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Influence of zirconia framework thickness on residual stress profile in veneering ceramic: Measurement by hole-drilling

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ABSTRACT

Objectives. Framework design is reported to influence chipping in zirconia-based restorations, which is an important cause of failure of such restorations. Residual stress profile in the veneering ceramic after the manufacturing process is an important predictive factor of the mechanical behavior of the material. The objective of this study is to investigate the influence of framework thickness on the stress profile measured in zirconia-based structures.

Methods. The stress profile was measured with the hole-drilling method in bilayered disc samples of 20 mm diameter with a 1.5 mm thick veneering ceramic layer. Six different framework thicknesses from 0.5 mm to 3 mm were studied. Two different cooling procedures were also investigated.

Results. Compressive stresses were observed in the surface, and tensile stresses in the depth of most of the samples. The slow cooling procedure was found to promote the development of interior tensile stresses, except for the sample with a 3 mm thick framework. With the tempering procedure, samples with a 1.5 mm thick framework exhibited the most favorable stress profile, while thicker and thinner frameworks exhibited respectively in surface or interior tensile stresses. **Significance:** The measurements performed highlight the importance of framework thickness, which determine the nature of stresses and can explain clinical failures encountered, especially with thin frameworks. The adequate ratio between veneering ceramic and zirconia is hard to define, restricting the range of indications of zirconia-based restorations until a better understanding of such a delicate veneering process is achieved.

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1. Introduction

Introduced in prosthodontics over ten years ago, Yttria-tetragonal-zirconia polycrystal (Y-TZP) is reported as a

biocompatible and esthetic alternative to metal frameworks. Its good mechanical properties in comparison with other ceramic materials has led manufacturers to propose Y-TZP for large bridges on teeth and implants. Unfortunately clinical

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studies report short-term clinical failures of zirconia-based restorations mainly due to cohesive fractures of the veneering ceramic (chipping), which is the weak link of the restoration [1]. This problem is less reported with porcelain-fused to metal (PFM) restorations and has often been associated to improper framework design [2]. Indeed, the results of some uncontrolled clinical studies [3–5] and in vitro studies about crowns fatigue and fracture load resistance [6–9] suggest that the use of an alternative core design, which ensures an optimal support to veneering ceramic, can prevent chipping. Anatomical frameworks, avoiding excessive veneer thickness and exhibiting an additional lingual shoulder, as proposed for porcelain-fused-to-metal (PFM) restorations, are then recommended. Moreover the core–veneer thickness ratio is pointed out as an important influencing factor in terms of failures [10].

But the mechanism of chipping is complex, multifactorial and still not well understood. A first step to the comprehension of the framework thickness influence in the chipping problem consists in studying residual stress. Residual stresses are “locked-in” stresses that are generated within the veneer and the framework during the cooling/solidification period of the firing process. These stresses are present within the structure without the application of any external load, but will add to functional loads and then constitute an important predicting factor for the mechanical behavior of restorations. Indeed, compressive residual stresses reinforce the ceramic while tensile residual stresses facilitate the initiation and the propagation of cracks. Therefore the knowledge of the residual stress distribution within the veneering ceramic as a function of depth, i.e. stress profile, is a key factor for understanding and predicting chipping and delaminations. The stress profile in the veneering ceramic is generated by the chronological effects of the thermal gradients occurring during the cooling/solidification period of the veneer liquid phase sintering process, and the mismatch in thermal expansion properties between core and veneering ceramic [11,12]. Thermal gradients are determined by cooling rate and by material thickness and conductivity. They induce non-uniform solidification, from the surface to the center, thereby causing contraction mismatch within the ceramic. Due to the tempering effect, residual stresses are compressive in the surface of the veneering ceramic, the magnitude of these stresses decreasing with depth and being influenced by the cooling rate around the glass transition temperature T_g [12–14]. Moreover, in the case of ceramic fused to metal frameworks, the thermal expansion coefficient (CTE) of the ceramic is generally slightly lower than the framework so that during cooling from T_g to room temperature, interior compressive stresses are developed within the ceramic near the framework.

Swain calculated the independent influence of the cooling rate, thickness and thermal expansion coefficient on residual stresses profile with a 2D bilayer mathematical model [15]. Among the three factors studied, thickness predominated as the most influential parameter. Some other authors [9,16] have used 3D-finite element analysis to study the influence of core design and components thickness on thermal residual stress and loading stress generated within a crown. Within the limitations of the mathematical models employed, the results highlighted the importance of cement more than core thickness, and did not support totally the alternative core

design theory. Actually the cited analysis did not account for thermal gradients and for the viscoelastic behavior of the ceramic in the glass transition range, where thermo-physical properties are submitted to variations and influence residual stresses. These parameters are challenging to simulate with models.

Recently a new method was introduced to measure the residual stress profile in the veneering ceramic [17,18]. This method is based on the removal of some stressed material and the measurement of the resulting deformations in the adjacent material [19]. 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. This method was used to study the influence of cooling rate on residual stress profile in veneered metal and zirconia disk samples [12]. In this study it was observed that zirconia samples with a 0.7 mm thick framework and a 1.5 mm thick veneer layer exhibited in-depth tensile stresses in the veneering ceramic, contrary to metal samples, which exhibited only compressive stresses. The hypothesis of the crystalline transformation of zirconia was proposed to explain these results.

The objectives of this study were to investigate the framework thickness dependence of stress profiles in veneered Y-TZP disks using the hole-drilling method and to understand how the framework thickness of zirconia-based-restorations can influence their mechanical behavior. Moreover the influence of cooling rate on stress profiles was also studied.

2. Materials and methods

2.1. Specimen preparation

Bilayered disc samples composed of veneering ceramic sintered on Y-TZP framework (VZr, 12 samples) were manufactured following standard dental laboratory procedures and manufacturer's recommendations. Y-TZP core discs were cut out of a pre-sintered Vita In-Ceram YZ blocks (Vita Zahnfabrik, Bad Säckingen, Germany), were rounded by polishing, and densely sintered at 1530 °C for 120 min with heating rate 10 °C/min, and heating time 149 min (Zircomat furnace, Vita Zahnfabrik, Bad Säckingen, Germany). The sintered Y-TZP discs, 20 mm diameter, were sequentially ground with 180-grit and 500-grit silicon carbide discs (Struers LabPol polishing machine, Copenhagen, Denmark) either to a 0.50 mm ($n=2$), a 0.70 mm ($n=2$), a 1.00 mm ($n=2$), a 1.50 mm ($n=2$), a 2.00 mm ($n=2$) or a 3.00 mm ($n=2$) ± 0.02 mm thickness. The Y-TZP discs were exposed to a “regeneration firing”, which is a final thermal treatment of the core to reverse any phase transitions in the zirconia due to the grinding procedures. A thin coat of Vita VM 9 Effect Bonder was applied and fired on the surface to be veneered. Then, Vita VM9 feldspar veneering ceramic (shade 3M2) (Vita Zahnfabrik, Bad Säckingen, Germany) was progressively layered on the effect bonder. A Vita Vacumat 4000 Premium furnace (Vita Zahnfabrik, Bad Säckingen, Germany) was used for all firing procedures, as summarized in Table 1. All samples were baked on the same ceramic mesh-tray. Three layers of dentin ceramic were successively fired. Samples were

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