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Alumina ceramic for dental applications: A review article

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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 (Al_2O_3). 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*

Mechanical Properties	Amount
Density	3.97 g/cm^3
Hardness	2200 Vickers
Bend strength	500 MPa
Compressive strength	4100 MPa
Fracture toughness	4 MPa/m$^{1/2}$
Young's modulus	380 GPa
Thermal expansion coefficient	8x10^{-6} 1/K

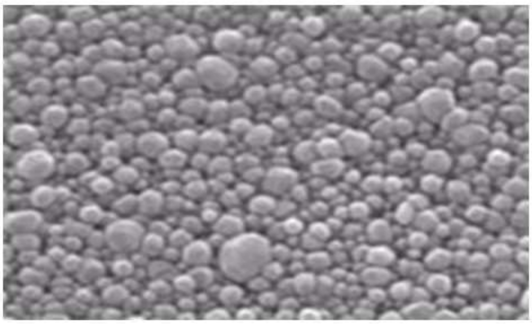

Fig. 1: *Microstructure of alumina.*

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 Al_2O_3-Ni nanocomposite. They reported that the fracture toughness was 3.84 MPam½. Sekino et al. [13] prepared Al_2O_3-Ni nanocomposite by reducing and hot pressing Al_2O_3-NiO mixture under 30 MPa at 1450^oC. They demonstrated that the fracture strength was over 1 GPa but the fracture toughness was only 3.5 MPam½ for 5 vol% of Ni. Konopka [14] used 20 and 35 vol% Mo in the composite with an Al_2O_3 and recorded fracture toughness of 4.84 and 6.62 MPam½ respectively. Lucchini et al. [15] reported the fracture toughness of 6, 9 and 12 MPam½ for 15, 20, and 25 vol% Mo. They showed that Mo enhanced Al_2O_3-Mo composites fracture toughness. However, Díaz et al. [16] fabricated an Al_2O_3-Mo nanocomposite via the colloidal processing route. They recorded that the fracture toughness and the flexural strength were 6.26 MPam½ and 700 MPa respectively for a Mo content of only 0.69 vol%. This was possible because the toughening mechanism activated in the Al_2O_3-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 Al_2O_3 and reported that the fracture toughness of Al_2O_3-Fe composite reached to 10.90 MPam½.

Some authors added intermetallic elements to achieve a combination of specific properties such as high ductility and strength. Sglavo et al. [18] fabricated an Al_2O_3-Ni_3Al nanocomposite and reported that the fracture toughness was about 7 MPam½ at room temperature for a 10 vol% composite hot pressed at 1350°C. Gong et al. [19] prepared an Al_2O_3-5 vol% Fe_3Al nanocomposite and reported that the bending strength and the fracture toughness were 832 MPa and 7.34 MPam½ 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]. Al_2O_3-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 MPam½. However, Belmonte et al. [24] utilized 20 vol% SiC (4.5 mm) and showed that the fracture toughness reached to 5.9 MPam½.

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 MPam½ have been recorded for Zirconia-Toughened Alumina (ZTA) containing 10 vol% zirconia. Toughness values of 10 MPam½ for 10 vol% zirconia [26] and 7.02 MPam½ for 50 vol% zirconia content have also been reported [27]. The microstructure of zirconia-toughened alumina is shown in Fig. (2).

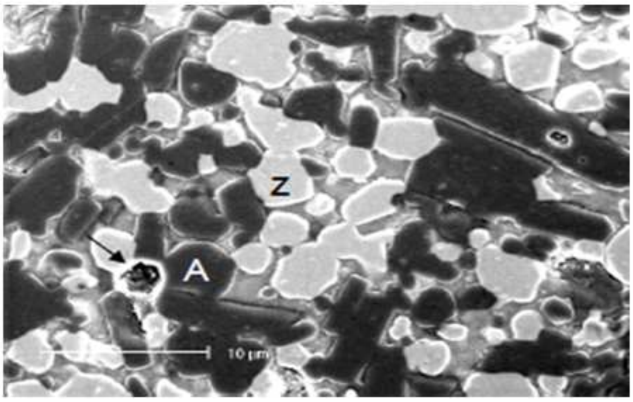

Fig. 2: *Microstructure of zirconia-toughened alumina. A: alumina grains, Z: zirconia grains, Arrow indicates pore [5]*

4. 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].

