Influence of thickness and cooling rate on development of spontaneous cracks in porcelain/zirconia structures

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ABSTRACT

Background: Clinical studies reporting the outcome of zirconia-based restorations indicate that the strength of the zirconia frameworks is sufficient to withstand masticatory forces. However, a significant incidence of cohesive fracture of the veneering porcelain has been reported. The aim of this study was to investigate spontaneous crack development (chipping, rupture) in a range of porcelains veneered to a zirconia core as a result of thermal stresses induced by changes in thickness and cooling rate. The hypothesis tested was that crack incidence would increase with increased veneer thickness and faster cooling rates.

Methods: Zirconia spheres (diameter 7.8 mm) were veneered with 1.5 gm (thickness ratio 1:2) and 2.5 gm (thickness ratio 1:1) of five nominally compatible commercially available porcelains. The manufacturers’ firing cycles and a rapid cooling firing cycle were followed.

Results: Multiple regression analysis showed positive associations between the occurrence of cracks and the three covariates (materials, thickness and cooling rate). The incidence of cracks and rupture of the veneering porcelain increased with a faster cooling rate and increased thickness of the specimens in three porcelain–zirconia combinations.

Conclusions: Crack incidence increased with increased porcelain veneer thickness and faster cooling rates in nominally compatible porcelain/zirconia systems in the geometrically configured specimens tested.

Keywords: Zirconia, porcelain, thermal compatibility, residual stresses, crack.

INTRODUCTION

The clinical applications of ceramic systems such as heat-pressed glass-ceramics, glass-infiltrated ceramics and fully sintered alumina have been limited by the mechanical properties of these materials. The introduction of computer aided design/computer aided milling (CAD/CAM) technology into the dental market has facilitated the use of yttria-partially stabilized zirconia (Y-PSZ), a strong and tough ceramic.

The few clinical studies reporting the outcome of Y-PSZ restorations appear to indicate that with appropriate design, the strength of Y-PSZ frameworks is sufficient to withstand masticatory forces. However, a significant incidence of cohesive fracture in the veneering porcelain has also been observed. The fracture mechanism of the porcelain layer (cohesive rather than adhesive) observed in these clinical studies indicates that a lack of adequate bond strength between porcelain and Y-PSZ is not the cause for this observed chipping. Other factors such as the design of the Y-PSZ frameworks, the mechanical properties of the veneering porcelain or a mismatch of the coefficient of thermal expansion (CTE) between porcelain and Y-PSZ have been implicated.

The compatibility between veneering porcelain and metal substructures has also been identified as a problem for metal ceramic restorations (MCRs). Walton and O’Brien investigated the effect of the mismatch of the CTE and the geometry on thermally induced stress failures in metal-ceramic discs and spheres. In addition to residual stresses caused by the mismatch of the CTE, significant residual stresses were generated by differential cooling rates (thermal gradient) of the materials, particularly evident in thicker and sphere-shaped specimens.

More recently Swain provided a theoretical analysis of the key processing parameters that may...
contribute to the development of residual stresses and spontaneous cracking in a range of different veneered bilayered materials. The analysis identified the importance of cooling rate, thickness and mismatch of the CTE in the development of residual stresses. Residual stresses within the porcelain layer may promote the propagation of a crack caused by contact damage of the in situ restoration leading to chipping of the veneering layer. Swain concluded that thick veneer layers on frameworks with low thermal diffusivity, such as Y-PSZ, are prone to generate high tensile stresses within the porcelain layer. Such stresses may result in unstable cracking or chipping. To date there are no studies investigating the influence of cooling rate and thickness on the development of cracks in a range of commercially available porcelains veneered to Y-PSZ cores.

The aim of this study was to assess spontaneous crack development in five nominally compatible porcelains veneered to Y-PSZ cores as a result of thermal stresses induced by geometry of the specimens, thickness and cooling rate. The hypothesis tested was that crack incidence would increase with increased veneer thickness and faster cooling rates.

