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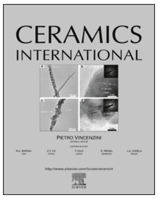

The bending stress distribution in bilayered and graded zirconia-based dental ceramics

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ABSTRACT

The purpose of this study was to evaluate the biaxial flexural stresses in classic bilayered and in graded zirconia-feldspathic porcelain composites. A finite element method and an analytical model were used to simulate the piston-on-ring test and to predict the biaxial stress distributions across the thickness of the bilayer and graded zirconia-feldspathic porcelain discs. An axisymmetric model and a flexure formula of Hsueh et al. were used in the FEM and analytical analysis, respectively. Four porcelain thicknesses were tested in the bilayered discs. In graded discs, continuous and stepwise transitions from the bottom zirconia layer to the top porcelain layer were studied. The resulting stresses across the thickness, measured along the central axis of the disc, for the bilayered and graded discs were compared. In bilayered discs, the maximum tensile stress decreased while the stress mismatch (at the interface) increased with the porcelain layer thickness. The optimised balance between both variables is achieved for a porcelain thickness ratio in the range of 0.30–0.35. In graded discs, the highest tensile stresses were registered for porcelain rich interlayers ($p=0.25$) whereas the zirconia rich ones ($p=8$) yield the lowest tensile stresses. In addition, the maximum stresses in a graded structure can be tailored by altering compositional gradients. A decrease in maximum stresses with increasing values of p (a scaling exponent in the power law function) was observed. Our findings showed a good agreement between the analytical and simulated models, particularly in the tensile region of the disc. Graded zirconia-feldspathic porcelain composites exhibited a more favourable stress distribution relative to conventional bilayered systems. This fact can significantly impact the clinical performance of zirconia-feldspathic porcelain prostheses, namely reducing the fracture incidence of zirconia and the chipping and delamination of porcelain.

1. Introduction

Dental restorations have two main requirements: adequate strength and good aesthetic. Feldspathic porcelain is widely used as dental material due to its aesthetic. But it has low strength and toughness, accordingly, it is unable to withstand high tensile stresses [1]. Therefore, it is necessary to use a stronger material to support porcelain, increasing the overall strength of the restoration [2]. Due to its high strength, fracture toughness, good aesthetics and biocompatibility, zirconia has been the material of choice for frameworks in all-ceramic dental restorations [2,3]. The feldspathic porcelain is fired onto the zirconia framework at high temperature, and residual thermal stresses are formed at the materials interface upon cooling to room temperature, due to the mismatch of thermal expansion coefficients between the two materials [4,5]. At the same time, when the restoration is subjected to occlusion loading, the mismatch of elastic properties between the two materials favours the formation of deleterious stress fields at the interface that can lead to crack formation, porcelain chipping and ultimately catastrophic failure of the prosthesis [5,6]. To overcome the problems related to thermal and mechanical mismatch between the different materials, several solutions based on a gradation of properties across the two materials have been proposed for dental restorations [7–13]. Studies on the mechanical properties of graded ceramic beams have shown superior load-bearing capacity and improved damage resistance [10,11,14,15]. Enhanced bond strength resistance was also

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reported for graded restorative systems [7,8,16]. Tsukada et al. showed the feasibility of the production of zirconia/feldspathic porcelain functionally graded materials by spark plasma sintering [12].

Uniaxial tests (e.g. three or four point bending tests) and biaxial tests (e.g. piston-on-three-balls and piston-on-ring tests) are the standard methods to evaluate the flexural strength of ceramics. One problem of uniaxial test is the sensitivity to flaws along the sample edges, resulting in large variations in the strength data recorded [17]. However, in a biaxial test, the multiaxial stress state is created near the centre of the specimen and edge failures are usually eliminated, resulting in a more accurate estimate of strength [18]. Besides, restorative materials are usually subjected to a multiaxial loading in clinical situations, thus the biaxial data are more useful for the material design [19]. In biaxial tests, the sample, generally a disc, is supported on its lower face and a load is applied on its upper face. The support can have several configurations, however the most used are rigid balls or ring. The force can be applied by a ball, a ring or a piston [20]. ISO 6872:2015 [21] is the international standard that describes the biaxial flexure test using “piston-on-three-balls”. However, its formulae are based on “piston-on-ring” test.

The objective of this study was to evaluate the mechanical behaviour of a compositionally graded zirconia-feldspathic porcelain disc and compare it with the classic situation, where a sharp interface exists between the two materials. The gradation of properties across the volume of the material can be continuous or stepwise. Because a continuous variation in the volume fraction throughout the graded region is more difficult to be obtained [22], this work also analysed the stepwise transition where the graded region was considered to have a finite number of layers with varying thickness, each layer with constant volume fraction of the two materials and, therefore, constant properties.

