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Abstract

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Reference


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Grinding damage assessment on four high-strength ceramics

Jean-Jacques Canneto\textsuperscript{a}, Maria Cattani-Lorente\textsuperscript{b}, Stéphane Duruau\textsuperscript{b}, Anselm H.W. Wiskott\textsuperscript{b}, Susanne S. Scherrer\textsuperscript{b,*}

\textsuperscript{a} Div Cariology and Endodontics, University of Geneva, University Clinic of Dental Medicine, Geneva, Switzerland
\textsuperscript{b} Div Fixed Prosthodontics – Biomaterials, University of Geneva, University Clinic of Dental Medicine, Geneva, Switzerland

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\textbf{ABSTRACT}

Objectives. The purpose of this study was to assess surface and subsurface damage on 4 CAD-CAM high-strength ceramics after grinding with diamond disks of 75 \textmu m, 54 \textmu m and 18 \textmu m and to estimate strength losses based on damage crack sizes.

Methods. The materials tested were: 3Y-TZP (Lava), dense Al\textsubscript{2}O\textsubscript{3} (In-Ceram AL), alumina glass-infiltrated (In-Ceram ALUMINA) and alumina–zirconia glass-infiltrated (In-Ceram ZIRCONIA). Rectangular specimens with 2 mirror polished orthogonal sides were bonded pairwise together prior to degrading the top polished surface with diamond disks of either 75 \textmu m, 54 \textmu m or 18 \textmu m. The induced chip damage was evaluated on the bonded interface using SEM for chip depth measurements. Fracture mechanics were used to estimate fracture stresses based on average and maximum chip depths considering these as critical flaws subjected to tension and to calculate possible losses in strength compared to manufacturer’s data.

Results. 3Y-TZP was hardly affected by grinding chip damage viewed on the bonded interface. Average chip depths were of 12.7 \pm 5.2 \textmu m when grinding with 75 \textmu m diamond inducing an estimated loss of 12% in strength compared to manufacturer’s reported flexural strength values of 1100 MPa. Dense alumina showed elongated chip cracks and was suffering damage of an average chip depth of 48.2 \pm 16.3 \textmu m after 75 \textmu m grinding, representing an estimated loss in strength of 49%. Grinding with 54 \textmu m was creating chips of 32.2 \pm 9.1 \textmu m in average, representing a loss in strength of 23%. Alumina glass-infiltrated ceramic was exposed to chipping after 75 \textmu m (mean chip size = 62.4 \pm 19.3 \textmu m) and 54 \textmu m grinding (mean chip size = 42.8 \pm 16.6 \textmu m), with respectively 38% and 25% estimated loss in strength. Alumina–zirconia glass-infiltrated ceramic was mainly affected by 75 \textmu m grinding damage with a chip average size of 56.8 \pm 15.1 \textmu m, representing an estimated loss in strength of 34%. All four ceramics were not exposed to critical chipping at 18 \textmu m diamond grinding.

\* Corresponding author. Tel.: +41 223794069.
E-mail address: susanne.scherrer@unige.ch (S.S. Scherrer).
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1. Introduction

High-strength ceramics like alumina (Al₂O₃) and zirconia (3Y-TZP) are being used for restorative frameworks as an alternative to metal for over 15 years thanks to the CAD-CAM technology [1]. The 3D machining of presintered ceramic blanks into the desired framework shape is followed by dense sintering. Manual grinding is however often performed in the laboratories post-sintering for shape adjustments of the sintered ceramic framework in critical areas such as margins, connectors or inner walls prior to veneering. The amount of reshaping with diamond burs post-sintering may vary from minor up to substantial depending on the computer generated 3D design of the framework, the precision milling of the CAD-CAM system and the shape and quality of the tooth preparation. Such reshaping procedure performed both by the laboratories and sometimes the dentist may have some critical mechanical consequences depending on the diamond bur grit used. As ceramics are intrinsically brittle and their mechanical properties largely influenced by their surface state, their flexural strength can be negatively affected by every treatment that increases surface roughness with the introduction of surface or subsurface flaws [2,3] that may be subjected to tensile stresses. The damage process during grinding of ceramics by an abrasive particle has been described with the formation of mainly two types of cracks: parallel cracks (long or short semi-elliptical) formed parallel to the direction of grinding, or short orthogonal cracks perpendicular to the abrasive motion direction [2]. Tangential forces may also apply during grinding which tend to increase tensile stresses normal to the direction of motion, favoring median crack propagation in the plane of motion [3].