MATERIALS AND METHODS

Two hundred and twenty Y-PSZ ceramic spheres measuring 7.8 mm in diameter were obtained from one company (Ekton-Straumann, Basel, Switzerland) and veneered with five nominally compatible commercially available porcelains (Table 1). Groups of 10 specimens were prepared as follows: group 1.5A (1.5 gm of porcelain applied to the spheres and fired according to the manufacturer's recommendations - normal cooling); group 1.5B (1.5 gm of porcelain applied to the spheres and rapidly cooled by opening the furnace immediately after the recommended holding time and moving the specimens to the furnace bench - rapid cooling); group 2.5A (2.5 gm of porcelain applied to the spheres and fired according to the manufacturer's recommendations); and group 2.5B (2.5 gm applied to the spheres and rapidly cooled as previously described). Details of the firing conditions are provided in Table 2.

Subsequent to the preparation of the specimens, one manufacturer changed the recommended firing schedule of its porcelain (Vita Zahnfabrik - VM9); the tests for group 1.5A and 2.5A were repeated according to the new firing schedule (Tables 1 and 2; Fig 1).

Specimens of each group were equally prepared by three experienced dental technicians to minimize the risk of bias and errors. The specimens prepared with 1.5 gm of porcelain had a mean final diameter of 11.5 mm, corresponding to a ratio Y-PSZ/porcelain of 2:1. The 2.5 gm specimens had a mean final diameter of 14.8 mm (thickness ratio 1:1). Specimens were well condensed and dried before initiating the sintering process. A thin wash layer (first dentine firing) followed by a dentine layer (second dentine firing) was initially applied to all the specimens according to the manufacturer's instructions (Table 2). The rapid cooling cycle was applied only after the second dentine firing of the B groups. After firing, each specimen was visually examined under magnification (x10) and UV light to verify the presence of cracks.

Multiple regression analysis was initially conducted to test the significance of the influence of thickness, cooling and material on the occurrence of crack events. The analysis was performed using a logistic regression model where all the independent variables (covariates) were included to test independent associations. Reduced models were also considered, where associations of the materials, cooling rate and thickness were tested against both a fixed cooling rate and a fixed thickness. Finally, the Kruskal-Wallis test was performed to re-evaluate the consistency of the results obtained from the logistic regression model. The statistical analysis was conducted using the software Package R (Revolution Computing). 13

The VM9-N groups were excluded from the statistical analysis because the porcelain in these groups was fired with a slower cooling rate, not comparable to that of the other groups.

RESULTS

The multiple regression analysis showed independent positive associations between the occurrence of cracks and the three covariates (materials, thickness and cooling rate). The statistical analysis showed that
For each group the initial abbreviation corresponds to the veneering porcelain (e.g., NR corresponds to Nobel Rondo) as illustrated by Table 1; the number corresponds to the quantity of porcelain used for the specimens and therefore the relative thickness (e.g., 1.5 corresponds to 1.5 grams); the letter A or B correspond to the cooling rate (A = according to manufacturer; B = rapid cooling).