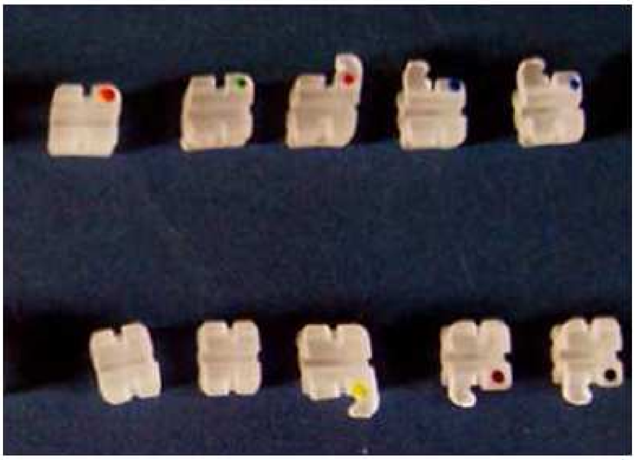

Fig. 3: *Ceramic alumina-based brackets*

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/Al_2O_3 nanocomposite showed higher cyclic fatigue strength compared. They indicated that Ce-TZP/Al_2O_3 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).

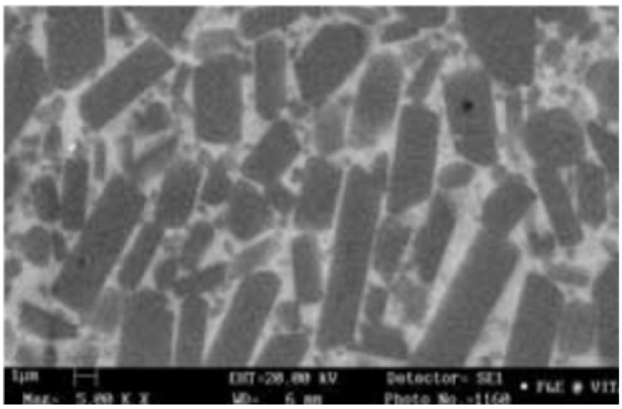

Fig. 4: *Scanning electron micrograph showing traverse section of glass-infiltrated alumina VITA In-Ceram.*

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).

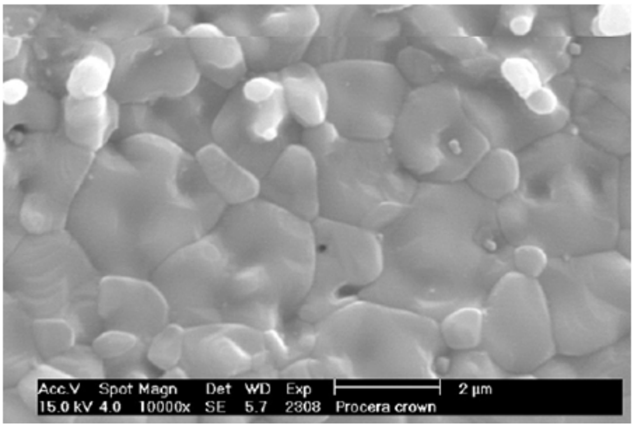

Fig. 5: *Microstructural of Procera Crown [52].*

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).