The scientific literature is unanimous on the fact that grinding procedures often dramatically lower fracture resistance and fatigue behavior depending on the type of ceramic. For zirconia, the ground surface will show under XRD a localized phase transformation, which involves an increased resistance to crack propagation. Nevertheless, depending on the diamond grit size and shape and the time-dependence of the applied forces, deep reaching surface cracks will show both a reduction in strength and reliability [4–10]. Grinding dense alumina will also induce surface residual compressive stresses which can enhance the average strength, but increasing the depth of cut will produce machining flaws in form of surface cracks penetrating deeper than the surface compressive layer lowering the reliability and strength [11,12]. The grits of diamond burs commonly used in dental laboratories are color labeled and defined as supercoarse (black ring) (150–180 μm), coarse (green ring) (125–150 μm), standard (blue ring) (100–110 μm), fine (red ring) (45–50 μm), superfine (yellow ring) (15–30 μm). Depending on the amount of reshaping, dental laboratories will work with any of these grit sizes. The consequences of such grinding on surface and subsurface damage should therefore be well understood by the professional which reshape ceramics, i.e. dental technician and dentist. In that respect, extensive research was performed by Yin et al. [13–19] reporting on edge chip damage of several dental ceramics created by grinding with diamond burs under controlled pressure, feed rate, grit size (180, 40, 10 μm) and water coolant. Her findings indicated that the average chip width decreased with the fracture toughness of the ceramic material except for a glass-infiltrated alumina. The severity of chip damage also correlated with the diamond grit size. The rougher the diamond grit the more severe the chip damage which will depend on the type of ceramic. Hence, a 180 μm coarse diamond mounted on a turbine at 260,000 rpm and 2N load induced severe edge chip damage on a glass-infiltrated alumina but only minor to negligible chipping on zirconia [13,17,18]. The threshold diamond grit size for negligible edge chip damage on a glass-infiltrated alumina was reported to be 40 μm [17]. Fischer et al. [20] estimated the strength reduction of several dental ceramics using fracture mechanics relationships by measuring under the SEM the maximal crack length developed after grinding a channel in a rod-shape ceramic specimen with a cylindrical 100 μm grit diamond bur mounted on a handpiece and compared it with the critical crack size known for the material. The highest strength reduction was reported for the glass-infiltrated alumina ceramic reaching 21%. Grinding induced surface/subsurface crack damage responsible for failure in bend test can also be visualized using none destructive optical techniques (stereo microscopy, Nomarski, SEM, TEM) in bonded interfaces [23,24]. The damage extending from the ground surface into the subsurface can be measured for a variety of diamond grits and ceramics on the specimen’s mirror polished bonded interface. If one considers the worst grinding damage as a potential critical flaw (of crack length a) located on a tensile zone (i.e. connector, internal angles, margins) and uses the materials’ reported fracture toughness (KIC), one can calculate a fracture stress estimate using the classic fracture mechanics equation KIC = Y σf √a (Eq. (1)) [21,22]. This stress estimate can then be compared to the fracture strength reported by the manufacturer and an estimated “loss” in strength may be calculated for specific diamond grit induced grinding damage.
Table 1 – Materials used and mechanical properties as listed in the manufacturer’s product profile.

<table>
<thead>
<tr>
<th>Brand name</th>
<th>Description</th>
<th>Manufacturer</th>
<th>E (GPa)</th>
<th>Fracture toughness $K_{IC}$ (MPa√m)</th>
<th>Flex. strength $S$ (MPa)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Lava</td>
<td>3Y-TZP</td>
<td>3M Espe Seefeld, D</td>
<td>&gt;205</td>
<td>5–10</td>
<td>&gt;1100</td>
</tr>
<tr>
<td>In-Ceram AL</td>
<td>Al$_2$O$_3$</td>
<td>Vita Zahnfabrik Bad Säckingen, D</td>
<td>380</td>
<td>3.5</td>
<td>&gt;500</td>
</tr>
<tr>
<td>In-Ceram ALUMINA</td>
<td>Al$_2$O$_3$ + glass</td>
<td>Vita Zahnfabrik Bad Säckingen, D</td>
<td>280</td>
<td>3.9</td>
<td>500</td>
</tr>
<tr>
<td>In-Ceram ZIRCONIA</td>
<td>Al$_2$O$_3$ + Ce–ZrO$_2$ + glass</td>
<td>Vita Zahnfabrik Bad Säckingen, D</td>
<td>258</td>
<td>4.4</td>
<td>550</td>
</tr>
</tbody>
</table>

Thus, the objectives of this study are:

1. To determine the extent of grinding damage induced with diamond grit sizes of 75 μm, 54 μm and 18 μm grain sizes on four high-strength ceramics (dense alumina, dense zirconia, alumina glass-infiltrated, alumina–zirconia glass-infiltrated) by measuring maximum and average damage depth on a bonded interface.
2. To calculate using Eq. (1) a “stress estimate” using average and maximum damage depth (crack length $a$) assuming these would be of a critical size, with corresponding $Y$ factor and manufacturer's $K_{IC}$ values. By further comparing the “estimated stress” to the manufacturer's reported strength values for each ceramic, potential “losses in strength” after grinding are calculated and discussed.
3. To describe on the basis of SEM images, the crack propagation mode within the damage zone and the surface grinding removal mode (ductile, brittle, microcracking) for each ceramic.

