked-in" stresses generated in a material or a component during the manufacturing process. In the case of dental prostheses, they develop within the veneer and the framework during the cooling and solidification period of the veneer firing process. Residual stresses mainly originate from the mismatch in the thermo-physical properties between both materials, as well as from the presence of temperature gradients within the bilayer during the cooling period, but they can also be attributed to solidification as phase transformation processes [5]. They persist within the material without the application of any external load, but will add to its effect [6]. They play a critical role in failures due to fracture, stress corrosion cracking, fatigue, wear and more [7]. Thus the knowledge of residual stress profile in the veneering ceramic as a function of depth constitutes a good predicting factor of fracture, residual compressive stress promoting resistance and residual tensile stress promoting crack initiation and propagation.

While mismatch in thermo-physical properties of materials greatly influences residual stress surprinsingly, the development of veneering ceramics for zirconia was empirical. Indeed, the veneer properties were copied and pasted from the porcelain-fused-to-metal (PFM) concept: the CTE of the veneering ceramic was adapted to obtain a slight positive mismatch between core and veneer ($\Delta\alpha = \alpha_{\text{core}} - \alpha_{\text{veneer}}$, ppm/°C). This slight $\Delta\alpha$ is supposed to induce, during ceramic cooling from T_g to room temperature, residual compressive stress within the veneer and compensating residual tensile stresses within the framework [8–10]. For PFM systems, $\Delta\alpha$ around +1 ppm/°C are commonly reported [11–13]. Consequently, the development of veneering ceramics for zirconia frameworks only consisted of CTE measurements and thermal shock testing [14]. The CTE values are adapted to obtain a positive $\Delta\alpha$, but they can vary significantly from one manufacturer to the other. In the literature, the positive $\Delta\alpha$ concept for zirconia-based structures is supported by in vitro studies on veneer-zirconia adhesion and crown fracture load [15–17]. However, other data on load at failure in biaxial flexure test of veneered zirconia discs showed better results with a $\Delta\alpha$ value of zero [18].

Recently, Belli et al. [19] reported, through a residual stress photoelastic assessment of crowns, that $\Delta\alpha$ is a major factor influencing the maximum stress development in the veneer in comparison with cooling rate. In their configuration, they showed a four- to five-fold stress magnitude escalation (from unknown nature: compressive or tensile) with a +1.1 ppm/°C $\Delta\alpha$ increase.

The $\Delta\alpha$ dependence of residual stress profiles in veneering ceramic layered on zirconia has been studied through pure linear elastic mathematical models. Swain studied the independent influence of the cooling rate, thickness and thermal expansion coefficient on residual stress profiles within a simple bilayer model composed of glass ceramic, alumina or zirconia substrates [9]. He calculated that a +1 ppm/°C $\Delta\alpha$ effect induces a linear switch from tensile to compressive stress, from the surface to the depth of the veneering ceramic, whatever the framework material or the thickness. Then he combined $\Delta\alpha$ with thermal gradients effect, for different veneer-framework thickness ratios, and he obtained non-linear stress profiles in the veneering ceramic with compressive stresses in the surface, these stresses decreasing with depth, sometimes becoming tensile depending on thicknesses, and then increasing again close to the framework. Bonfante et al. showed, using a 3D-molar crown finite element analysis, i.e. a more complex sample geometry with non uniform veneer thickness, slight tensile stress at the core-veneer interface with a +0.7 ppm/°C $\Delta\alpha$.

But the main drawback of elastic models is that they do not take into account important parameters influencing the residual stress profile as the viscoelastic phenomena occurring during the firing process, the variations of thermal gradients, the variations of material thermal properties such as CTE with temperature, as well as the impact of potential solidification or phase transformation processes. The residual stress problem is very complex and most of the time predictive capabilities are insufficient to give adequate knowledge of residual stresses [6]. Consequently, the ability to measure residual stress is critical to understanding failures and also to aiding in the development of predictive capabilities by verifying models [6].

Up to now, the independent influence of $\Delta\alpha$ on the residual stress profile in the veneering ceramic layered on zirconia has never been measured. In the last few years, a residual stress measurement method was introduced for dental applications to measure residual stress profiles in the veneering ceramic layered on metal or ceramic disc frameworks [20]. The hole-drilling method was chosen because of its flexibility and convenience of use, its demonstrated reliability in industrial applications, and the existence of a standardized test procedure [21]. This method is based on the removal of some stressed material and the measurement of the resulting deformations in the adjacent material [22]. The deformations are measured on the surface, typically using strain gages, from which the residual stresses can be calculated. Stresses are calculated from surface to depth, typically with 0.1 mm steps, and giving a stress profile within a 1.2 mm depth. The advantage of the disc configuration is the axial and simple sample geometry, which reduces the influence of a non-uniform design on residual stress development.

The hole-drilling method was already used to study the independent influence of cooling rate and veneer as