Strength, fracture toughness and microstructure of a selection of all-ceramic materials. Part I. Pressable and alumina glass-infiltrated ceramics

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Strength; Fracture toughness; Microstructure; glass-ceramic; Alumina; Lithium disilicate

Summary
Objective. The present study, divided into two parts, aimed to compare the strength, fracture toughness and microstructure of a range of all-ceramic materials. In part I, three hot-pressed glass-ceramics (IPS-Empress, Empress 2 and a new experimental ceramic) and alumina glass-infiltrated ceramics (In-Ceram Alumina), processed by both slip casting and dry pressing, were compared.

Methods. Tensile strength was appraised on 10 bar-shaped specimens (20 × 4 × 1.2 mm³) for each material with the three-point bending method; the fracture toughness was measured from 20 specimens (20 × 4 × 2 mm³), by using the indentation strength technique. Data were compared with ANOVA and the Sheffe post hoc test (p = 0.05). The volume fraction of each phase, the dimensions and shapes of the grains, porosity and the crack patterns were investigated using SEM.

Results. The average and standard deviation in strength (MPa) and fracture toughness (MPa m⅓/2) were: IPS-Empress 106(17) 1, 1.2(0.14) 1; Empress 2 306(29) 2, 2.9(0.51) 2, new experimental ceramic 303(49) 2, 3.0(0.65) 2, In-Ceram Alumina dry-pressed 440(50) 3, 3.6(0.26) 3, In-Ceram Alumina slip 594(52) 3, 4.4(0.48) 3. Values with the same superscript number showed no significant statistical difference. Microscopy revealed the relationship between the glass matrix and the crystalline phase and the characteristics of the latter were correlated to the strengthening and toughening mechanisms of these glass-ceramics.

Significance. The mechanical properties and microstructure of core materials have been advocated as crucial to the clinical long-term performance of all-ceramic dental restorations. This investigation provides the clinician with data regarding strength, fracture toughness and microstructure of a broad range of current materials.

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Introduction

The interest of dentists, dental technicians and patients in all-ceramic materials is rapidly...
increasing as stronger and tougher materials are developed and commercialized along with novel processing technologies. Currently, a wide range of materials and systems are available. However, relatively little is known about their microstructure and toughening mechanisms and the relationship between them and the mechanical properties of the corresponding ceramic.

Some of the most representative materials are: the pressable IPS-Empress (E1) and Empress 2 (E2) (Ivoclar, Schaan, Liechtenstein); the glass-infiltrated In-Ceram Alumina (IA) and In-Ceram Zirconia (IZ) (Vita Zahnfabrik, Bad Säckingen, Germany); the fully sintered DC-Zirkon (DZ) (DCS Dental, Allschwil, Switzerland). E1 is a leucite-reinforced glass-ceramic which was released in the early 1990s. With E1, a dental restoration is fabricated by hot-pressing an ingot of the material into a mold. E1 is recommended for inlays, onlays, veneers and anterior crowns. Strength values range from 95 to 180 MPa and the fracture toughness is approximately 1.3 MPa m^{1/2}. In 1998, Ivoclar released E2, which is a lithium disilicate-reinforced glass-ceramic processed with the same laboratory procedure and equipment used for E1. E2 is recommended for the fabrication of a 3-unit fixed partial denture (FPD). Strength and fracture toughness values range from 340 to 400 MPa and 2 to 3.3 MPa m^{1/2}, respectively. More recently, Ivoclar have developed a new pressable experimental material (EC) with the same chemical composition as E2 (lithium disilicate glass-ceramic). An investigation conducted by Albakry et al. showed that there is no difference between EC and E2 in the biaxial flexural strength and phase composition. IA was developed by Sadoun and consists of a partially sintered porous alumina structure infiltrated with molten glass. IA is available in two forms, slip and dry-pressed. The slip is a dispersion of alumina powder in water, which is painted onto a special plaster dye to fabricate a framework of an all-ceramic restoration. The dry-pressed material is provided already processed by the manufacturer. The framework is obtained from the dry-pressed material by milling before glass-infiltration. For this purpose several milling systems can be used. The dry-pressed material is thought to possess better mechanical properties on the basis of a more consistent sintering process, although a recent investigation has shown the opposite. Flexural strength and fracture toughness values ranging from 352 to 600 MPa and from 2.7 to 4.49, respectively, were reported. IZ and DZ are two examples of the new generation of zirconia-based dental ceramics and will be discussed in part II.