Overall, this research on grinding damage will provide the dental technician and the dentist information about the surface/subsurface damage induced with diamonds ranging in the category of medium to fine and superfine (75, 54, 18 μm) grits and their possible loss in strength when alumina and zirconia framework adjustments are performed without further polishing and prior to veneering.

2. Materials and methods

2.1. Materials

Table 1 lists the materials used in this study with manufacturer's data for modulus of elasticity ($E$), flexural strength ($S$) and fracture toughness ($K_{IC}$). Lava (3M Espe) is a 3Y-TZP with an average grain size of 500 nm. In-Ceram AL (Vita) is a dense alumina with an average grain size of 2 μm. In-Ceram ALUMINA (Vita) is a lanthanum silicate glass-infiltrated alumina containing 75 wt % of Al$_2$O$_3$ and 25 wt % of lanthanum silicate. In-Ceram ZIRCONIA (Vita) is a lanthanum silicate glass-infiltrated alumina–zirconia containing 56 wt% of Al$_2$O$_3$, 24 wt% of Ce–ZrO$_2$ and 20 wt% of lanthanum silicate glass.

2.2. Specimen preparation

3Y-TZP (Lava) sintered bars of $3 \times 5 \times 40 \text{mm}^3$ were provided by the manufacturer and broken in halves to obtain matching pairs. In-Ceram AL, In-Ceram ALUMINA and In-Ceram ZIRCONIA were cut from CAD-CAM presintered blanks using a low speed rotatory fine cutting diamond disk under cooling water in an ISOMET machine (Buehler). Each slice was then cut in two equal halves (approx. $4 \times 5 \times 10 \text{mm}^3$) using this same procedure. The cut specimens from In-Ceram AL were sintered to full density in an oven (Sirona in Fire HTC, Sirona) following the manufacturer’s instructions. In-Ceram ALUMINA and In-Ceram ZIRCONIA presintered cut specimens were infiltrated with their respective lanthanum silicate glass and sintered following the manufacturer’s instructions. The excess glass was removed using sandblasting with 50 μm Al$_2$O$_3$ particles at a pressure of 4 bars. For the bonded interface, specimens were tightly glued together pairwise with sticky wax onto a metal support (Fig. 1). In step 1, surface A of the two halves was facing the top and consecutively ground by hand using diamond disks of decreasing grit size (75, 54, 18 μm) mounted on a turntable (RotoPol, Struers) rotating at 300 rpm with water irrigation and hand pressure followed by polishing with diamond pastes of 6, 3 and 1 μm and rotating at 150 rpm. After debonding and cleaning, the pairs were bonded together by their surface A, the top surface B ground and polished down to 1 μm (step 2). After debonding and cleaning, the matching halves were again bonded together with sticky wax as in step 1 with their side B adjacent to each other and surface A.

Fig. 1 – Bonded interface specimen preparation. Step1: mirror polishing top surface A of bonded pairs to a metal support. Step 2: rotate specimens and bond pairs with their side A together and B facing the top. Step 3: mirror polishing of top surface B. Step 4: damage grinding of top surface A lengthwise of the pairs bonded by their side B.
Fig. 2 – Schematic of grinding induced flaws. Sets of cracks running parallel (median crack) or orthogonal (radial crack) to the ground surface are shown. On the bonded surface (B), semi-elliptical chips spaced out are the result of parallel running cracks. Within these chips, orthogonal cracks and subsurface lateral cracks can be viewed. The top ground surface (A) will show the abrasion mode (ductile or brittle) with grinding grooves and surface chipping (lateral cracks).

2.3. SEM damage evaluation

Each pair of ceramic specimens (two halves) was analyzed under the SEM. Chip depths on the bonded surface (B) (Figs. 2 and 3) were measured for each pair of ceramic specimens with a minimum of 15 and maximum 25 chips measured on the bonded interface. The top ground surface (A) was analyzed to determine the abrasion mode (ductile or brittle), type of crack propagation (intergranular, transgranular) and presence of lateral (horizontal) or radial/median extending cracks.

2.4. Stress estimates and strength loss

The semi-elliptical damage formed on the bonded interface was measured over approximately two thirds of the specimen’s length (Fig. 2). The grinding damage (Fig. 3) was assessed measuring its depth (a) and length (2c) by SEM. Mean crack depth (\(a_{\text{mean}}\)) and maximum crack depth (\(a_{\text{max}}\)) were assessed for a minimum of 15 localized chip-damages along the bonded interface for each grinding condition and ceramic. According to Eq. (1), \(K_{\text{IC}} = Y \sigma_Y \sqrt{a}\), the fracture toughness \(K_{\text{IC}}\) is related to a stress intensity shape factor \(Y\), a stress at fracture \(\sigma_Y\) and a crack depth \(a\). The stress intensity shape factor \(Y\) will range between a value of 1.3 and 1.99 depending on the overall crack shape (width and depth) [21]. Hence, an elongated surface crack (long semi-ellipse) will have a shape factor \(Y\) of 1.99 which will more severely affect the strength than a semi-circle shaped crack with a \(Y\) of 1.3. The shape factor \(Y\) was estimated from crack depth and length ratio. A semi-ellipse with \(c = 2a\) will have a \(Y = 1.6\), but an elongated elliptical chip with \(c > a\) will have a \(Y = 1.99\) [21]. Stress estimates were then calculated assuming that the chip depth (a) is a strength limiting flaw and using manufacturer’s \(K_{\text{IC}}\) values in Eq. (1). The estimated stress for a given chip size was then compared to the stress values reported by the manufacturer for each material (Table 1) and an indicative possible loss in strength calculated.

