Alumina Ceramic for Dental Applications: A Review Article.

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Citation

Abstract
Alumina has received considerable attention and has been historically well-accepted as biomaterials for dental and medical applications. This article reviews the applications of this material in dentistry. It presents a brief history, dental applications and methods for improving the mechanical properties of alumina-based materials. It also offers perspectives on recent research aimed at the further development of alumina for clinical uses, at their evaluation and selection, and very importantly, their clinical performance. This article also stated about the Functionally Graded Materials (FGMs) which has been conceived as a new material design approach to improve performance compared to traditional homogeneous and uniform materials. This technique allows the production of a material with very different characteristics within the same material at various interfaces. The importance of the FGM concept in biological applications and functions was highlighted. Fundamentally, the combination of mechanical properties and biocompatibility are very important factors in application of any biomaterial to medical or dental fields. The characteristics of the surface govern the biocompatibility of the material, and the mechanical strength is determined by the average mechanical strength of the materials. However, the fabrication of FGMs is most often hindered by the variation of elastic, plastic, thermal, chemical, and kinetic properties within the composite. Across a material interface, these discontinuities in material properties lead to the formation of residual stresses. Despite these challenges, compositional gradient structures offer significant benefits. Notable research literature is highlighted regarding (1) applications of alumina in various fields in dentistry; (2) improvement of the mechanical properties of alumina by microstructural manipulation, FGM as well as composite formulations involving metallic, intermetallic elements and bioceramics.

1. Introduction

Ceramics have a great potential in the biomedical field due to their compatibility with the physiological environment, their strength and wear resistance. Bioceramics (such as alumina, zirconia, Hap, etc.) is mainly used in orthopaedic and dental reparation. This review article will focus only on alumina...
for dental applications.

Alumina, also called Aluminium oxide, is the only solid oxide form of aluminium (Al₂O₃). It has been technologically significant ceramic material throughout human history. Alumina was first introduced in the 1970s, but early clinical applications showed a fracture rate as high as 13% [1]. Failure in this first generation of ceramics was due to the fact that they could not be processed to full final density. A second improved generation of ceramics, developed in the late 1980s, resulted in higher density and smaller grains. The fracture rate associated to the second generation of alumina decreased to less than 5% [2]. Finally, today a third generation of ceramic components is available, characterized by high purity, full density and finer microstructure. Mechanical properties and microstructure of biomedical grade alumina are given in Table 1 and Fig. (1).

In the last few decades, there have been remarkable advances in the mechanical properties and methods of fabrication of ceramic materials [3-5]. Therefore, this article is highlighted regarding the (i) application of alumina in various fields in dentistry; (ii) improvement of the mechanical properties of alumina by microstructural manipulation, FGM as well as composite formulations involving metallic, intermetallic elements and bioceramics.

### Table 1: Mechanical properties of biomedical grade alumina

<table>
<thead>
<tr>
<th>Mechanical Properties</th>
<th>Amount</th>
</tr>
</thead>
<tbody>
<tr>
<td>Density</td>
<td>3.97 g/cm³</td>
</tr>
<tr>
<td>Hardness</td>
<td>2200 Vickers</td>
</tr>
<tr>
<td>Bend strength</td>
<td>500 MPa</td>
</tr>
<tr>
<td>Compressive strength</td>
<td>4100 MPa</td>
</tr>
<tr>
<td>Fracture toughness</td>
<td>4 MPa/m¹/²</td>
</tr>
<tr>
<td>Young’s modulus</td>
<td>380 GPa</td>
</tr>
<tr>
<td>Thermal expansion coefficient</td>
<td>8x10⁻⁶ 1/K</td>
</tr>
</tbody>
</table>

![Fig. 1: Microstructure of alumina.](image)

However, despite its enviable properties and potential, its use as a structural material has been considerably hindered by its low-fracture strength and low-fracture toughness (as is typical of ceramics) [6-8]. Cracks readily propagate in ceramics. Thus, they fail unexpectedly in service, and in most cases, catastrophically, during impact even when the impact load is below the strength of the ceramic material. Resistance to crack growth lies in the ability to activate a toughening mechanism such as crack-bridging, deflection, or transformation toughening, among others. Researchers have utilized numerous formulations and processing methods aiming to improve the fracture toughness and other mechanical properties of alumina. These methods fall under two basic approaches: microstructural refinement and composite.