The clinical failure of all-ceramic restorations is very often associated with their brittleness and low fracture toughness. The lack of sufficient clinical studies regarding the latest generation of materials has led manufacturers and dental operators to place great emphasis on mechanical properties to define the clinical indications of these materials. In this regard, the most relevant mechanical properties are strength and fracture toughness. Unfortunately, ceramics do not have a well-defined ultimate tensile strength. Strength values in ceramics are affected by several factors, such as the flaw distribution and the test methodology. Such variability makes comparison of materials tested under different conditions inappropriate. Fracture toughness, which is independent of flaw distribution, is believed to be a more consistent property. However, the interpretation of data regarding the fracture toughness of materials exhibiting R-curve behavior, which has been reported for the dental ceramics investigated here, may also be problematic.

The improvement of the in-service reliability of a material can be achieved by increasing its fracture toughness. Several toughening mechanisms with differing effectiveness have been used to improve the properties of dental ceramics. The most relevant mechanisms, described by Swain and subsequently by Evans, can be classified by: crack deflection; zone shielding; contact shielding and crack bridging. Crack deflection occurs when a crack is deflected from its trajectory as a result of residual stresses, fracture-resistant second phase and grain boundaries. The reorientation of the crack plane away from normal to the applied tensile stresses causes dispersion of its energy which corresponds to an increase of the fracture toughness of the material. A shielding zone, which brings about a reduction of stress intensification at the crack tip, can result from microcrack and transformation toughening. Microcrack toughening can occur in ceramics that contain high-localized residual stresses. These residual stresses can occur in a region with thermal expansion anisotropy in polycrystalline materials with elongated grains and/or thermal expansion or elastic mismatch in polyphase materials and/or in transforming materials. Microcracks normally occur along the lowest energy path, such as the lower modulus and toughness glassy phase in a glass-ceramic. Transformation toughening is characteristic of zirconia-based ceramics and will be discussed in the second part of the present study. In materials where contact shielding is involved, the crack deviation and the dissipation of its energy are due to the physical contact between the opening faces of
a growing crack which may result in friction between interlocking grains (pull-out of grains). The stresses at the crack tip are also reduced because of the closure forces resulting from such crack bridging sites.

The aim of this study was to compare the uniaxial flexural strength, fracture toughness and microstructure of nine dental ceramics, namely E1, E2, EC, IA slip, IA dry-pressed, IZ slip, IZ dry-pressed, DZ and an experimental 3 mol% Y₂O₃ ZrO₂. With respect to the microstructure, our aim was firstly to describe those features which may explain the results and secondly to provide information regarding the toughening mechanisms. The study is divided into two parts. In part I the pressable ceramics (E1, E2 and EC) and the alumina glass-infiltrated ceramics (IA slip and Dry-pressed) are discussed. Part II will focus on the zirconia-based ceramics.

Materials and methods

Preparation of the specimens

Five different materials were tested in Part I. The specimens of ceramics E1 (unshaded, batch No. 484065) and E2 (batch No. A21562) were produced by sprueing bars of PMMA (Perspex®), reproducing the desired dimensions and shapes. Pressing and divestment procedures were carried out as recommended by the manufacturer. Ivoclar provided the EC specimens already pressed and partially polished. The IA slip (Lot 6153) specimens were obtained by preparing a slip as recommended and pouring it into a silicon mold mounted on a special plaster. The slip was left to dry for at least 24 h and then sintered at 1100 °C for 10 h in a high-temperature furnace (In-Ceramat II, Vita Zahnfabrik, Bad Säckingen, Germany). After drying, the upper part of the slip, which shrank unevenly, was gently ground with silicon carbide paper until even surfaces and dimensions resembling those of the IA dry-pressed were obtained. Then the specimens were cut by using a diamond blade (Isomet, Buehler Ltd, Lake Bluff, IL, USA) from plates attained from the IA slip and an IA dry-pressed (lot No. 60645, Vita In-Ceram Blank for Cerec, Vita Zahnfabrik, Bad Säckingen, Germany). All specimens were afterwards infused with a corresponding infiltration-glass. The excess glass was removed by sandblasting with 50 μm Al₂O₃ at the maximum pressure of 0.25 MPa. All specimens were serially ground and wet polished with diamond discs of nominal grit size 120, 70, 30 and 15 μm to the final dimensions. Finally, the specimens were cleaned using an ultrasonic bath with acetone at room temperature for 15 min. One hundred and fifty specimens were prepared overall. Ten samples for each material, with final dimensions of approximately 20 mm long, 1.2 mm thick and 4 mm wide, were used to test strength with the three-point bending method. Twenty specimens for each material, with the final dimensions of approximately 20 × 3 × 4 mm³, were used to appraise the fracture toughness.

