DENTAL MATERIALS 31 (2015) 77–87

Available online at www.sciencedirect.com

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journal homepage: www.intl.elsevierhealth.com/journals/dema

Slow cooling protocol improves fatigue life of zirconia crowns

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ARTICLE INFO

Article history:
Received 2 September 2013
Received in revised form
22 December 2013
Accepted 27 October 2014

Keywords:
Ceramics
Fatigue
Weibayes
Cooling rate
Fractography
Zirconia

ABSTRACT

Objective. To compare the fatigue life and damage modes of zirconia crowns fabricated with and without framework design modification when porcelain veneered using a fast or slow cooling protocol.

Methods. Composite resin replicas of a first molar full crown preparation were fabricated. Zirconia copings were milled as conventional (0.5 mm even thickness, Zr-C, $n = 20$,) or modified (lingual margin of 1.0 mm thickness, 2.0 mm height connected to two proximal struts of 3.5 mm height, Zr-M, $n = 20$). These groups were subdivided ($n = 10$ each) according to the veneer cooling protocol employed: fast cooling (Zr-CFast and Zr-MFast) and slow cooling (Zr-CSlow and Zr-MSlow). Crowns were cemented and fatigued for 10^6 cycles in water. The number of cycles to failure was recorded and used to determine the interval databased 2-parameter probability Weibull distribution parameter Beta (β) and characteristic life value Eta (η).

Results. 2-parameter Weibull calculation presented $\beta = 5.53$ and $\beta = 4.38$ for Zr-MFast and Zr-CFast, respectively. Slow cooled crowns did not fail by completion of 10^6 cycles, thereby Weibayes calculation was applied. Increased fatigue life was observed for slow cooled crowns compared to fast cooled ones. Groups Zr-MFast and Zr-MSlow presented no statistical difference. Porcelain cohesive fractures were mainly observed in fast cooled groups. Slow cooled crowns presented in some instances inner cone cracks not reaching the zirconia/veneer interface.

Significance. Improved fatigue life in tandem with the absence of porcelain fractures were observed in slow cooled crowns, regardless of framework design. Crowns fast cooled chiefly failed by porcelain cohesive fractures.

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http://dx.doi.org/10.1016/j.dental.2014.10.005
0109-5641/

1. Introduction

Over the past ten years several *in vitro* [1–5] and clinical studies [6,7] have attempted to document and understand the nature of porcelain veneer cohesive fractures in all-ceramic restorations, specially yttria-tetragonal zirconia polycrystals (Y-TZP) [6,7]. Besides issues related to manufacturing process (i.e., porosities and micro-structural defects) [8], chipping has been suggested to be strongly related with; residual thermal stress [9–12], coefficient of thermal expansion mismatches [1], poor framework design [3,4,13–15], and others [12].

Changes in the porcelain physical properties (during the transition from the visco-elastic to solid state) when it is cooled down from the sintering temperature to room temperature take place in every firing cycle [16,17]. As a result, non-uniform residual thermal stresses may be produced throughout the porcelain veneer as a function of cooling rates [18,19]. Such residual stress may be induced within the porcelain veneer either by thermal expansion mismatches or by the temperature gradients produced during cooling or both [12,17]. Similarly to tempered glass, during a fast cooling process the outer crown surface becomes solid first and starts to contract inducing a compressive stress. However, while the inner surface is still in a visco-elastic state and at high temperature, leading to high tensile stress when the system reaches room temperature [12,17,19]. This process is expected given that the porcelain veneer inner bulk remains in a temperature above its glass-transition temperature (T_g), leading to the gradient temperature (difference between the inner and outer temperature) [12]. As a consequence, residual thermal stresses are held within the porcelain veneer [9,12,20], also known as tempering. In addition, Y-TZP shows a low thermal diffusivity (thermal conductivity of $2\,W\,m^{-1}\,K^{-1}$ whereas metals vary from 100 to $300\,W\,m^{-1}\,K^{-1}$) [21,22], which may increase the thermal gradient intensity within veneer porcelain [9,12,20,23]. Therefore, the multifaceted role of the above factors, has been speculated as potential sources related to high Y-TZP chipping rates reported in the literature [5,8,10,12,23].