**Table 2. Firing conditions**

<table>
<thead>
<tr>
<th>Group</th>
<th>Layer</th>
<th>Heating rate</th>
<th>Firing temp.</th>
<th>Extended cooling</th>
<th>Normal cooling</th>
<th>Rapid cooling</th>
</tr>
</thead>
<tbody>
<tr>
<td>NR 1.5A and NR 2.5A</td>
<td>1st dentine</td>
<td>45 °C</td>
<td>910 °C</td>
<td>-</td>
<td>Yes</td>
<td>-</td>
</tr>
<tr>
<td>NR 1.5B and NR 2.5B</td>
<td>2nd dentine</td>
<td>45 °C</td>
<td>900 °C</td>
<td>-</td>
<td>Yes</td>
<td>-</td>
</tr>
<tr>
<td>ICE 1.5A and ICE 2.5A</td>
<td>1st dentine</td>
<td>45 °C</td>
<td>910 °C</td>
<td>-</td>
<td>Yes</td>
<td>-</td>
</tr>
<tr>
<td>ICE 1.5B and ICE 2.5B</td>
<td>2nd dentine</td>
<td>45 °C</td>
<td>900 °C</td>
<td>-</td>
<td>Yes</td>
<td>-</td>
</tr>
<tr>
<td>ZR 1.5A and ZR 2.5A</td>
<td>1st dentine</td>
<td>45 °C</td>
<td>920 °C</td>
<td>-</td>
<td>Yes</td>
<td>-</td>
</tr>
<tr>
<td>ZR 1.5B and ZR 2.5B</td>
<td>2nd dentine</td>
<td>45 °C</td>
<td>920 °C</td>
<td>-</td>
<td>Yes</td>
<td>-</td>
</tr>
<tr>
<td>ZI 1.5A and ZI 2.5A</td>
<td>1st dentine</td>
<td>45 °C</td>
<td>930 °C</td>
<td>-</td>
<td>Yes</td>
<td>-</td>
</tr>
<tr>
<td>ZI 1.5B and ZI 2.5B</td>
<td>2nd dentine</td>
<td>45 °C</td>
<td>930 °C</td>
<td>-</td>
<td>Yes</td>
<td>-</td>
</tr>
<tr>
<td>VM9-O 1.5A and VM9-O 2.5A</td>
<td>1st dentine</td>
<td>55 °C</td>
<td>910 °C</td>
<td>-</td>
<td>Yes</td>
<td>-</td>
</tr>
<tr>
<td>VM9-O 1.5B and VM9-O 2.5B</td>
<td>1st dentine</td>
<td>55 °C</td>
<td>950 °C</td>
<td>-</td>
<td>Yes</td>
<td>-</td>
</tr>
<tr>
<td>VM9-N 1.5A and VM9-N 2.5A</td>
<td>1st dentine</td>
<td>55 °C</td>
<td>950 °C</td>
<td>-</td>
<td>Yes</td>
<td>-</td>
</tr>
</tbody>
</table>

For each group the initial abbreviation corresponds to the veneering porcelain (e.g., NR corresponds to Nobel Rondo) as illustrated by Table 1; the number corresponds to the quantity of porcelain used for the specimens and therefore the relative thickness (e.g., 1.5 corresponds to 1.5 grams); the letter A or B correspond to the cooling rate (A = according to manufacturer; B = rapid cooling).

**Table 3. Crack development in each group (specimens cracked/sample size)**

<table>
<thead>
<tr>
<th>Material</th>
<th>Group 1.5A</th>
<th>Group 1.5B</th>
<th>Group 2.5A</th>
<th>Group 2.5B</th>
</tr>
</thead>
<tbody>
<tr>
<td>NR</td>
<td>0/10</td>
<td>0/10</td>
<td>0/10</td>
<td>0/10</td>
</tr>
<tr>
<td>ICE</td>
<td>0/10</td>
<td>0/10</td>
<td>0/10</td>
<td>0/10</td>
</tr>
<tr>
<td>ZR</td>
<td>0/10</td>
<td>0/10</td>
<td>0/10</td>
<td>0/10</td>
</tr>
<tr>
<td>ZI</td>
<td>0/10</td>
<td>0/10</td>
<td>0/10</td>
<td>0/10</td>
</tr>
<tr>
<td>VM9-O</td>
<td>2/10</td>
<td>8/10</td>
<td>4/10</td>
<td>8/10</td>
</tr>
<tr>
<td>VM9-N</td>
<td>0/10</td>
<td>N/A</td>
<td>0/10</td>
<td>N/A</td>
</tr>
</tbody>
</table>

Increasing thickness was positively associated with crack events \( (p = 0.000049) \). Rapid cooling (B groups, Table 2) was also significantly associated with increased crack events \( (p = 0.0018) \). Of the five combinations of porcelain/Y-PSZ ceramic used in this study, VM9-O \( (p = 0.00014) \), ICE \( (p = 0.00000025) \) and ZI \( (p = 0.01) \) were significantly associated with the spontaneous development of cracks upon firing.