Uniaxial flexural strength

The uniaxial flexural strength (M) was measured with the three-point bending test and calculated by the following equation

\[
M = \frac{3Wl}{2bd^2}
\]

where \(W\) is the breaking load (N); \(l\) is the test span (mm), \(b\) is the width of the specimen (mm); \(d\) is the thickness of the specimen (mm). The specimens were tested with a universal testing machine (Shimadzu Ag-50 KNE, Kyoto, Japan), rested on a self aligning fixture with a span of 14 mm. Tests were conducted at a crosshead speed of 0.5 mm/min at room temperature (20 ± 1 °C) with a relative humidity of 70 ± 5%. Before testing the edges of the surface of the specimens undergoing tensile stresses were chamfered with a diamond disc (grit size 9 μm). After testing, the fracture surface of the specimens was observed with an optical microscope. It was found that very few specimens had fracture originating from an edge.

Fracture toughness

The fracture toughness (\(K_{IC}\)) was calculated with the indentation strength method and the following equation proposed by Chantikul et al.

\[
K_{IC} = 0.59(E/H)^{1/8}(S_P^{1/3})^{3/4}
\]

where 0.59 is a geometrical constant, \(E\) is the Young's modulus, \(H\) is the hardness, \(S_P\) is the stress at fracture, \(P\) is the indentation load. With this method a stable crack was generated with a Vickers indenter and the residual strength was measured with a conventional three point bending test. Particular attention was paid to the selection of the indentation loads and to the alignment of the specimens. The maximum load was the heaviest load compatible with the condition postulated by Chantikul et al., which states that the equation is not valid if a ratio crack length/thickness of the specimen of 1:10 is not respected. The minimum load corresponded to the lightest load capable of
generating a crack greater than the flaws already present on the surface of the specimen and from which catastrophic failure originates. The following ranges of loads were then used: E1 10, 20, 40 and 60 N; E2 and EC 10, 30, 60 and 120 N; IA slip and IA dry-pressed 20, 60, 120 and 200 N. The indentation was made in the middle of the specimen with two cracks directed along the length of the sample and the other two oriented normally to the length. The specimens were cleaned in an ultrasonic bath with acetone and dried in a thermostatically controlled oven at 120 °C. A drop of oil was then placed on the area prior to indentation to minimize the access of moisture into the crack tip. All specimens were examined after failure to ensure that fracture occurred from the indentation site.

Elastic moduli and hardness

Young’s modulus ($E$) was determined by testing the 3 bar specimens (dimensions approximately $30 \times 12 \times 1.2 \text{ mm}^3$) with a non-destructive dynamic method by impulse excitation of vibration according to the ASTM 1259-94.\textsuperscript{16} Hardness was measured as recommended by the ASTMC1327-99.\textsuperscript{17}

Statistics

The flexural strength and fracture toughness data of the groups were compared with one-way ANOVA and the Sheffe post hoc test. The alpha value was set at 0.05.

Microscopy

Several specimens of each material were polished to 1 μm and carbon-coated for SEM observation (XL 30, Philips, Eindhoven, Holland). Additional polished samples were etched and observed with a field emission SEM (JSM 6000 FSEM, Jeol, Tokyo, Japan) after coating with platinum (20 nm). The etching procedure was different according to the material: E1 was etched with 0.2 vol% of HF acid for 1 min; E2 and EC were etched with 10 vol% HF acid (range of time from 2 to 20 min); IA slip and dry-pressed were etched for 30 min with a beam of argon ions (gun current 1.0 mA and gun voltage 5.5 kV) (Dual Ion Mill, Model 600, Gatan Pleasanton, CA, USA). Five SEM micrographs taken from five different specimens for each group were used to appraise the volume fraction of each phase and porosity using the point counting technique.\textsuperscript{18} All points of the mesh covering the micrograph were considered to calculate average and standard deviation. Observations of cracks emanating from indentations on the coated surface of selected specimens were also made to investigate the crack-microstructure interaction.