2.5. Statistical analysis

Chip-damage sizes were compared using a one-way ANOVA. Differences of chips among materials and grits were compared using Fischer’s least significant difference test at 95% level of significance \((p < 0.05)\)

3. Results

3.1. Grinding damage evaluation on the bonded interface

Table 2 and Fig. 4 summarize the average chip size developed on the bonded interface after 75 \(\mu\)m, 54 \(\mu\)m or 18 \(\mu\)m diamond grit grinding measured by SEM. For each ceramic material and diamond grit a minimum of 15 chip measurements over the length of the specimen were performed for the average depth calculation. The standard deviation is a reflection of the variation in chip sizes within the same specimen. The average and maximum crack depth for each grinding condition and material is discussed further in this paper in Table 3 for possible strength limiting effects.

The results in Table 2 show that for all four ceramics a significant difference in chip damage was found for each diamond grinding grit. Coarser diamond grinding led to deeper chip damage (Fig. 4). Zirconia ground at 75 \(\mu\)m had in average the smallest chips which were approximately four times less
Table 2 – Average chip sizes measured on the bonded interface as a function of diamond grit grinding and ceramic material tested. Values with the same letter (column) denote no significant difference (p < 0.05). Values with the same number (row) denote no significant difference. * Could not be measured properly as chips were below 2 μm.

<table>
<thead>
<tr>
<th>Material brand</th>
<th>Description</th>
<th>Damage 75 μm diamond grinding Mean ± SD (μm)</th>
<th>Damage 54 μm diamond grinding Mean ± SD (μm)</th>
<th>Damage 18 μm diamond grinding Mean ± SD (μm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Lava</td>
<td>3Y-TZP</td>
<td>12.7 ± 5.2&lt;sup&gt;a&lt;/sup&gt;</td>
<td>6.4 ± 2.2&lt;sup&gt;b&lt;/sup&gt;</td>
<td>&lt;2&lt;sup&gt;c&lt;/sup&gt;</td>
</tr>
<tr>
<td>In-Ceram AL</td>
<td>Al&lt;sub&gt;2&lt;/sub&gt;O&lt;sub&gt;3&lt;/sub&gt;</td>
<td>48.2 ± 16.3&lt;sup&gt;b&lt;/sup&gt;</td>
<td>32.2 ± 9.1&lt;sup&gt;b&lt;/sup&gt;</td>
<td>6.6 ± 0.9&lt;sup&gt;c&lt;/sup&gt;</td>
</tr>
<tr>
<td>In-Ceram ALUMINA</td>
<td>Al&lt;sub&gt;2&lt;/sub&gt;O&lt;sub&gt;3&lt;/sub&gt; + glass</td>
<td>62.4 ± 19.3&lt;sup&gt;c&lt;/sup&gt;</td>
<td>42.8 ± 16.6&lt;sup&gt;c&lt;/sup&gt;</td>
<td>11.5 ± 2.4&lt;sup&gt;c&lt;/sup&gt;</td>
</tr>
<tr>
<td>In-Ceram ZIRCONIA</td>
<td>Al&lt;sub&gt;2&lt;/sub&gt;O&lt;sub&gt;3&lt;/sub&gt; + Ce-ZrO&lt;sub&gt;2&lt;/sub&gt; + glass</td>
<td>56.8 ± 15.1&lt;sup&gt;b&lt;/sup&gt;</td>
<td>33.9 ± 8.1&lt;sup&gt;b&lt;/sup&gt;</td>
<td>7.8 ± 1.7&lt;sup&gt;c&lt;/sup&gt;</td>
</tr>
</tbody>
</table>

Table 3 – Stress at failure estimates as a function of crack depth (a) (a<sub>mean</sub>, a<sub>max</sub>). K<sub>IC</sub> and Y factor after diamond grinding. Estimation of a<sub>critical</sub> using equation 2 and manufacturer's data of strength and toughness for each material.