A statistical analysis performed on a reduced model with thickness (2.5 groups, Table 2) as the fixed parameter showed results consistent with the full model. In this instance, the cooling rate \( (p = 0.001) \), ICE \( (p = 0.0001) \), VM9-O \( (p = 0.0012) \) and ZI \( (p = 0.0056) \) had a positive association with the variation in thickness. Similar results were observed when the analysis was performed with the cooling rate (B groups, Table 2) as the fixed parameter. In this instance, a positive association was reported for thickness \( (p = 0.00016) \), ICE \( (p = 0.00002) \), VM9-O \( (p = 0.0017) \) and ZI \( (p = 0.018) \).

The Kruskal-Wallis rank sum test as non-parametric analysis confirmed the results obtained with multiple regression analysis \( (p = 0.0001) \).

The number of cracked or ruptured specimens is reported in Table 3. The cracks consistently ran virtually parallel to the surface and in some samples propagated throughout the porcelain layer causing rupture. The rupture was consistently cohesive without exposure of the Y-PSZ core (Fig 1).

**DISCUSSION**

A mathematical analysis by Swain\(^\text{12}\) indicated the mismatch of the CTE; the thickness and the cooling rate play an important role in the development of residual stresses within porcelain/Y-PSZ prostheses. Such stresses may be responsible for chipping of the
Compatibility of porcelain/zirconia structures

Porcelain reported in clinical studies.\textsuperscript{8–10} The present study showed that for some of the groups, spontaneous cracking and cohesive fracture of the porcelain increased with an increase in the porcelain thickness and faster cooling rates. These results appear to support the concept that mismatch of the CTE, cooling rate and thickness may play an important role in explaining chipping observed in porcelain/Y-PSZ prostheses.

The spherical geometric form of the specimens was utilized as it has been shown to induce maximum thermal stresses in bilayered structures and represents the extreme form that can occur clinically.\textsuperscript{11,14,15} DeHoff \textit{et al.}\textsuperscript{15} showed that bilayer ceramic cylinders and spheres provide confirmation of thermal incompatibility stress that was predicted by finite element analysis. They veneered cylindrical and spherical pressable ceramic cores with four thermally incompatible dental ceramics (with markedly different CTE) and four thermally compatible dental porcelains (with CTE in a nominally compatible range). When spheres were used as the core material, 100% of the thermally incompatible specimens failed, whereas only 4% of the thermally compatible specimens developed cracks after firing. Finite element analysis confirmed that failure was consistently linked to high residual stresses, whereas low residual stresses were measured for those specimens that did not fail. The results of this study indicate that the use of either cylindrical or spherical specimens is a simple and reliable method that can be used to identify highly incompatible ceramic combinations.

All porcelains tested in the present study have, according to the manufacturers, a CTE that renders them thermally compatible with that of Y-PSZ materials. However, in some groups the percentage of failed specimens was greater than that reported by DeHoff \textit{et al.}\textsuperscript{15} for nominally compatible ceramic systems, even when the manufacturer's firing schedule was followed. Multiple regression analysis showed that cooling rate, thickness and material were associated with the development of spontaneous cracks. Surprisingly, even when the manufacturer's firing schedule was followed, cracks were observed in two of the six systems (VM9-0 1.5A and ZI 2.5A).