Results

Analysis of the data by ANOVA and the Sheffe post hoc test shows that IA slip is the strongest material of the group ($p = 0.025$ when compared to IA dry-pressed and $p < 0.0001$ when compared to the other materials) (Table 1). Although the strength value of IA dry-pressed is 30% greater than those of EC and E2, there is no significant statistical difference in strength between these materials ($p = 0.052$). All materials are significantly stronger than E1 ($p < 0.0001$).

IA slip is also the toughest material ($p < 0.0001$). There is no significant statistical difference in fracture toughness between IA dry-pressed, EC and E2 ($p = 0.434$). All materials are significantly tougher than E1 ($p = 0.0001$).

Elastic modulus and hardness values are reported in Table 1.

The volume fractions of each phase, the glassy matrix and porosity for every material are reported in Table 2 along with the corresponding standard deviation.

E1 consisted of evenly distributed crystals of tetragonal leucite (mean diameter 1.7 μm), which are dispersed in a glassy matrix. Micro-cracking is often observed in the matrix and less frequently in grains (Fig. 1A). Furthermore, there is no tendency of the microcracks to coalesce (coupling). Twinning of the leucite grains is also frequently seen (Fig. 1A). The crack propagation pattern is both intergranular and transgranular (Fig. 1B).

E2 mainly consisted of elongated crystals of lithium disilicate (mean length 5.2 μm and mean diameter 0.8 μm) (Fig. 2). SEM observation of polished and etched surfaces shows the presence of bands where the crystals seem to be aligned and are denser. Some images show that the crack can be deflected by these, apparently denser, regions. However, higher magnification images show the tortuous path of a crack in the areas where random orientation is predominant compared to the areas where the crystals appear oriented. Microcracks are not seen in this investigation. The cracks produced with the indenter are constantly asymmetric. The crack pattern is both transgranular and intergranular (Fig. 2).

The microstructure of EC, apart from the grain length (mean grain length 3.4 μm), is virtually identical to that of E2.
Three different particle sizes of alumina are present in IA slip (Fig. 3A); large elongated grains (10–12 μm long and 2.5–4 μm wide); faceted particles with diameter from 1 to 4 μm; and spherical grains with diameter less than 1 μm. The elongated grains are oriented with their length along the length of the specimen (indicated with an arrow in Fig. 3A). Crack trajectories and lengths within IA slip are markedly affected by the orientation of the elongated grains, that is, the crack is longer and the pattern is intergranular when the direction is oriented along the length of the grains, whereas the crack is shorter and the fracture pattern transgranular when the crack extends normal to the length of the grains (Fig. 3B).

Microscopy shows that the microstructure of IA dry-pressed is rather different from that of IA slip (Figs. 3 and 4). In IA dry-pressed, the elongated grains are absent and only the other two particles (faceted and spherical) are present (Fig. 4). The cracks produced with the indenter are symmetric. The crack propagation is predominantly intergranular. Despite these differences, evidence of several toughening mechanisms, such as crack deflection, pullout of the grains with frictional interlock, bridging and microcracks, are similarly observed in both IA slip and dry-pressed (Figs. 3 and 4).

### Table 1

<table>
<thead>
<tr>
<th>Material</th>
<th>Strength (MPa)</th>
<th>Fracture toughness (MPa m$^{1/2}$)</th>
<th>Elastic modulus (GPa)</th>
<th>Hardness (GPa)</th>
</tr>
</thead>
<tbody>
<tr>
<td>E1</td>
<td>106 (17)$^1$</td>
<td>1.2 (0.14)$^1$</td>
<td>65 (1.5)</td>
<td>6.5 (0.4)</td>
</tr>
<tr>
<td>EC</td>
<td>303 (49)$^2$</td>
<td>3.0 (0.65)$^2$</td>
<td>90 (3.7)</td>
<td>5.5 (0.2)</td>
</tr>
<tr>
<td>E2</td>
<td>306 (29)$^2$</td>
<td>2.9 (0.51)$^2$</td>
<td>105 (4.8)</td>
<td>5.3 (0.2)</td>
</tr>
<tr>
<td>IA dry-pressed</td>
<td>440 (50)$^2$</td>
<td>3.6 (0.26)$^2$</td>
<td>265 (10)</td>
<td>11 (1.1)</td>
</tr>
<tr>
<td>IA slip</td>
<td>594 (52)$^3$</td>
<td>4.4 (0.48)$^3$</td>
<td>265 (10)</td>
<td>11 (0.3)</td>
</tr>
</tbody>
</table>

There is no significant statistical difference between materials with the same superscript number.