<table>
<thead>
<tr>
<th>Crack depth a (μm)</th>
<th>K&lt;sub&gt;IC&lt;/sub&gt;</th>
<th>Y</th>
<th>Estimated Stress σ for failure (MPa)</th>
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</thead>
<tbody>
<tr>
<td>Lava (3Y-TZP) 75 μm</td>
<td>a&lt;sub&gt;mean&lt;/sub&gt; = 13</td>
<td>5.5</td>
<td>1.6</td>
</tr>
<tr>
<td></td>
<td>a&lt;sub&gt;max&lt;/sub&gt; = 28</td>
<td>5.5</td>
<td>1.6</td>
</tr>
<tr>
<td></td>
<td>a&lt;sub&gt;critical&lt;/sub&gt; = 10</td>
<td>5.5</td>
<td>1.6</td>
</tr>
<tr>
<td>In-Ceram AL (Al&lt;sub&gt;2&lt;/sub&gt;O&lt;sub&gt;3&lt;/sub&gt;) 75 μm</td>
<td>a&lt;sub&gt;mean&lt;/sub&gt; = 48</td>
<td>3.5</td>
<td>1.6</td>
</tr>
<tr>
<td></td>
<td>a&lt;sub&gt;max&lt;/sub&gt; = 83</td>
<td>3.5</td>
<td>1.6</td>
</tr>
<tr>
<td></td>
<td>a&lt;sub&gt;critical&lt;/sub&gt; = 10</td>
<td>5.5</td>
<td>1.6</td>
</tr>
<tr>
<td>In-Ceram AL (Al&lt;sub&gt;2&lt;/sub&gt;O&lt;sub&gt;3&lt;/sub&gt;) 54 μm</td>
<td>a&lt;sub&gt;mean&lt;/sub&gt; = 48</td>
<td>3.5</td>
<td>1.6</td>
</tr>
<tr>
<td></td>
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<td>3.5</td>
<td>1.6</td>
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<td>a&lt;sub&gt;critical&lt;/sub&gt; = 10</td>
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<td>1.6</td>
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<td>In-Ceram AL (Al&lt;sub&gt;2&lt;/sub&gt;O&lt;sub&gt;3&lt;/sub&gt;) 18 μm</td>
<td>a&lt;sub&gt;mean&lt;/sub&gt; = 47</td>
<td>3.5</td>
<td>1.6</td>
</tr>
<tr>
<td></td>
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<td>3.5</td>
<td>1.6</td>
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<td></td>
<td>a&lt;sub&gt;critical&lt;/sub&gt; = 10</td>
<td>5.5</td>
<td>1.6</td>
</tr>
<tr>
<td>In-Ceram ALUMINA (glass infiltrated) 75 μm</td>
<td>a&lt;sub&gt;mean&lt;/sub&gt; = 62</td>
<td>3.9</td>
<td>1.6</td>
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<td></td>
<td>a&lt;sub&gt;max&lt;/sub&gt; = 102</td>
<td>3.9</td>
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<td>a&lt;sub&gt;critical&lt;/sub&gt; = 10</td>
<td>5.5</td>
<td>1.6</td>
</tr>
<tr>
<td>In-Ceram ALUMINA (glass infiltrated) 54 μm</td>
<td>a&lt;sub&gt;mean&lt;/sub&gt; = 43</td>
<td>3.9</td>
<td>1.6</td>
</tr>
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<td>a&lt;sub&gt;critical&lt;/sub&gt; = 24</td>
<td>3.9</td>
<td>1.6</td>
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<td>In-Ceram ZIRCONIA (glass infiltrated) 75 μm</td>
<td>a&lt;sub&gt;mean&lt;/sub&gt; = 57</td>
<td>4.4</td>
<td>1.6</td>
</tr>
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<td>a&lt;sub&gt;max&lt;/sub&gt; = 80</td>
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<td>a&lt;sub&gt;critical&lt;/sub&gt; = 25</td>
<td>4.4</td>
<td>1.6</td>
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<tr>
<td>In-Ceram ZIRCONIA (glass infiltrated) 54 μm</td>
<td>a&lt;sub&gt;mean&lt;/sub&gt; = 34</td>
<td>4.4</td>
<td>1.6</td>
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<td></td>
<td>a&lt;sub&gt;max&lt;/sub&gt; = 51</td>
<td>4.4</td>
<td>1.6</td>
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<tr>
<td></td>
<td>a&lt;sub&gt;critical&lt;/sub&gt; = 25</td>
<td>4.4</td>
<td>1.6</td>
</tr>
</tbody>
</table>

Fig. 4 – Overview of average damage size as a function of diamond grain size grinding (18 μm, 54 μm, 75 μm). The larger the diamond grain, the bigger the damage. For mean values and standard deviations see Table 2. (This image is available in colour online at Science Direct).

Deep than those formed on the other three alumina ceramics. For In-Ceram AL, In-Ceram ALUMINA and In-Ceram ZIRCONIA 75 μm and 54 μm ground specimens presented notable defects, while 18 μm diamond grinding induced only very small chips of negligible size.