Finite elements method (FEM) was used to simulate the stress state in a “piston-on-ring” biaxial test for all specimen configurations. Several different gradation profiles were simulated in discs with continuous and stepwise variation of the graded interlayer. For the classic situation, the influence of the layer thickness in the stress state was also evaluated. To verify the accuracy of our FEM model, the results were compared with an analytical solution proposed by Hsueh et al. [19,23,24].

2. Materials and methods

2.1. Materials properties and model configuration

For the analysis of the classic situation, with a sharp interface between zirconia and feldspathic porcelain, a disc consisting two layers with 1 mm each was considered. The top layer was made of monolithic feldspathic porcelain and the bottom one contained pure zirconia (Y-TZP). Additionally, simulations considering the porcelain layer thickness as 0.3 mm, 0.6 mm, 0.9 mm while holding the bilayer thickness constant were also conducted (Fig. 1).

For the graded material, two approaches were considered, a continuous and a stepwise gradation between the two base materials. In the first case, continuous gradation, three layers were considered, where the top and bottom layers were monolithic feldspathic porcelain and zirconia, respectively, and the middle layer varied its composition continuously from zirconia to feldspathic porcelain.

In the stepwise gradation, each disc contained seven layers, each one made of constant composition. The top and the bottom layers were still monolithic feldspathic porcelain and zirconia, respectively, and had a constant thickness (0.2 mm). The five intermediate layers were made of a feldspathic porcelain and zirconia mixture, having constant volume fraction of porcelain (0.1, 0.3, 0.5, 0.7 and 0.9, from the bottom to top layer, respectively) and varying thickness. In order to calculate the thickness of each intermediate layer, first it is considered a continuous change in the volume fraction of porcelain along the thickness. This change is represented by a power law function:

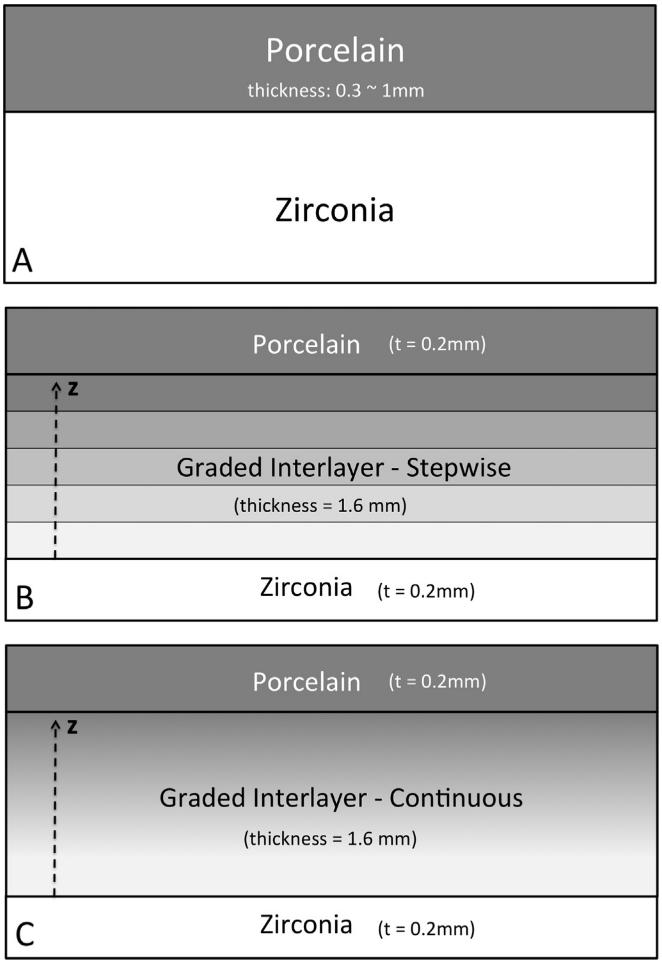

Fig. 1. Schematic of the classic bilayered (a) and graded (b and c) zirconia-feldspathic porcelain systems.

$$V_p = \left(\frac{z}{t}\right)^p \tag{1}$$

where V_p is the volume fraction of porcelain, z is the distance from the bottom (pure zirconia) and t is the thickness of the graded region. For different values of p, the concentration of zirconia and porcelain along the thickness changes as shown in Fig. 2. To calculate the thickness of each layer, first the values of z/t for a given value of p was calculated for the corresponding values of volume fraction of porcelain of 0.0, 0.2, 0.4, 0.8 and 1.0. These values were used to calculate the thickness of each layer as shown in Fig. 3. In order to evaluate the influence of the composition in the graded region, different values of p were used.

The mechanical properties of intermediate layers, such as Young's modulus, Poisson's ratio and density, were calculated by Voigt's rule of the mixtures:

$$P_i = P_z V_z + P_p V_p \tag{2}$$

where P_i is the property of the ith layer calculated by Voigt's rule of mixtures, P_z and P_p are the properties of the zirconia and porcelain placed on the top and bottom layers, respectively. V_z and V_p