Recently, efforts have been devoted to the reduction of residual thermal stresses in Y-TZP restorations by managing the rates of cooling [9,10,24,25]. It has been reported that overall thermal gradients within the porcelain veneered to Y-TZP decreased when a slow cooling protocol was used [23,26]. Also, thermodynamic analysis performed in molar crowns showed that different results may be achieved as a function of cooling protocols [23]. It has been shown that slow cooling (the furnace door opened when the temperature was below the porcelain veneer T_g) produced a small temperature variation between the inner and outer surfaces of crowns and, more important, it decreased the residual thermal stresses within the veneer layer [23]. However, to date few attempts regarding the influence of cooling rate on the fatigue life of Y-TZP crowns are available.

Most manufacturers of porcelain veneers for Y-TZP restorations have modified their firing guidelines, advocating that technicians adopt a slow cooling rate protocol. In 2009 for example, one manufacturer recommended that the furnace was opened soon after the end of the firing cycle [27], and a year later it was modified and crowns should be kept into the closed furnace up to temperature reaching 450 °C, slightly below the T_g (490 °C) of the veneer porcelain [28].

Another topic that has frequently been revisited is framework design modifications in Y-TZP restorations [4,14,29]. Clinical evaluations have suggested that porcelain chipping is frequently associated with areas without appropriate porcelain support (proximal areas) [14,15,30]. This empirical concept relies on the fact that the porcelain veneer should have an even thickness, of no more than 2 mm, and be supported by the core [31]. Although framework design modifications have shown to decrease chipping rates in clinical trials [15,32,33] no control groups (i.e., even thickness framework) have been included, hindering a more comprehensive understanding between framework design modification and chipping [15,32].

In light of the aforementioned information, this study sought to evaluate the fatigue life and failure modes of Y-TZP molar crowns fabricated with two different porcelain veneer cooling protocols with and without framework design modification. The following null hypotheses were tested: (1) cooling protocols during glazing will not improve the fatigue life of Y-TZP systems and (2) framework design modification will not improve the fatigue life of Y-TZP crown systems, irrespective of cooling rate.

2. Materials and methods

2.1. *Sample preparation*

A plastic maxillary first molar positioned in a mannequin (Plastic mannequin tooth – MOM, Marilia, SP, Brazil) was prepared to receive a full crown by reducing the axial walls by 1.5 mm, the occlusal surface by 2.0 mm and shoulder margin (1.2 mm of thickness) with rounded internal angles. Afterwards, 40 composite resin replicas were obtained from a vinyl polysiloxane impression (Express – 3M ESPE, St. Paul, MN, USA) of the prepared tooth, which was incrementally (2.0 mm of thickness) packed with composite resin (Z100 – 3M ESPE, St. Paul, MN, USA) and light-cured (Ultralux, Dabi Atlante, Ribeirão Preto, SP, Brazil) according to manufacturer's instructions. All resin tooth replicas were stored in distilled water for at least 30 days to minimize dimensional changes during testing [34]. Each replica was vertically positioned in 25 mm diameter PVC tubes and potted with acrylic resin (Jet, Clássico Artigos Odontológicos, São Paulo, SP, Brazil). The preparation finish line was maintained 2 mm above the potting surface. Stone dies were acquired from polyether impressions (Impregum F – 3M-ESPE, St. Paul, MN, USA) of each resin-tooth replica and sent to a dental laboratory.

Stone dies were randomly divided in 2 groups ($n = 20$, each) according to framework design, as: conventional (Zr-C) or modified design (Zr-M). Subsequently, each group was subdivided in two subgroups ($n = 10$) according to thermal cooling protocol as: fast cooling protocol (Zr-CFast and Zr-MFast) and slow cooling protocol (Zr-CSlow and Zr-MSlow).

Frameworks were milled from pre-sintered Y-TZP blocks (e.max ZirCAD, shade MO 0, block size 15C – Ivoclar Vivadent, Schaan, Liechtenstein) and sintered in the furnace (Sintramat, Ivoclar Vivadent AG, Schaan, Liechtenstein) at 1500 °C