Figs. 5–8 illustrate typical bonded interface damage morphologies for each ceramic material and grinding condition (a = 75 μm, b = 54 μm, c = 18 μm) as viewed on the mirror polished bonded face oriented perpendicular to the ground surface. Crack depths are marked directly over the corresponding damage zone on each image. Damage was in general getting smaller in size with finer diamond grits. For the 3Y-TZP zirconia material, damage was in form of semi-elliptical chips overlapping with each additional passage of the grinding diamond disk but remained restricted in their chip extension depth as seen in Fig. 5. No chips could be measured after the 18 μm diamond disk grinding. Dense alumina (Fig. 6) and the two glass-infiltrated In-Ceram ALUMINA (Fig. 7) and In-Ceram ZIRCONIA (Fig. 8) showed deeper chips with elongated morphologies. Grinding with the finer diamond disk (18 μm) produced only small chips (<10 μm).
3.2. Strength degradation estimates as a function of chip crack size and fracture toughness ($K_{\text{IC}}$)

Fig. 9 provides examples of chip crack sizes formed after grinding on the bonded interface and measured by SEM. The majority of the chip damage had a semi-elliptical shape (Fig. 9 a, c, and d) with a ratio of $c = 2a$ and thus a Y shape factor = 1.6. For dense alumina, the chip damage was rather elongated at 75 $\mu$m grinding with $c \gg a$ and less favorable Y = 1.99 (Fig. 9b). The implication of varying Y factor based on Eq. (1) is demonstrated in Table 3 which provides the measured average ($\delta_{\text{mean}}$) and maximum ($\delta_{\text{max}}$) chip depths for each ceramic material and grinding diamond disk with an estimated stress at failure using toughness values from the manufacturer and Y shape factor of 1.6 corresponding to $c = 2a$ semi-elliptical crack shape or 1.99 in case of elongated cracks. The estimated loss in strength (%) is calculated compared to the manufacturer’s strength values for which a critical crack depth ($c_{\text{critical}}$) has been calculated (Eq. (1)). Only chips that would lower the strength compared to the manufacturer’s values are considered in the table. As it appears, grinding with 18 $\mu$m did not induce critical chip sizes which would lower the strength.

3.3. Fracture propagation within the chipped surface

Detailed views within a chipped surface after 75 $\mu$m grinding for In-Ceram AL (Fig. 10a) and In-Ceram ALUMINA (Fig. 10b). Cracks departing from the ground surface (bottom) are running radially downwards into the substrate (Fig. 10a). Horizontally running cracks (lateral cracks, parallel to the
ground surface) are seen within the sub surface (Fig. 10b). The chipped alumina shows mainly intergranular cracking (a), whereas the glass-infiltrated alumina shows both, intergranular and transgranular crack propagation (b).

Fig. 11 illustrates chipped surfaces of a zirconia (Fig. 11a) and a glass-infiltrated alumina–zirconia (Fig. 11b). The chip cracking is transgranular as well as intergranular for both materials. The ground surface is at the bottom of the images.

Fig. 12 illustrates the fractured chipped surfaces of dense alumina at 5000× (Fig. 12a) and 10000× magnifications (Fig. 12b) which is a higher magnification of Fig. 10a. The individual grains are visible because of the intergranular fracture mode. Some alumina grains show twinning (steps on their fracture surface) which is a grain distortion or deformation (dislocation of glide planes) occurring during the grinding crack damage.

3.4. Ground surface appearance

The appearance of the ground surface varied depending on the ceramic material. For dense alumina (In-Ceram AL) (Fig. 13a, 10000× mag.) a large fraction of the abraded surface was removed by grain pull-out from grain boundary fracture, a phenomenon also described as intergranular brittle cracking. As a comparison with the same magnification, the glass-infiltrated alumina shows in addition to pull-out also some burnished (plastically deformed) surface texture which is represented by

Fig. 8 – In-Ceram ZIRCONIA (Al2O3 + ZrO2 + glass infiltration). Illustrations of 3 diamond disk (75 μm, 54 μm, and 18 μm) ground surfaces (bottom) and induced damage viewed on the perpendicular polished sides (top). The elongated semi-elliptical chips for 75 μm and 54 μm ground surfaces were, respectively, 53 μm (Fig. 8a, 800× mag.) and 33 μm (Fig. 8b, 1500× mag.) deep. Grinding with 18 μm diamond disk (Fig. 8c, 6500× mag.) induced negligible damage of ≤10 μm.

Fig. 9 – Chip size delineation after 75 μm diamond grinding for Lava (3Y-TZP) (a), In-Ceram AL (Al2O3) (b), In-Ceram ZIRCONIA (Al2O3 + Ce–ZrO2 + glass infiltration) (c) and In-Ceram ALUMINA (Al2O3 + glass infiltration) (d). Crack depth (a) and crack axis length (2c) will determine the overall flaw shape and allow for an estimate of the stress intensity shape factor Y.
flattened localized surface marks resulting from the abrasive diamond grit (Fig. 13b). The glass-infiltration of the porous alumina structure may be related with that plastically deformed surface.

The surface of a dense zirconia (Lava) after 75 μm grinding (Fig. 14a) has a rather smooth and plastically deformed aspect as a result of grinding. The grinding grooves are spaced out and material removal is piling up on top of the grooves. Some localized step-like cracking is visible (center) in the direction of grinding. The alumina–zirconia glass-infiltrated ceramic (Fig. 14b) shows an identical surface as the alumina glass-infiltrated ceramic in Fig. 13b. Removal of material from grinding is occurring by pull-out as well as plastic deformation (flattened smooth areas).