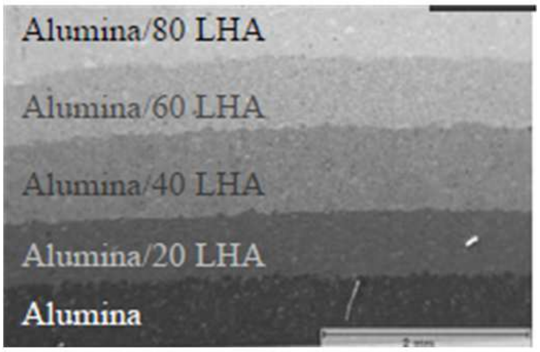

Fig. 6: *Microstructure of FG Al_2O_3-Lanthanum Hexaaluminate [73]*

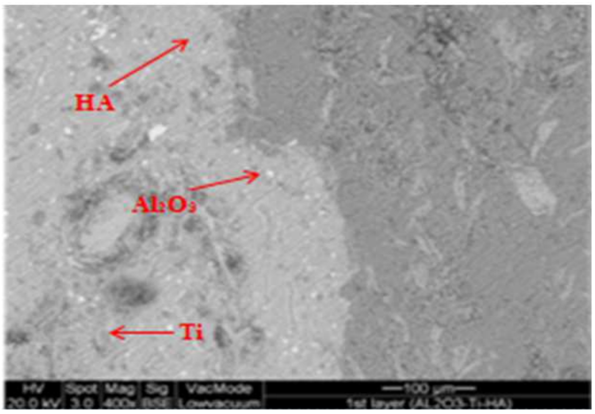

Fig. 7: *Microstructure of FG Al_2O_3-HA-Ti [74]*

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 cancelous 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_2O_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_2O_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

[1] Willmann G. Ceramic femoral heads retrievals data, Clinical Orthopedics, 2000; 379: 173-177.

[2] Willmann G and Von Chamier W. Bioceramics in orthopedics: New applications. Stuttgart, Germany, Enke Verlag, 1998.

[3] Lawson NC, Burgess JO. Dental ceramics: A current review. Compend Contin Educ Dent, 2014.

[4] Shenoy A, Shenoy N. Dental ceramics: An update. J Conserv Dent, 2010; 13: 195-203.

[5] Denry I, Holloway JA. Ceramics for dental applications: A review. Materials, 2010; 3: 351-368.

[6] Chen RZ and Tuan WH. Toughening alumina with silver and zirconia inclusions. J Eur Ceram Soc, 2001; 21:2887-2893.

[7] Miyazaki H, Yoshizawa Y and Hirao K. Preparation and mechanical properties of 10 vol.% zirconia/alumina composite with fine-scale fibrous microstructure by co-extrusion process. Mater Lett, 2004; 58:1410-1414.

[8] Liu C, Zhang J, Sun J and Zhang X. Addition of Al-Ti-B master alloys to improve the performances of alumina matrix ceramic materials. Ceram Int, 2007; 33:1319-1324.

[9] Kovar D, Bennison SJ and Readey MJ. Crack stability and strength variability in alumina ceramics with rising toughness-curve behavior. Acta mater, 2000; 48: 565-578.

[10] Xu L, Xie Z, Gao L, Wang X, Lian F, Liu T and Li W. Synthesis, evaluation and characterization of alumina ceramics with elongated grains. Ceram Int, 2005; 31:953-958.

[11] Bragdon CR, Jasty M, Kawate K, McGrory BJ, Elder JR, Lowenstein J and Harris WH. Wear of retrieved cemented polyethylene acetabular with alumina femoral heads. J Arthroplasty, 1997; 12:119-125.

[12] Yao X, Huanga Z, Chen L, Jiang D, Tan S, Michel D, Wang G, Mazerolles L and Pastol J-L. Alumina-nickel composites densified by spark plasma sintering. Mater Lett, 2005; 59:2314-2318.

[13] Sekino T, Nakajima T and Niihara K. Mechanical and magnetic properties of nickel dispersed alumina-based nanocomposite. Mater Lett, 1996; 29: 165-169.

[14] Konopka K, Maj M and Owski JK. Studies of the Effect of metal particles on the fracture toughness of ceramic matrix composites. Mater Characterization, 2003; 51:335-340.

[15] Lucchini E, Lo Casto S and Sbaizero O. The performance of molybdenum toughened alumina cutting tools in turning a particulate metal matrix composite. Mater Sci Eng A, 2003; 357:369-375.

[16] Díaz LA, Valdés AF, Díaz C, Espino AM and Torrecillas R. Alumina/molybdenum nanocomposites obtained in organic media. J Eur Ceram Soc, 2003; 23:2829-2834.