Manufacturers tend to produce veneering porcelain with a CTE slightly lower than the CTE of the framework so that compressive stresses are developed in the porcelain surface. One can assume that the difference in results between the six systems tested is not only affected by the thickness and the cooling rate, but also by minimal differences in mismatch of CTE among the porcelain/Y-PSZ systems given the same geometry and, therefore, thermal diffusivity of the specimens. To date, the range of CTE that is defined as compatible in porcelain/Y-PSZ structures has not been investigated. However, it is likely that the range of compatible CTE in porcelain/Y-PSZ structure is considerably narrower than that measured for MCR.\textsuperscript{11,14} In the latter, some of the developing residual thermal stress is relieved by creep deformation.\textsuperscript{16} Y-PSZ is a high fusing brittle ceramic material not able to relieve thermal stress by deformation under the conditions tested here, or in clinical situations, and therefore a minimal mismatch of the CTE may count for the development of significant residual stress even in nominally compatible systems. This hypothesis should be confirmed by a quantitative analysis of the residual stresses in the systems investigated.

The importance of the cooling cycle was especially demonstrated by the results of the VM9 specimens. Cracks were observed in the VM9 specimens as the thickness was increased and, more importantly, when the cooling rate was faster (the originally recommended cooling cycle). However, no cracks were seen when the updated firing recommendations involving slow cooling of the specimens to 600 °C were used (compared to 800 °C previously recommended). These findings support the assumption that in addition to a potential mismatch of the CTE of the materials, the thickness of the structure and cooling rates may be even more significant factors responsible for the development of cracks and chipping of porcelain/Y-PSZ prostheses.

Tempering-induced residual tensile stress develops within the porcelain layer when it cools below the glass transition phase. Above this temperature, stresses are relieved by plastic deformation. Temperature gradients through the cooling porcelain can result in areas that are above and below this glass transition phase. These temperature gradients will be affected by the cooling rate, thickness and thermal conductivity of both the porcelain and zirconia core. Because the CTE is not linear with temperature change, small differences in CTE through the porcelain layer and between the porcelain and zirconia are accentuated. The faster the cooling rate, the greater the temperature gradients through the porcelain. The external regions will cool faster, thus concentrating stresses near the surface. Therefore, the thicker the porcelain, the faster the cooling rate, and the slower the thermal diffusivity (thermal conductivity), the greater will be the stress development.

Swain's mathematical model predicted that with small differences in CTE compressive stresses develop at the porcelain/Y-PSZ interface, whereas tensile stresses concentrate at the surface of the porcelain layer. This is consistent with the observation of the cracks and rupture of the specimens in this study, since the cracks appeared to originate within the porcelain layer near the surface and when rupture occurred it never extended to the interface where presumably the layer of compressive stresses diverted its propagation (Fig 1).

Zirconia has low thermal conductivity compared to metals, and zero creep at porcelain firing temperatures.
Thus, given the same geometry (shape and thickness), same cooling rate and same CTE differential, higher stresses are likely to develop in Y-PSZ combinations compared to porcelain/metal combinations.

The role of thickness in the development of unstable cracks is controversial. Some clinical studies support the view that chipping of the porcelain layer can be eliminated by increasing the thickness of Y-PSZ and by reducing the thickness of the porcelain layer. However, according to Swain, when materials have poor thermal diffusivity, such as Y-PSZ and porcelain, the effective thickness for stress development corresponds to the total thickness of the restoration and therefore changing the ratio within the same restoration may have no effect on the development of tensile stresses.

It is important to note that the lack of visible cracks in some porcelain tested does not necessarily correspond to the lack of residual stresses within the structure. This would also apply to in situ restorations and does not guarantee they would be immune from chipping. Crack development and slow growth may be initiated by contact forces, facilitated by the residual stress, and exacerbated by the presence of moisture.

This study suggests that the development of thermally induced residual stress affected by several factors including overall thickness, shape and cooling rate may contribute to the chipping of the porcelain observed clinically in restorations made from nominally thermally compatible porcelain/Y-PSZ systems. Further research is required to quantify the contribution of each factor. This would enable protocols to be implemented to minimize the development of thermal residual stresses and in turn the number of clinical complications experienced with porcelain veneered to Y-PSZ prostheses.

CONCLUSIONS
Crack incidence increased with increased porcelain veneer thickness and faster cooling rates in nominally compatible porcelain/zirconia systems in the geometrically configured specimens tested.

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