Mirror polishing dense alumina (In-Ceram AL) (Fig. 15) did not completely remove the cavities occurring from grain

Fig. 10 – Illustration of a 75 μm diamond disk grinding damage chip surface on dense alumina (a) (In-Ceram AL) and glass-infiltrated alumina (b) (In-Ceram ALUMINA). Both materials show brittle fracture with grain pullout. Intergranular fracture dominates for dense alumina, whereas a mixed mode of transgranular and intergranular fracture is observed for the glass-infiltrated alumina ceramic.

Fig. 11 – Illustration of a 75 μm diamond disk grinding damage chip surface on dense zirconia (a) (3Y-TZP Lava) and glass-infiltrated alumina–zirconia (b) (In-Ceram ZIRCONIA). A mixed mode of transgranular and intergranular fracture is observed for both ceramics.

Fig. 12 – Dense alumina (In-Ceram AL). Magnifications of chipped surfaces as a result of 75 μm diamond grinding damage. Some alumina grains located in the cracked subsurface show twinning which is a grain distortion or deformation (dislocation of glide planes) occurring during the grinding crack damage. Deformation twins look like steps with larger habit planes and narrow widths.
pull-out from previous grinding steps with rougher diamonds, leaving an overall pitted surface. In addition, the presence of inherent volume distributed processing defects of approx. 20 μm in length contained within the presintered blanks appeared on the bonded interface surface during polishing (Fig. 15).

4. Discussion

CAD-CAM technology is used in dentistry to design and manufacture frameworks for crowns and bridges (fixed dental prostheses, FDP) out of high-strength presintered zirconia or
alumina blocs. More recently, full anatomic zirconia crowns or fixed dental prostheses are also manufactured by CAD-CAM. The frameworks or crown and bridge restorations are usually well designed and little to no reshaping has to be performed after sintering. Nevertheless, when reshaping with diamond burs is necessary in areas such as connectors (Fig. 16), margins or internal angles of the inner side of the framework over an abutment tooth, it is critical not to introduce possible damage from using too coarse diamonds in these areas where tensile stresses are concentrated.

It was the aim of this study to document and measure crack damage induced by grinding with respectively 75 \( \mu \text{m} \), 54 \( \mu \text{m} \) and 18 \( \mu \text{m} \) diamond grain size on four sintered high-strength ceramics (zirconia, alumina, alumina glass-infiltrated, alumina–zirconia glass-infiltrated) used in prosthetic dentistry. The diamond can be assimilated to a sharp indenter while moving and scratching the ceramic surface. The induced surface damage is a result of localized plastic deformation, crack initiation, crack growth and linking, and finally chipping [25]. The resultant chips can be visualized using the bonded interface technique and their shape (i.e. depth and length) characterized under the SEM. In this study, the grinding direction was always longitudinal to the long axis of the specimen and parallel to the bonded interface generating edge chips. The applied grinding force on the 150 rpm rotating diamond disk during 3 min was manual and performed by one single operator. Possible small variations in the final diamond grit grinding pressure may have contributed to the scatter in the results. Nevertheless, as expected, the larger diamond grain sizes induced larger chips on all the high-strength ceramic materials tested but the chip depth and shape was material related. The zirconia ceramic showed chips in the form of semi-ellipses usually at depth and length ratio of \( c = 2a \) which corresponds to a shape intensity factor \( Y \) of 1.6. Hence, for 3Y-TZP, 75 \( \mu \text{m} \) grinding induced chips that were in average slightly deeper (\( a_{\text{mean}} = 13 \mu \text{m} \)) than the calculated critical crack size (\( a_{\text{critical}} = 10 \mu \text{m} \)) when using the manufacturer’s strength and toughness values. Nevertheless, 75 \( \mu \text{m} \) grinding should be avoided with zirconia as the deepest chip (\( a_{\text{max}} \)) was measured to be 28 \( \mu \text{m} \) which would represent a strength at failure of 649 MPa instead of 1100 MPa (manufacturer’s data) and thus a possible maximum loss in strength of 41%. It is therefore not recommended to readjust the zirconia frameworks after sintering with diamonds that have a grain size of 75 \( \mu \text{m} \) or more. If such diamond burs are used, the ground surface needs to be smoothened with finer diamonds in order to eliminate the depth of cracks so that these are below the critical crack size of 10 \( \mu \text{m} \). Both 54 \( \mu \text{m} \) and 18 \( \mu \text{m} \) diamond grinding did not produce any critical chip size for the zirconia tested which could induce a loss in strength.