### 2. Microstructural Refinement of Alumina

Microstructural and morphological factors play leading roles in the improvement of properties of ceramic materials. For monolithic alumina, only elongated grains and high aspect ratio grains [9-10], as well as small grain sizes less than 4 µm and narrow grain size distribution, can lead to an improvement in fracture toughness and produce very low surface roughness. An increase in average grain size can lead to decrease in mechanical properties up to 20%. Rapid wear of bearing surfaces takes place in the case of large grain presence owing to grain pull out due to local dry friction. Thus, approximately 0.5% of MgO should be added to alumina, where it acts as inhibitor of debris by a factor of 10 or greater [11].

### 3. Alumina-Composite

Alumina-composite with other materials, ranging from metals, intermetallics to ceramics, can improve the mechanical properties of alumina. Yao et al. [12] experimented with spark-plasma sintering for the mending of an Al₂O₃-Ni nanocomposite. They reported that the fracture toughness was 3.84 MPa m¹/². Sekino et al. [13] prepared Al₂O₃-Ni nanocomposite by reducing and hot pressing Al₂O₃-NiO mixture under 30 MPa at 1450°C. They demonstrated that the fracture strength was over 1 GPa but the fracture toughness was only 3.5 MPa m¹/² for 5 vol% of Ni. Konopka [14] used 20 and 35 vol% Mo in the composite with an Al₂O₃ and recorded fracture toughness of 4.84 and 6.62 MPa m¹/² respectively. Lucchini et al. [15] reported the fracture toughness of 6, 9 and 12 MPa m¹/² for 15, 20, and 25 vol% Mo. They showed that Mo enhanced Al₂O₃-Mo composites fracture toughness. However, Diaz et al. [16] fabricated an Al₂O₃-Mo nanocomposite via the colloidal processing route. They recorded that the fracture toughness and the flexural strength were 6.26 MPa m¹/² and 700 MPa respectively for a Mo content of only 0.69 vol%. This was possible because the toughening mechanism activated in the Al₂O₃-Mo nanocomposite is not crack bridging or plastic deformation (due to the small size of the Mo nanoparticles), but it is a result of the stresses generated by the differential thermal expansion between alumina and Mo. Additionally, Trusty et al. [17] mixed 20 vol% of ductile iron particles into Al₂O₃ and reported that the fracture toughness of Al₂O₃-Fe composite reached to 10.90 MPa m¹/².
Some authors added intermetallic elements to achieve a combination of specific properties such as high ductility and strength. Sglavo et al. [18] fabricated an $\text{Al}_2\text{O}_3-\text{Ni}_3\text{Al}$ nanocomposite and reported that the fracture toughness was about 7 MPa m$^{1/2}$ at room temperature for a 10 vol% composite hot pressed at 1350°C. Gong et al. [19] prepared an $\text{Al}_2\text{O}_3-5$ vol% $\text{Fe}_3\text{Al}$ nanocomposite and reported that the bending strength and the fracture toughness were 832 MPa and 7.34 MPa m$^{1/2}$ respectively. These values reveal the potency of intermetallics for enhancing the fracture strength and the fracture toughness.

Others added ceramic composites such as SiC and zirconia to improve mechanical properties of alumina. These ceramic-ceramic composites generally possess the highest hardness of all composites. Unfortunately, most ceramic second phases that enhance hardness and strength only modestly enhance fracture toughness [20-21]. An $\text{Al}_2\text{O}_3-\text{SiC}$ nanocomposite has been reported to have the most improved properties [22]. SiC significantly increases the wear resistance of alumina. Doğan and Hawk [23] toughened alumina with 34 vol% SiC whiskers and reported a toughness increase of 35%, improving the toughness of monolithic alumina from 3.4 to 4.6 MPa m$^{1/2}$. However, Belmonte et al. [24] utilized 20 vol% SiC (4.5 mm) and showed that the fracture toughness reached to 5.9 MPa m$^{1/2}$.