### Table 2

<table>
<thead>
<tr>
<th>Materials</th>
<th>Phase</th>
<th>Volume fraction (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>E1</td>
<td>Leucite</td>
<td>36 (1.2)</td>
</tr>
<tr>
<td></td>
<td>Glass</td>
<td>55 (1.5)</td>
</tr>
<tr>
<td></td>
<td>Porosity</td>
<td>9 (1.0)</td>
</tr>
<tr>
<td>E2</td>
<td>Lithium disilicate</td>
<td>65 (2.5)</td>
</tr>
<tr>
<td></td>
<td>Glass</td>
<td>34 (2.0)</td>
</tr>
<tr>
<td></td>
<td>Porosity</td>
<td>1 (0.2)</td>
</tr>
<tr>
<td>EC</td>
<td>Lithium disilicate</td>
<td>67 (2.3)</td>
</tr>
<tr>
<td></td>
<td>Glass</td>
<td>30 (1.8)</td>
</tr>
<tr>
<td></td>
<td>Porosity</td>
<td>3 (0.7)</td>
</tr>
<tr>
<td>IA slip</td>
<td>Alumina</td>
<td>68 (2.1)</td>
</tr>
<tr>
<td></td>
<td>Glass</td>
<td>27 (1.7)</td>
</tr>
<tr>
<td></td>
<td>Porosity</td>
<td>5 (1.1)</td>
</tr>
<tr>
<td>IA dry-pressed</td>
<td>Alumina</td>
<td>67 (1.9)</td>
</tr>
<tr>
<td></td>
<td>Glass</td>
<td>29 (2.0)</td>
</tr>
<tr>
<td></td>
<td>Porosity</td>
<td>4 (0.9)</td>
</tr>
</tbody>
</table>

Standard deviation is between brackets.

### Discussion

A common feature of all ceramics investigated here is the presence of a significant volume fraction of glass phase (ranging from 27 to 55%). The major difference between the pressable versus the infiltrated ceramics is that the latter consist of two interpenetrating networks that are both the ceramic and the glass phase, whereas in the pressable materials only the glass phase is continuous.

![Figure 1](image)

**Figure 1** Micrographs of IPS-Empress. (A) Twinning in the crystal of leucite and microcracks in the glassy matrix. (B) The crack propagates through both the crystals and the glassy matrix.
Not surprisingly, E1, having a much greater content of glass and a lower content of reinforcing material, is the weakest ceramic of the group (Tables 1 and 2). E1, which has been widely studied, was included in this study mainly as a benchmark for the more recent peer materials. The microscope observations reported in this study support previous statements regarding the toughening mechanism, which is based on a uniform distribution of the leucite crystals and the microcrack toughening due to the mismatch of the coefficient of thermal expansion between the crystalline and glassy phases (Fig. 1).1,2,19,20 The extensive twinning of the crystals seen on several micrographs (Fig. 1A and B) is also an expression of the shear deformation of the grains resulting from the tensile stresses generated by the mismatch of the coefficient of thermal expansion. The role of the microcracks in glass-ceramics is contradictory. It has been proposed that the microcracks can contribute to deflecting a crack and dispersing its energy, increasing the strength and fracture toughness of a given ceramic.21 However, if clusters of crystals are present, microcracks tend to coalesce, forming a crack, which surrounds the cluster (decoupling of leucite particles) as if it were a single grain, and causing a degeneration of the strength and fracture toughness.22 In E1, pressing contributes to generating an even distribution of the grains, which plays an important role in avoiding such a phenomenon. Even so, the proposed mechanism is scarcely effective and E1 is not significantly stronger than some frit feldspathic ceramics.23 The considerable clinical success of E1 cannot hence be explained on the basis of its mechanical properties. Other factors, such as glazing, staining and adhesive cementation, have been proposed to explain the apparent greater strength and reliability of the in-service restoration.24

Figure 2 Micrographs of Empress 2. (A) Preferred orientation of the grains, which is perpendicular to that of the crack. (B) The crack is deflected by the needle-shaped crystals of lithium disilicate, giving a mixture of transgranular and intergranular crack pattern.

