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Finite element analysis of the residual thermal stresses on functionally gradated dental restorations

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ABSTRACT

The aim of this work was to study, using the finite element method (FEM), the distribution of thermal residual stresses arising in metal–ceramic dental restorations after cooling from the processing temperature. Three different interface configurations were studied: with conventional sharp transition; one with a 50% metal–50% ceramic interlayer; and one with a compositionally functionally gradated material (FGM) interlayer. The FE analysis was performed based on experimental data obtained from Dynamic Mechanical Analysis (DMA) and Dilatometry (DIL) studies of the monolithic materials and metal/ceramic composites.

Results have shown significant benefits of using the 50% metal–50% ceramic interlayer and the FGM interlayer over the conventional sharp transition interface configuration in reduction of the thermal residual stress and improvement of stress profiles. Maximum stresses magnitudes were reduced by 10% for the crowns with 50% metal–50% ceramic interlayer and by 20% with FGM interlayer. The reduction in stress magnitude and smoothness of the stress distribution profile due to the gradated architectures might explain the improved behavior of these novel dental restorative systems relative to the conventional one, demonstrated by in-vitro studies already reported in literature.

1. Introduction

Dental restorations such as crowns and fixed partial dentures (FPD) are designed to restore functionality and esthetics to failed teeth. They are based on multi-material and multilayered systems, comprising a strong metallic or ceramic substructure veneered and esthetic dental porcelain that mimic the color of the remaining teeth. Failures of the restorative systems are undesired occurrences as they often imply money expenditure and discomfort to patients. Several studies have been conducted

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to understand and determine the failure mechanisms of the metal–ceramic and all-ceramic restorative systems (Yesil et al., 2009; Özcan, 2003; Anusavice, 2012; Swain, 2009, Arman et al., 2009; Zhang et al., 2010, 2012). Failures during the fabrication process related to thermal residual stresses arising from cooling after high temperature processing, and problems due to poor chemical compatibility have been pointed as the main causes for such events (Fischer et al. 2009). The cooling rates, the mismatching thermomechanical properties of materials and the geometry of specimens can greatly impact the transient residual stresses in metal–ceramic and all-ceramic restorations (Zhang et al. 2010; Asaoka and Tesk, 1990; Taskonak et al., 2005, 2008; DeHoff et al., 2008). Moreover, the thermal incompatibility between the materials to join can result in high stresses in regions close to free surface and near the interface, which can lead to either cracking of the ceramic or joints having poor strength (DeHoff et al. 2008; Ravichandran, 1995).

Functionally Gradated Materials (FGMs) can be an answer to the thermal stress problems (Gasik, 1998, Gasik et al., 2005) consisting in a gradual change in the volume fractions of constituents from one location to the other in a component. The FGMs were first applied in minimizing thermal stresses and increasing thermal shock resistance of blades in gas turbine engines, with great success (Ravichandran, 1995; Chi and Chung, 2003). The philosophy was rapidly adapted by engineers to other fields of activity such as optics, nuclear energy, engineering, electronics, biomaterials, among others.

The employment of FGM to restorative dentistry is rather novel. Several studies were carried out involving metal–ceramic and all-ceramic dental restorative systems, aiming for the enhancement of the overall clinical performance. Gradated restorations have been shown to display improved properties relative to conventional ones, especially concerning to higher resistance to contact and sliding (Suresh, 2001); higher adhesion of porcelain to the substructure (metal or ceramic) (Henriques et al., 2011, 2012a, 2012b; Zhang and Kim, 2009); improved esthetical properties and improved fatigue performance (Henriques et al. 2012b).

In this study, the finite element analysis (FEA) was used to investigate the influence of the presence of a 50% metal–50% ceramic composite interlayer and a gradated interlayer at interface of a metal–ceramic dental crown on the post processing thermal residual stresses. Therefore, two different classes of gradation were studied, one consisting in a one-step transition only (interlayer with the composition of 50% metal–50% ceramic), and the other consisting in multiple layers of different compositions (each layer with constant composition), both performing a compositional discrete transition between metal and ceramic as a function of distance. The results obtained with these new interface configurations were compared with the conventional sharp transition system. The mechanical and thermal properties of the materials used in this study were experimentally determined through the production and testing of homogeneous specimens of several compositions. The elastic and thermal experimental data were afterwards modeled and uploaded in the materials properties database of the finite element method software.

2. Materials and methods

2.1. *Experimental determination of the elastic modulus and the coefficient of thermal expansion*

In this study a CoCrMo alloy (Nobil 4000, Nobilmetal, Villafranca d'Asti, Italy) and a dental porcelain (Ceramco3, Dentsply, York, USA) (batch number: 08004925) were used. The chemical compositions of the metallic and ceramic particles are presented in Table 1 and Table 2, respectively. The micrographs of CoCrMo and porcelain powders show angular shapes and spherical shapes, respectively (Fig. 1). The CoCrMo powders display a broad size distribution: $D_{10}=4.44\ \mu m$; $D_{50}=8.27\ \mu m$ and $D_{90}=12.76\ \mu m$.

The manufacturing of the metal–ceramic composite specimens comprised the following steps: several powder mixtures with different metal/porcelain volume fractions were produced. After weighting, the powders mixtures were blended in a rotary machine at 40 rpm during 10 min. The following mixtures were produced (vol%): pure porcelain (with 0% metal) and compositions with 20% metal, 40%, 60%, 80% and 100% metal, marked further as “nnM” where nn stays for the percentage of metal phase. Afterwards, the powder mixtures were hot pressed in a graphite die (Fig. 2). The hot pressing sequence comprised the following steps: first, the cavity of the graphite die was veneered with ZrO_2 paint to prevent carbon diffusion to specimens. Then the metal–ceramic powder mixture was inserted into the cavity. The hot pressing was performed under vacuum ($\sim 10^{-2}$ mBar) at a temperature of 970 °C and a constant pressure of $\sim$20 MPa. The selected heat rate was 70 °C/min and after a 2 min stage at 970 °C the induction heating furnace was shut down. Specimens cooled down to room temperature inside the hot pressing equipment.

Two types of specimens' geometries were processed, rectangular and cylindrical. The dimensions of the rectangular samples used for flexural tests were 36 × 6 × 2.5 mm, while those of the cylindrical samples used for shear tests were Ø4 × 4 mm.

The measurements of Young's moduli (YM) of all materials were obtained by the means of Dynamic Mechanical Analysis (DMA 242C, Netzsch Gerätebau GmbH, Germany) using a three-point bending sample holder. The coefficient of thermal expansion (CTE) of composites and the monolithic materials was also assessed using dilatometry (DIL 402C, Netzsch Gerätebau GmbH, Germany). Both properties were measured through a range of temperatures starting in 100 °C up to 500 °C. It was estimated that materials properties at 100 °C did not differ significantly from properties at room temperature. Poisson's ratio was fixed to be the following for the different materials: metal (0.25); porcelain (0.2); 50M composite interlayer (0.23). For the gradated transition Poisson's ratio was approximated varying linearly from that of metal to that of porcelain. Data were post-processed with the

Table 1 – Base alloy composition (wt%) (according to manufacturer).

Co	Cr	Mo	Si	Impurities
62	31	4	2.2	Mn, Fe, W