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Descriptions of crack growth behaviors in glass–ZrO₂ bilayers under thermal residual stresses

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ABSTRACT

Objectives. This study was intended to separate residual stresses arising from the mismatch in coefficients of thermal expansion between glass and zirconia (ZrO₂) from those stresses arising solely from the cooling process. Slow crack growth experiments were undertaken to demonstrate how cracks grow in different residual stress fields.

Methods. Aluminosilicate glass discs were sintered onto ZrO₂ to form glass–ZrO₂ bilayers. Glass discs were allowed to bond to the ZrO₂ substrate during sintering or prevented from bonding by means of coating the ZrO₂ with a thin boron nitride coating. Residual stress gradients on “bonded” and “unbonded” bilayers were assessed using birefringence measurements. Unbonded glass discs were further tested under biaxial flexure in dynamic fatigue conditions in order to evaluate the effect of residual stress on the slow crack growth behavior.

Results. When fast-cooling was induced, residual tensile stresses on the glass increased significantly on the side toward the ZrO₂ substrate. By allowing the bond between glass and ZrO₂, those tensile stresses observed in unbonded specimens are overwhelmed by the contraction mismatch stresses between the ZrO₂ substrate and the glassy overlayer. Specimens containing residual tensile stresses on the bending surface showed a time-dependent strength increase in relation to stress-free annealed samples in the dynamic biaxial bending test, with this effect being dependent on the magnitude of the residual tensile stress. The phenomenon observed is explained here on the basis of the *water toughening* effect, in which water diffuses into the glass promoting local swelling. An additional residual tensile stress at the crack tip adds an applied-stress-independent (K_{res}) term to the total tip stress intensity factor (K_{tip}), increasing the stress-enhanced diffusion and the shielding of the crack tip through swelling of the crack faces.

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Significance. Residual stresses in the glass influence the crack growth behavior of veneered-ZrO₂ bilayered dental prostheses. The role of water in crack growth might be of higher complexity when residual stresses are present in the glass layer.

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1. Introduction

The fast-cooling of glass plates is known to induce a parabolic residual stress profile, with both surfaces put in compression and the interior experiencing compensating residual tensile stresses [1]. The compressive outer layers strengthen the glass and benefit structural applications of glass monoliths, but cracks reaching the inner region under tension cause the glass to shatter. Residual tensile stresses are therefore believed to be highly detrimental to the crack resistance and lifetime of glass-based structures.

In dentistry partially crystallized glasses (usually silicate glasses reinforced with feldspar, leucite or other crystal) are widely used in the monolithic form, but are mostly fused onto high-strength polycrystalline ceramics like aluminum oxide (Al₂O₃) and zirconium dioxide (ZrO₂). In such bilayer constructs the framework material is deliberately set to contract more in order not to crack the fragile glass overlayer during the cooling phase. For the purpose of further strengthening the glass, bench-cooling processes have been inherited from the era of metal–glass systems in order to induce “tempering” to the piece by quickly removing it from the oven and exposing it to ambient air. As this practice was transferred to zirconia-based structures in the early 2000s, clinical studies sounded the alarm shortly thereafter. While the ZrO₂ component of bilayer prosthetic constructs has shown to survive clinical challenges satisfactorily, the fracture of the overlaying veneering material was shown to occur in unexpectedly earlier stages of clinical usage when compared to well-established conventional metal–glass systems [2–5]. These fractures are usually limited to the glassy layer, which chip off, leaving some remaining material attached to the ZrO₂ substrate (see Fig. 1),

but not rarely lead to full prosthetic replacement. Detailed descriptions of such shell-like fracture patterns occurring *in vivo* can be found in [6,7], and in [8] for those reproduced *in vitro*.

It turns out that thermomechanical processes of fused glass/ceramic bilayers are a bit more complex. The thickness ratio has been known from the early elastic deformation theories [9] to determine whether the (coating) glass layer would be fully engulfed in a compressive state or develop tensile stress on the surface. Fast-cooling protocols, in turn, have shown to induce a much more severe temperature gradient within the glass layer in ZrO₂-based than in metal-based systems [10]. Compared to metals, ZrO₂ acts rather as a thermal insulator, supplying the glass layer with further heat from the interior, and detrimental tensile stresses may develop therein during cooling [11–13]. Some evidence has been provided to support this, in that residual tensile stresses have been accounted for the lower lifetime of fast-cooled constructs under cyclic contact loading [14] and peculiar fractographic patterns [8]. By and large, how cooling stresses and contraction stresses develop in isolation and how they synergistically contribute to the global stress state of bilayer systems is still a poorly understood problem. The final stress state is usually assessed in a cooled, bonded condition, and masks their weighted contributions.

To address this issue we designed this study to isolate the stresses arising solely due to the cooling process from the contraction mismatch stresses in glass–ZrO₂ bilayers. For that, we created an unbonded condition between layers by isolating the ZrO₂ substrate using a boron nitride (BN) coating. This allowed free contraction of both layers while enabling thermal exchange between parts, once heat flow from the ZrO₂ substrate during cooling is thought to influence the solidification rate of the overlaying glass and stress build-up therein.

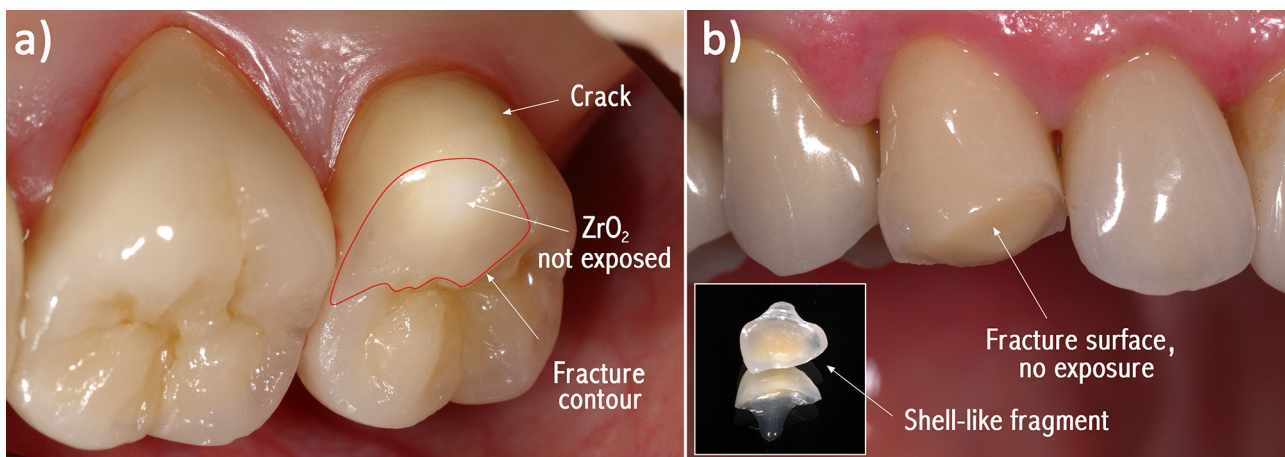


Fig. 1 – Chipping of the glassy veneer layer in two veneer-ZrO₂ dental prosthetic constructs *in vivo*. Detailed fractographic analyses of both cases are found in [6,7].

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