Figure 3 Micrographs of In-Ceram Alumina slip. (A) The arrow indicates the direction of the crack; several toughening mechanisms are recognizable, such as pull-out of the grains (A), bridging (B), crack deflection (C). (B) Impression of a Vickers indenter producing asymmetric cracks, where the longer cracks are propagating along the main axis of the elongated crystals, which, at higher magnification, showed to be orientated horizontally. The shorter cracks are propagating normally to the elongated grains.
Two toughening mechanisms were described for lithia-disilicate glass-ceramics: thermally induced microcracking and crack deflection. Microcrack toughening was suggested as a possible mechanism in fine grain size ceramics (smaller than 20 μm); it may hence be a possible mechanism in E2 and EC. However, observation of microcracks and the estimation of their contribution to the ultimate fracture toughness require an approach somewhat more complicated than that used in the present study. The deflection of the crack along the crystals into the lower elastic modulus glassy matrix was seen in both E2 (Fig. 2) and EC. The increment of the fracture toughness results from the dissipation of the crack driving force as the crack plane is repeatedly reoriented away from the applied tensile stresses. The crack deflection mechanism is independent of particle size. This is consistent with the measurement of the grain size and the mechanical tests. In fact, although the grains of EC are shorter than those of E2, this did not result in any significant difference in strength and fracture toughness between the two ceramics. An X-ray diffraction analysis conducted in a previous investigation showed that preferred crystal orientations may occur upon pressing. In the present study, the observation of cracks propagating around rather than from the corners of some indentations also indicates that a preferred alignment of the lithium disilicate crystals due to flow through the sprueing arrangement may be operating in EC and E2. Low magnification micrographs taken from etched specimens showed the presence of bands where clusters of crystals appeared denser, apparently aligned and affecting the crack propagation. On the other hand, observations at higher magnification are not always consistent, showing areas with apparent preferred alignment of the crystals along with other regions where the grains are randomly distributed (Fig. 2). Further investigation is currently in progress to better understand how the crystals orient within the glassy matrix and how this would affect the properties of these ceramics.

Microscopy showed that a number of toughening mechanisms such as crack deflection, contact shielding and microcrack toughening operate in IA dry-pressed and slip (Fig. 4A and B). However, the microstructure of the two materials is somewhat diverse and accounts, along with the test method, for the greater values of strength and fracture toughness of IA slip over IA dry-pressed. IA dry-pressed consists of equi-axed particles embedded into a glassy phase and the crack pattern is constantly intergranular (Fig. 4A and B). Conversely, IA slip mainly consists of elongated grains whose main axis was, in the present study, coincidentally oriented in the same direction as the length of the specimens and normal to the applied tensile stress (Fig. 3A). This induced the crack to propagate through (transgranular crack pattern) and/or around (intergranular crack pattern) the alumina grains according to their orientation, generating asymmetric cracks and dissipating a greater amount of energy (Fig. 3A and B). Therefore, as also reported by Tan et al., in the case of IA slip, compared to IA dry-pressed, a material with greater fracture toughness should be expected when the crack is perpendicularly oriented to the elongated grains.

Conclusion

The first part of the present study has shown that, in general an increase of crystalline content of a glass-ceramic is accompanied with an increase of the strength and fracture toughness. However, in materials with comparable crystalline content,
some other factors such as porosity, the grain size, shape and orientation are important in determining the mechanical properties. In the case of the lithium disilicate containing pressable ceramics, the difference in mean grain length has no measurable effect on the strength and fracture toughness. Conversely, the minimal variations of the grain size, shape and orientation in the glass-infiltrated alumina-reinforced ceramics strongly affects the strength and fracture toughness of two otherwise similar ceramics. From a clinical standpoint, the alignment of elongated grains parallel to the surface is preferred over perpendicular or random alignment, as the greatest resistance to crack propagation through the core material is achieved. However, the techniques of fabrication of all-ceramic restorations used with the materials investigated in the present study do not seem to take into account such issues and the orientation of the crystals is most likely due to coincidental factors. Additional studies are necessary to fully understand the role played by every toughening mechanism and how these mechanisms can be exploited to further improve the properties of dental ceramics. The reader should also consider that other factors, such as fatigue, cementation, handling and design of the restoration, affect the clinical performance of dental ceramics.

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