Tuan et al. [25] incorporated zirconia particles into alumina and reported that the fracture toughness improved. Fracture strength and fracture toughness values as high as 943 MPa and 11.8 MPa m$^{1/2}$ have been recorded for Zirconia-Toughened Alumina (ZTA) containing 10 vol% zirconia. Toughness values of 10 MPa m$^{1/2}$ for 10 vol% zirconia [26] and 7.02 MPa m$^{1/2}$ for 50 vol% zirconia content have also been reported [27]. The microstructure of zirconia-toughened alumina is shown in Fig. (2).

Dental Application of Alumina

A great progress in dental restorations technique has been established by the use of ceramic materials since the 70’s. Alumina has been used in dental applications for fabrication of endodontic posts, orthodontic brackets, dental implants, crowns and bridges and in ceramic abutments. High-strength alumina ceramics are indicated in all areas of the mouth for copings and frameworks of full-coverage crowns and fixed prostheses [28]. It has been used to increase the strength of dental porcelains for more than 4 decades [29].

4.1. Orthodontic Brackets

Ceramic alumina-based brackets were also introduced in the 1980’s, offering many advantages over the traditional aesthetic appliances. They provide higher strength, more resistance to wear and deformation, better color stability and, most important to the patient, superior aesthetics as shown in Fig. (3). These brackets were composed one of two forms: monocrystalline or polycrystalline, depending on their distinct method of fabrication. The first brackets were milled from single crystals of sapphire using diamond tools [30]. These were closely followed by polycrystalline sapphire (alumina) brackets, which are manufactured and sintered using special binders to thermally fuse the particles together [31, 32].

4.2. Dental Implant

Alumina was also used as dental implant. Since 1970, numerous new implant materials and designs followed, including the use of polymers, porcelain, high-density aluminum oxide, bioactive glass and carbon.

In 1976, Schulte and Heimke introduced the Tübingen immediate implant, which could be used for immediate restoration of an extracted or lost tooth, and was made of an alumina ceramic material [33, 34]. Other investigations, utilizing various alumina implant systems, found less bone-implant contact compared to titanium [35], and reduced survival rates [36]. Osseointegrated dental implants have been used since the 80’s in rehabilitation of partially and totally edentulous patients [37]. The metallic abutments used in prosthetic restorations with implants compromise the aesthetic in some cases [38]. To minimize this problem, some implant systems developed ceramic abutments. To the knowledge of the authors, however, no alumina implant...
system is marketed anymore in these days. Recently, the Bioceram (single-crystal sapphire) implant was withdrawn from the market. Some investigations reported on early implant loss (no osseointegration occurred obviously) and others on implant fractures. The latter adverse event seemed to prevent dentists to use this ceramic implant material. When screening the literature, it was realized that no scientific investigations could be found dealing with the stability of alumina ceramic implants before its clinical use.

Recently, Takano et al. [39] reported that Ce-TZP/Al₂O₃ nanocomposite showed higher cyclic fatigue strength compared. They indicated that Ce-TZP/Al₂O₃ nanocomposite is promising material for use in dental implants.

4.3. Core Material for Fixed Prostheses

In 1982, McLean introduced the platinum-bonded alumina fixed partial dentures to reduce the problem of fracture through the connector area while eliminating the traditional cast metal framework. However, this restorative option demonstrated a high rate of failure at the connector sites [40]. Since then, developments in dental ceramics have led to the introduction of new high-strength ceramic core materials for all-ceramic fixed prostheses.

Studies have shown that glass-infiltrated alumina (In-Ceram®) has a flexural strength up to four times greater than that of conventional ceramics. The authors concluded that it seemed possible to make restorations with all-ceramic fixed prostheses in cases not only of anterior but also posterior tooth loss. They emphasized, however, that long-term follow-up studies were necessary to establish the advisability of such a procedure [41-46]. The microstructural of glass-infiltrated alumina (In-Ceram®) is shown in Fig. (4).