[17] Trusty PA and Yeomans JA. The toughening of alumina with iron: effects of iron distribution on fracture toughness. J Eur Ceram Soc, 1997; 17:495-504.

[18] Sglavo VM, Marinob F and Zhang B-R. The Preparation and mechanical properties of Al_2O_3/Ni3Al composites. Comp Sci Technol, 1999; 59:1207-1212.

[19] Gong H, Yin Y, Fan R and Zhang J. Mechanical properties of in-situ toughened Al_2O_3/Fe3Al. Mater Res Bull, 2003; 38:1509-1517.

[20] Pillai SKC, Baron B, Pomeroy MJ and Hampshire S. Effect of oxide dopants on densification, microstructure and mechanical properties of alumina-silicon carbide nanocomposite ceramics prepared by pressureless sintering. J Eur Ceram Soc, 2004; 24: 3317-3326.

[21] Lu H-X, Sun H-W, Li G-X, Chen C-P, Yang D-I and Hu X. Microstructure and mechanical properties of Al_2O_3-MgB2 composites. Ceram Int, 2005; 31:105-108.

[22] Carroll L, Sternitzke M and Derby B. Silicon carbide particle size effects in alumina-based nanocomposites. Acta Mater, 1996; 44:4543-4552.

[23] Doğan CP and Hawk JA. Influence of whisker reinforcement on the abrasive wear behavior of silicon nitride and alumina-based composites. Wear, 1997; 203-204:267-277.

[24] Belmonte M, Nieto MI, Osendi MI and Miranzo P. Influence of the SiC grain size on the wear behaviour of Al_2O_3/SiC composites. J Eur Ceram Soc, 2006; 26:1273-1279.

[25] Tuan WH, Chen RZ, Wang TC, Cheng CH and Kuo PS. Mechanical properties of Al_2O_3/ZrO_2 composites. J Eur Ceram Soc, 2002; 22:2827-2833.

[26] Wang YS, He C, Hockey BJ, Lacey PI and Hsu SM. Wear transitions in monolithic alumina and zirconia-alumina composites. Wear, 1995; 181-183, Part 1: 156-164.

[27] Huang XW, Wang SW and Huang XX. Microstructure and mechanical properties of ZTA fabricated by liquid phase sintering. Ceram Int, 2003; 29:765-769.

[28] Blatz MB. Long-term clinical success of all-ceramic posterior restorations. Quintessence Int, 2002; 33:415-426.

[29] McLean JW. The Nature of dental ceramics and their clinical use. In: The science and art of dental ceramics. Quintessence Publishing Co., Inc. Chicago: USA; 1979.

[30] Swartz ML. Ceramic brackets. J Clin Orthod, 1988; 22:82-88.

[31] Kusy RP. Morphology of polycrystalline alumina brackets and its relationship to fracture toughness and strength. Angle Orthod, 1988; 58:197-203.

[32] Saunders CR and Kusy RP. Surface topography and frictional characteristics of ceramic brackets. Am J Orthod Dentofacial Orthop, 1994; 106:76-87.

[33] Schulte W and Heimke G. The Tübinger immediate implant. Quintessenz, 1976; 27:17- 23.

[34] Schulte W. The intraosseous Al_2O_3 (Frialit) Tüebingen implant. Developmental status after eight years (I-III). Quintessence Int, 1984; 15:1-39.

[35] Steflik DE, Lake FT, Sisk AL, Parr GR, Hanes PJ, Davis HC, Adams BO and Yavari J. A comparative investigation in dogs: 2-year morphometric results of the dental implant-bone interface. Int J Oral Maxillofac Implants, 1996; 11:15-25.

[36] Berge TI and Grønningsaeter AG. Survival of single crystal sapphire implants supporting mandibular overdentures. Clin Oral Implants Res, 2000; 11:154-162.

[37] Brånemark PI, Zarb GA and Albrektsson T. Tissue-integrated prostheses: osseointegration in clinical dentistry. Quintessence Verlags–GmbH: Berlin; 1987.