Grinding dense alumina with 75 \( \mu \text{m} \) introduced detrimental and elongated chips (\( c \gg a \), and \( Y = 1.99 \)). The average chip size of 48 \( \mu \text{m} \) represented a loss in strength of 49% as compared to manufacturer’s given strength and toughness values. The worse chip (\( a_{\text{max}} = 83 \mu \text{m} \)) would be responsible for a possible loss in strength of 61%. Similar detrimental chips were found for the 54 \( \mu \text{m} \) diamond grinding. The average chip size of 32 \( \mu \text{m} \) represented a loss in strength of 23% whereas the most critical chip of 47 \( \mu \text{m} \) would still induce a loss in strength of 36%. Clearly, grinding dense alumina with 75 or 54 \( \mu \text{m} \) diamond grain sizes should be avoided.

Grinding glass-infiltrated alumina was detrimental for both 75 and 54 \( \mu \text{m} \) with respective losses in strength of 38% and 25% for their average crack sizes. Maximum chip depths of 102 \( \mu \text{m} \) and 75 \( \mu \text{m} \) could be created inducing respective strength losses of 52% and 45%. Similarly, although reinforced with a second phase (zirconia), glass-infiltrated alumina–zirconia (In-Ceram ZIRCONIA) ground with 75 \( \mu \text{m} \) diamond induced chips averaging 57 \( \mu \text{m} \) and reducing the strength by 34%. Even 54 \( \mu \text{m} \) diamond disk grinding still induced a reduction in strength of 14% and should not be considered as negligible as the maximum chip size of 51 \( \mu \text{m} \) would induce as strength loss of 30%.

In addition to the chemical nature, powder granule sizes, firing schedules and microstructure, a ceramic strength value will depend on the processing residual stress state, the specimen’s surface finish and critical flaw size at the failure location. Strength values will reflect the specimen’s flaw population with a strong correlation to surface flaws from surface preparation. In this study, manufacturer’s strength and toughness values used for calculating estimates of possible strength losses were based on a 15 \( \mu \text{m} \) surface finish (ISO 6872 and SEVNB toughness test). None of the four highly crystalline ceramics suffered any estimated loss in strength after 18 \( \mu \text{m} \) diamond disk grinding close to the 15 \( \mu \text{m} \) surface finish of the manufacturer’s reference strength values, whereas the rougher surface finish showed critical chip sizes which could potentially weaken the ceramic.

In this research, water cooling was used as an aid to the removal process, cleaning off grinding debris on the ceramic surface and avoiding localized overheating with possible phase transformation consequences. There are heatless diamond bonded burs on the market for zirconia grinding without water, especially for laboratory use, along with specific instructions as to the number of rpm’s at which they may operate. Nevertheless, the diamond grain size is the critical parameter when it comes to damage production on a ceramic surface. It is known that surface abrasion, grinding or machining of alumina builds-up residual damage at the surface which highly influences the mechanical properties.
Vita prime for essential, if diamond deformed surface and resultant chip for dense alumina (In-Ceram AL) showed primarily grain pull-out. The abrasive cycles (150 rpm for 3 min) of the 75 μm diamond disk induced a fractured surface topography exposing grain pull-out as the major damage mode which has been often described for alumina [25–28]. Some alumina grains were also plastically deformed or showed dislocation and twinning. Such deformations have been described to occur on the surface of alumina during abrasion impact with diamond grains [25,27,29,30]. The diamond grain impact on the alumina can be assimilated to an indenter moving and scratching the surface. The induced surface damage is a result of localized crack initiation, crack growth and finally chipping, leaving some remnant surface damage [25]. Wu et al. [27,29,30] described the localized damage under a scratch groove in alumina which contains a high density of micro-cracks in all directions (lateral, median, radial). A residual plastic deformation zone is associated with scratching alumina. Plastic deformation and grain pull-out was also the prime surface damage viewed for the two glass-infiltrated alumina and alumina–zirconia ceramics. The prime difference with the dense alumina was a larger surface deformed plastically from the diamond abrasion.

Overall, these findings in this research are coherent with the instructions given by the manufacturer for all the ceramics we have tested. Hence, 3M Espe (Lava, 3Y-TZP) recommends in case of reshaping zirconia to use only fine-grain diamonds with grain sizes between 30 μm (fine) and 15 μm (extra-fine) and goes even further with diamond-equipped rubber polishers in areas such as connectors or margins. Similarly, Vita Zahnfabrik (In-Ceram AL, In-Ceram ALUMINA, In-Ceram ZIRCONIA) mentions in their instructions to avoid contour corrections after sintering, especially the connector areas. If reshaping is necessary they also provide general recommendations such as using fine to micro fine diamonds or diamond-coated rubber polishers.

5. Conclusion

The present study has shown that grinding with medium rough diamond disks (75 μm or 54 μm) on high strength-ceramics will introduce some grinding damage which may have negative consequences on the mechanical behavior, particularly in zones such as gingival side of connectors, margins and inner angles of the intaglio. If, major adjustments are necessary, we recommend to perform them by using decreasing diamond grain sizes down to 18 μm or below, in order to obtain chips that are limited in depth and non-critical.

Overall, this research may contribute to make every professional who takes part to the processing of all-ceramic FDP aware of grinding induced damages and the importance of surface finishing.

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