![Fig. 4: Scanning electron micrograph showing traverse section of glass-infiltrated alumina VITA In-Ceram.](image)

Other authors densely sintered high-purity alumina (Procera® All-Ceram) as core materials. They measured, using various types of tests, the flexural strength of the framework material and demonstrated that the flexural strength range between 487 to 699 MPa [47-48]. For this core material, the fracture toughness ranges between 4.48 and 6 MPam½ [47]. Other combined 35% partially stabilized zirconia with the glass-infiltrated alumina for the core material. The results of various types of tests measuring the flexural strength of the core material have been reported to range from 421 to 800 MPa [49-50]. For the glass-infiltrated zirconia/alumina core material, the fracture toughness ranges between 6 and 8 MPam½ [49-51]. The microstructural of Procera Crown is shown in Fig. (5).

![Fig. 5: Microstructural of Procera Crown [52].](image)

Another all-ceramic system based on alumina employs a technique where high purity alumina crown copings or fixed prostheses cores are fabricated using computer-aided design/computer-aided manufacturing (CAD/CAM) techniques [53]. Subsequently, the alumina substructures are densely sintered and veneered with dental porcelain. Clinical studies have indicated that such alumina-based crowns may be used for crowns in all locations of the oral cavity [54]. The system includes a technique for producing all-ceramic fixed prostheses. This technique combines alumina copings with an alumina pontic that is joined to the copings using a specially formulated connecting and fusing material [55]. The glass added to alumina can increase toughness and strength of such composite, because the crack cannot pass through the alumina particles as easily as it can pass through the glass matrix [56]. The amount of toughening depends on the crystal type, its size, its volume fraction, the inter particle spacing, and its relative thermal expansion coefficient to the glass matrix. In most instances, the use of a dispersed crystalline phase to disrupt crack propagation requires a close match between the thermal contraction coefficients of the crystalline material and the surrounding glass matrix [56].

Borba et al. [57] predicted the reliability of an alumina-based dental core subjected to a mechanical aging test. They found the aging was effective to reduce alumina ceramic strength as predicted by the reliability estimate, confirming the study hypothesis. Zhao et al. [58] evaluated the shear bond strength between alumina-toughened zirconia (ATZ) cores and veneering ceramics. They found that the shear bond strength between the ATZ core and the veneering ceramics was not affected by aging. Fukushima
et al. [59] compared the residual stress in the veneering ceramic layered on three different polycrystalline ceramic framework materials: Y-TZP, alumina polycrystal (AL) and zirconia toughened alumina (ZTA). Y-TZP samples exhibited a less favorable stress profile than those of AL and ZTA samples.

Cehreli et al. [60] compared the outcome of feldspathic porcelain with glass-infiltrated alumina all-ceramic crowns. They found that feldspathic and glass-infiltrated alumina all-ceramic crowns placed predominantly in the anterior portion have comparable biologic and prosthetic outcomes, as well as survival probabilities.

Rinke et al. [61] evaluated the long-term performance of conventionally luted In-Ceram® crowns with a maximum follow-up period of 18.6 years. They found that survival and success rates of anterior In-Ceram® crowns at 15 years. Galindo et al. [62] estimated the long-term survival of alumina crowns in anterior and posterior areas over an observation period of up to 10 years. The results suggest that the expected 10-year survival rate of alumina crowns due to technical failures. Selz et al. [63] investigated the 5-year performance of In-Ceram® alumina posterior crowns cemented with three different luting cements. They reported that posterior In-Ceram® alumina crowns showed acceptable long-term survival and success rates independent of luting agent used. Kim et al. [64] studied the long-term clinical survival and complication rates of alumina-toughened zirconia abutments used for implant-supported restorations. They stated that alumina-toughened zirconia abutments exhibited excellent long-term survival in clinical use for fixed restorations.

4.4. Filler for the Dental Composites and Bone Cement Materials

A few studies have been published with respect to the alumina/Bis-GMA composites for bone cement applications, in which the size of alumina powder is about 10 µm [65-66]. In comparison with conventional bone cement material, PMMA mixed with hydroxyapatite powder; alumina/Bis-GMA composites exhibit superior mechanical properties and osteoconductivity. Shinzato et al. [66] also compared the silica/Bis-GMA composites and alumina/Bis-GMA composites, the latter of which have better osteoconductivity, characteristic of the much more bone formed directly opposed to the composite surface. This shows that alumina has excellent biocompatibility.