[38] Sadoun M and Perelmuter S. Alumina-zirconia machinable abutments for implant-supported single-tooth anterior crowns. Pract Periodontics Aesthet Dent, 1997; 9:1047-1053.

[39] Takano T, Tasaka A, Yoshinari M, Sakurai K. Fatigue strength of Ce-TZP/Al_2O_3 nanocomposite with different surfaces. J Dent Res, 2012; 91:800-4.

[40] McLean JW. Alumina reinforced ceramics special applications. In: The science and art of dental ceramics. Vol. 2: Bridge design and laboratory procedures in dental ceramics. Chicago: Quintessence; 1982.

[41] Pröbster L and Diehl J. Slip-casting alumina ceramics for crown and bridge restorations. Quintessence Int, 1992; 23:25-31.

[42] Wen MY, Mueller HJ, Chai J and Wozniak WT. Comparative mechanical Property characterization of 3 all-ceramic core materials. Int J Prosthodont, 1999; 12:534-541.

[43] Wall JG and Cipra DL. Alternative crown systems. Is the metal-ceramic crown always the restoration of choice? Dent Clin North Am, 1992; 36:765-782.

[44] Seghi RR and Sorensen JA. Relative flexural strength of six new ceramic materials. Int J Prosthodont, 1995; 8:239-246.

[45] Giordano RA, Pelletier L, Cambell S and Pober R. Flexural strength of an infused ceramic, glass ceramic and feldspathic porcelain. J Prosthet Dent, 1995; 73:411-418.

[46] Neiva G, Yaman P, Dennison JB, Razzoog ME and Lang BR. Resistance to fracture of three All-Ceramic systems. J Esthetic Dent, 1998; 10:60-66.

[47] Wagner WC and Chu TM. Biaxial flexural strength and indentation fracture toughness of three new dental core ceramics. J Prosthet Dent, 1996; 76:140-144.

[48] Zeng K, Odén A and Rowcliffe D. Flexure tests on dental ceramics. Int J Prosthodont, 1996; 9:434-439.

[49] McLaren EA and White SN. Glass-infiltrated zirconia/alumina-based ceramic for crowns and fixed partial dentures: clinical and laboratory guidelines. Quintessence Dental Technol, 2000; 23:63-76.

[50] Guazzato M, Albakry M, Swain MV and Ironside J. Mechanical properties of in-ceram alumina and in-ceram zirconia. Int J Prosthodont, 2002; 15:339-346.

[51] Chong KH, Chai J, Takahashi Y and Wozniak W. Flexural strength of In-Ceram alumina and In-Ceram zirconia core materials. Int J Prosthodont, 2002; 15:183-188.

[52] Giordano R, McLaren EA. Ceramics Overview: Classification by Microstructure and Processing Methods. Compend Contin Educ Dent, 2010; 31: 682-697.

[53] Andersson M and Odén A. A new all-ceramic crown. A dense-sintered, high-purity alumina coping with porcelain. Acta Odontol Scand, 1993; 1:59-64.

[54] Odman P and Andersson B. Procera All-Ceram crowns followed for 5 to 10.5 years: a prospective clinical study. Int J Prosthodont, 2001; 14:504-509.

[55] Lang BR, Maló P, Guedes CM, Wang R-F, Kang B, Lang LA and Razzoog ME. Procera All-Ceram bridge. Appl Osseointegration Res, 2004; 4:13-21.

[56] Jones DW. The strength and strengthening mechanisms of dental ceramics. In: 1st international symposium on dental ceramics proceedings (McLean JW ed.), Chicago: Quintessence Publication Co., 96-98 and 110-116; 1983.

[57] Borba M, Cesar PF, Griggs JA, Della Bona A. Step-stress analysis for predicting dental ceramic reliability. Dent Mater. 2013; 29:913-8.

[58] Zhao YQ, Li J, Zhang JC, Liao YM, Lu JJ, Li W. Shear bond strengths between alumina-toughened zirconia cores and veneering ceramics and their susceptibility to aging. Asian Pac J Trop Med, 2012; 5: 402-5.

[59] Fukushima KA, Sadoun MJ, Cesar PF, Mainjot AK. Residual stress profiles in veneering ceramic on Y-TZP, alumina and ZTA frameworks: measurement by hole-drilling. Dent Mater, 2014; 30:105-11.

[60] Cehreli MC, Kokat AM, Ozpay C, Karasoy D, Akca K. A randomized controlled clinical trial of feldspathic versus glass-infiltrated alumina all-ceramic crowns: a 3-year follow-up. Int J Prosthodont, 2011; 24:77-84.

[61] Rinke S, Tsigaras A, Huels A, Roediger M. An 18-year retrospective evaluation of glass-infiltrated alumina crowns. Quintessence Int, 2011; 42: 625-33.

[62] Galindo ML, Sendi P, Marinello CP. Estimating long-term survival of densely sintered alumina crowns: a cohort study over 10 years. J Prosthet Dent. 2011; 106:23-8.

[63] Selz CF, Strub JR, Vach K, Guess PC. Long-term performance of posterior InCeram Alumina crowns cemented with different luting agents: a prospective, randomized clinical split-mouth study over 5 years. Clin Oral Investig. 2013 Nov 22.

[64] Kim SS, Yeo IS, Lee SJ, Kim DJ, Jang BM, Kim SH, Han JS. Clinical use of alumina-toughened zirconia abutments for implant-supported restoration: prospective cohort study of survival analysis. Clin Oral Implants Res, 2013; 24:517-22.

[65] Shinzato S, Kobayashi M, Choju K, et al. Bone-bnding behavior of alumina bead composite. J Biomed Mater Res, 1999; 46: 287-300.

[66] Kobayashi M, Shinzato S, Kawanabe K, et al. Alumina powder/Bis-GMA composite: Effect of filler content on mechanical properties and osteoconductivity. J Biomed Mater Res, 2000; 49: 319-327.

[67] Thorat S, Diaspro A, Salerno M. Effect of alumina reinforcing fillers in BisGMA-based resin composites for dental applications. Adv Mater Lett, 2013: 4:15-21.

[68] Watanabe Y, Kawamoto A, Matsuda K. Particle size distributions in functionally graded materials fabricated by the centrifugal solid-particle method. Comp Sci Tech, 2002; 62: 881-88.

[69] Watari F, Yokoyama A, Omori M, et al. Biocompatibility of materials and development to functionally graded implant for bio-medical application. Comp Sci Tech, 2004; 64: 893-908.

[70] Hedia HS, Mahmoud NA. Design optimization of functionally graded dental implant. Biomed Mater Eng, 2004; 14: 133-43.

[71] Hedia HS. Design of functionally graded dental implant in the presence of cancellous bone. J Biomedical Mater Res B: Applied Biomater, 2005; 75: 74-80.

[72] Hedia HS. Effect of cancellous bone on the functionally graded dental implant concept. Biomed Mater Eng, 2005; 15: 199-209.

[73] Negahdari Z, Willert-Porada M, Scherm F. Development of novel functionally graded al2o3-lanthanum hexaaluminate ceramics for thermal barrier coatings. Mater Sci Forum, 2010; 631-632: 97-102.

[74] Madfa AA. Development of functionally graded composite for fabrication of dental post. PhD Thesis, University Malaya, 2011.

[75] Huang M, Rahbar N, Wang R, et al. Bioinspired design of dental multilayers. Mater Sci Eng A, 2007; 464: 315-20.

[76] Wang F, Lee HP, Lu C. Thermal-mechanical study of functionally graded dental implants with the finite element method. J Biomedical Mater Res A, 2007; 80: 146-58.

[77] Yang J, Xiang H-J. Three-dimensional finite element study on the biomechanical behavior of an FGBM dental implant in surrounding bone. J Biomech, 2007; 40: 2377-85.

[78] Rahbar N, Soboyejo WO. Design of functionally graded dental multilayers. Fatig Fract Eng Mater Struct, 2011; 34: 887-97.