More recently, alumina is also used as filler for reinforcing the dental restorative composite. Alumina filler with higher elastic modulus (370 GPa) is benefit to reinforce the dental composites. The elastic modulus and strength of composites can be increased with relatively low volume fractions compared to the counterparts reinforced with silica glass. Therefore, use of ultra-stiff filler materials such as alumina, especially in nanoscale size, appears a viable strategy to improving the elastic properties of dental composites [67].

5. Future Opportunities in Functionally Graded Materials (FGM)

The concept of functionally graded materials (FGMs) is a new material design approach to improve performance compared to traditional homogeneous and uniform materials [68].

Ceramics typically exhibit high hardness, low density and weight, brittleness, and excellent high-temperature fracture, creep, corrosion, radiation, wear, and thermal shock resistance. On the other hand, metals are typically ductile, have high tensile strength, high toughness, and high density. Metal-ceramic FGMs can also be designed to take advantage of the heat and corrosion resistance of ceramics and the mechanical strength of metals [69-72].

FGMs are a new generation of engineered materials that have become of much interest in recent years. The graded materials are ideal candidates for various applications ranging from functional and structural materials. The microstructure of the FGMs is shown in Fig. (6). The microstructure depended on the volume fractions of each composite material; the final structure has a different appearance that can easily be compared to the adjacent layers. The microstructure of sintered FGM varied gradually from one side to other side with the diversification of chemical compositions as shown in Fig. (7).

Fig. 6: Microstructure of FG Al₂O₃-Lanthanum Hexaaluminate [73]

Fig. 7: Microstructure of FG Al₂O₃-HA-Ti [74]
Development of implants based on biocompatible FGMs for medical and dental applications has been emphasized [69-89]. The development of FGM concept had its origin in the sophisticated properties which arise from materials in nature, such as teeth [90] and bones [91].

For instance, the design of a bone with a change from dense, stiff external structure (the cortical bone) to a porous internal one (the cancellous bone) demonstrates that functional gradation has been utilized by biological adaptation [91]. Thus, optimized structure for an artificial implant should show similar gradation. The same trend has been observed in the development of FG dental implants with the introduction of surface coatings, porosity gradients and composite materials made essentially of metal and ceramics (e.g. hydroxyapatite), which aimed to improve the implant performance in terms of biocompatibility and stress distribution [92-93].

He and Swain [90] investigated the nanoindentation mechanical behaviour of the inner and outer regions of human enamel. They reported that inner enamel has lower stiffness and hardness but higher creep and stress redistribution abilities than their outer counterpart. They attributed this observation to the gradual compositional change throughout the enamel from the outer region near the occlusal surface to the inner region near EDJ. They suggested that enamel can be regarded as a FG natural biocomposite.

Natural teeth are composed by layered structures, dentin and enamel, that are bonded by a FG dentin-enamel junction (DEJ) layer that is about 10-100 micrometers thick [94-95]. The DEJ acts as a bridge between the hard brittle enamel (E~70GPa) and the softer durable dentin layer (E~20GPa), allowing a smooth Young modulus transition between the two structures [96].

A new tailored zirconia–mullite/alumina as FG ceramics was designed and synthesized by reaction sintering of zircon and alumina. Results showed that the tailored zirconia–mullite/alumina as FG ceramics gave continuous homogenous structure with highly improved physical, mechanical and thermal properties [97].

Abu Kasim et al. [98] patented three types of multilayered composite materials that were produced using powders of zirconia (ZrO$_2$), alumina (Al$_2$O$_3$), hydroxyapatite (HA), and titanium (Ti) to develop newly designed FG dental posts. Likewise, Abu Kasim et al. [99] also investigated the stress distribution of newly designed FG dental posts which consisted of multilayer design of Al$_2$O$_3$-Ti-HA and compared it to posts fabricated from homogeneous material such as titanium and zirconia. They reported that this new dental post exhibited several advantages in terms of stress distribution compared to posts fabricated from homogeneous material. The stress and strain distribution at the post-dentin interface of FG dental posts was better than that of homogenous posts.

6. Conclusion

Recent progress in the synthesis, characterization, and improvement in mechanical properties of alumina-based materials for dental applications is reviewed. Although there were major recent developments and improvements in this field, further studies are needed to assess the properties of the involved materials. These developments in alumina, an especially alumina composites, may hopefully improve the function and longer life span in their clinical uses.

References