[79] Niu X, Rahbar N, Farias S, et al. Bio-inspired design of dental multilayers: experiments and model. J Mech Behav Biomed Mater, 2009; 2: 596-602.

[80] Sadollah A, Bahreininejad A. Optimum gradient material for a functionally graded dental implant using metaheuristic algorithms. J Mech Behav Biomed Mater, 2011; 4:1384-95.

[81] Sandukas S, Yamamoto A, Rabiei A. Osteoblast adhesion to functionally graded hydroxyapatite coatings doped with silver. J Biomed Mater Res A, 2011; 97:490-7.

[82] Mehrali M, Shirazi FS, Mehrali M, Metselaar HS, Kadri NA, Osman NA. Dental implants from functionally graded materials. J Biomed Mater Res A, 2013; 101:3046-57.

[83] Lin WS, Starr TL, Harris BT, Zandinejad A, Morton D. Additive manufacturing technology (direct metal laser sintering) as a novel approach to fabricate functionally graded titanium implants: preliminary investigation of fabrication parameters. Int J Oral Maxillofac Implants, 2013; 28: 1490-5.

[84] Al-Sanabani JS, Madfa AA, Al-Sanabani FA. Application of calcium phosphate materials in dentistry. Int J Biomater, 2013; 2013: 876132.

[85] He LH, Yin ZH, van Vuuren LJ, Carter EA, Liang XW. A natural functionally graded biocomposite coating--human enamel. Acta Biomater, 2013; 9:6330-7.

[86] Du J, Niu X, Rahbar N, Soboyejo W. Bio-inspired dental multilayers: effects of layer architecture on the contact-induced deformation. Acta Biomater, 2013; 9:5273-9.

[87] Henriques B, Gonçalves S, Soares D, Silva FS. Shear bond strength comparison between conventional porcelain fused to metal and new functionally graded dental restorations after thermal-mechanical cycling. J Mech Behav Biomed Mater, 2012; 13:194-205.

[88] Family R, Solati-Hashjin M, Namjoy Nik S, Nemati A. Surface modification for titanium implants by hydroxyapatite nanocomposite. Caspian J Intern Med, 2012 Summer; 3: 460-5.

[89] Ren L and Zhang Y. Sliding contact fracture of dental ceramics: Principles and validation. Acta Biomater, 2014 Mar 12.

[90] He LH, Swain MV. Enamel—A functionally graded natural coating. J Dent, 2009; 37: 596-603.

[91] Pompe W, Worch H, Epple M, et al. Functionally graded materials for biomedical applications. Mater Sci Eng A, 2003; 362:40–60.

[92] Marshall Jr GW, Balooch M, Gallagher RR, et al. Mechanical properties of the dentinoenamel junction: AFM studies of nanohardness, elastic modulus, and fracture. J Biomed Mater Res A, 2001; 54: 87-95.

[93] Lin D, Li Q, Li W, et al. Design optimization of functionally graded dental implant for bone remodeling. Comp Part B, 2009; 40:668-675.

[94] Sadollah A, Bahreininejad A. Optimum gradient material for a functionally graded dentalimplant using metaheuristic algorithms. J Mech Behav Biomed Mater, 2011; 4:1384-1395.

[95] Lin CP, Douglas WH, Erlandsen SL. Scanning electron microscopy of type I collagen at the dentin-enamel junction of human teeth. J Histochem Cytochem, 1993; 41: 381-388.

[96] Francis LF, Vaidya KJ, Huang HY, et al. Design and processing of ceramicbased analogs to the dental crown. Mater Sci Eng C, 1995; 3: 63-74.

[97] Ewais EMM, Besisa DHA, Zaki ZI. Tailoring of functionally graded zirconia–mullite/alumina ceramics. J Eur Ceram Soci, 2012; 32:1561-1573.

[98] Abu Kasim NH, Madfa AA, Abd Shukor MH, et al. Metal-ceramic dental post. Patent no. WO2013043039 (A2), 2013.

[99] Abu Kasim NH, Madfa AA, Abd Shukor MH, et al. FE Analysis of functionally graded structured dental posts. Dent Mater J, 2011; 30: 869-880.