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An Overview of the Development and Strengthening of All-Ceramic Dental Materials

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High-strength all-ceramic systems for fixed partial dentures (FPDs) are necessary for replacing missing teeth. The ability to fabricate a restoration outside the mouth and subsequently integrate it with a tooth extends the range of materials available to be utilized by a dentist. This article presents a review of the development of all-ceramic restorations, including the evolution and development of materials, technologies and how to improve the strength of all-ceramic restorations, with respect to survival, applications, strength, color, and aesthetics. New core/framework materials have developed and evolved over the last decade because of the growth of ceramic materials and systems currently available for utilization. A search of English language reviewed literature was undertaken, which focused on the evidence-based published research articles. This review also elucidates the various all-ceramic materials and systems currently available for clinical use, and that no single universal material or system exists for all clinical cases. Successful implementation depends on the clinicians, materials, manufacturing techniques, and individual clinical condition. Further longitudinal clinical studies are recommended for the development of ceramic materials and systems.

Keywords: All-ceramic materials; CAD/CAM system;
Aluminum oxide; Ceramic strengthening, Aesthetic.

Ceramic materials are rapidly progressed for a wide range of applications. The term ceramic is defined as a highly crystalline solids derived from nonmetallic raw materials which is fabricated by firing at a high temperature to achieve the desirable properties[1]. Most ceramics are characterized by their chemical inertness and biocompatibility, superior hardness, excellent wear resistance, susceptibility to tensile fracture, and low to moderate fracture toughness[2].

In the early 1700s, many European governors spent massive funds by importing porcelains from China and Japan with over three million pieces of Chinese porcelain arrived in Europe between 1604 and 1657[3]. In dentistry, ceramic was first introduced as restorative materials in the late 1700s, taking advantage that they can replicate the shape and color of the natural dentition. Later around 1710, Böttger introduced feldspar as the flux in Chinese porcelains. This

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feldspathic glass later became the main ingredient in aesthetic porcelain formulations in dentistry[4]. In 1808, a Parisian dentist (Fonzi) significantly improved the applicability of porcelain teeth by attaching a platinum pin to each denture tooth. This invention facilitated the fixture of teeth to metal frameworks which, in turn, enabled partial denture fabrication, improved aesthetics and repair processes[2]. In 1817, Planteau a French dentist introduced porcelain teeth to the United States through an artist, which subsequently developed the commercial production of porcelain teeth in 1825 by Stockton. In England, an Ash company processed an improved version of porcelain teeth in 1837. Two years later Pfaff from Germany developed a technique that allowed the porcelain teeth to be used effectively in denture base construction in 1839[2].

In 1903, Land fabricated one of the first ceramic crowns consisting of high-fusing feldspathic porcelain baked on a thin platinum foil. These porcelain crowns showed good aesthetic properties, but low flexural strength resulting in a higher incidence of clinical failures[5, 6]. Afterwards feldspathic porcelains with reliable chemical bonding were used in metal ceramic restorations for more than 50 years[2]. Metal-ceramic systems were the first system developed in 1962 that used approximately 17–25 wt% of leucite-containing feldspathic porcelain to avoid poor matches in the coefficient of thermal expansion between the metal framework and veneering ceramic[7].

In 1965, McLean and Hughes used a glass matrix core comprising of 40 to 50 wt% Al_2O_3 to fabricate the first all-ceramic porcelain jacket crown (alumina-reinforced core ceramic). The aluminous ceramic core material did not possess adequate translucency (opaque, chalky-white appearance), which led to the additional veneer of feldspathic porcelain to achieve acceptable aesthetics. The flexural strength of this core material was low, i.e. approximately 131 MPa which limited their application in the anterior teeth[8, 9]. Castable ceramics (Dicor) were later developed by Grossman in 1972 at corning glass works[10] and the commercially available Dicor (Dentsply International, Inc., York, PA, USA) was released to the dental community in 1984[11]. Dicor is a highly translucent polycrystalline glass–ceramic material composed of 70% tetrasilicic fluormica crystals incorporated with 30% glass matrix[12]. It shows high translucency, high chemical resistance, moderate thermal expansion, good machinability, the hardness similar to natural dentition, and low flexural strength (150 MPa), which thus limits its application for a single crown restoration[11, 13].

The introduction of computer-aided design/computer-aided manufacturing (CAD/CAM) technology to restorative dentistry was carried out in the Cerec system (Sirona, Bensheim, Germany) and developed in 1982. CAD/CAM systems are used in the fabrication of ceramic onlays, inlays, veneers, and crowns[14].

In-Ceram system was introduced for the first all-ceramic core materials for crowns and three-unit anterior fixed partial dentures (FPDs) in the Europe market in 1989[15]. This system was developed by the French dental material scientist Michael Sadoun based on the glass infiltration of partially sintered porous aluminum oxide ceramics[16]. In 1993, Andersson and Oden developed the Procera all-ceramic restorations (Nobel Biocare AB, Gothenburg, Sweden). These restorations were composed of a densely sintered, high purity aluminum oxide (Al_2O_3) using more than 99.9% veneered with a compatible low-fusing dental porcelain[17]. Composition, processing methods, properties and clinical indications of the different ceramic systems are summarized in Table 1.

Classification of all-ceramic systems

In restorative dentistry, substituting metal-based restorations with all-ceramic ones has shown much growth[18]. This article further reviews a variety of all-ceramic systems with different methods of fabrication, strength and translucency that are currently available in the dentistry field.

Conventional powder-slurry ceramics

Conventional feldspathic porcelain can be developed using a powder slurry technique. This product is supplied as a powder, in which water is added to produce the slurry. The aqueous material is condensed in a layer on a platinum foil or refractory die and then sintered to produce the restoration[19]. However, feldspathic porcelains are brittle and have low flexural strength approximately 60 to 70 MPa, hence, leucite-reinforced feldspar porcelains were developed using the same powder-slurry technique. The leucite incorporation to porcelain makes the dental porcelain more opaque and stronger with higher fusing temperature and higher expansion coefficient [20]. Thus, these porcelains are used as veneering materials for metal and ceramic frameworks [11].

Leucite feldspar ceramic has greater strength than conventional feldspathic porcelain because of the fusion between leucite and glassy components of the ceramic material during the sintering process at 1020 °C–1035 °C [21]. Therefore, the presence of leucite in the glass matrix will slow down crack propagation and enhance the fracture toughness of the dental porcelain [22].

Cast glass and polycrystalline ceramics

Castable ceramics are used as solid ceramic ingot products. These ceramics are used in the fabrication of cores or full contour restorations via lost wax and centrifugal casting technique [23]. Yttrium tetragonal zirconia polycrystal (Y-TZP) is a recently developed ceramic core in which yttrium oxide is mixed with pure zirconium oxide (ZrO_2) at room temperature to produce a multiphase product known as partially stabilised zirconia [24, 13]. This material may be processed by casting technique or milling method from monolithic blocks of partially or fully sintered materials [13]. Christel et al. [25] conducted an *in-vitro* study in which Y-TZP ceramics exhibited higher values of flexural strength of up to 900–1200 MPa and fracture toughness of 9–10 MPa•$m^{1/2}$, that may be attributed to their polycrystallinity. However, the transformation toughening mechanism of ZrO2 phase results in localized expansion of 3–5% which can cause compressive stresses to converge at or around the tip of the cracks. This will help to reduce further propagation of the cracks.

Pressable ceramics

Pressable ceramics are supplied as ceramic ingot products. These products are melted at 1180 °C and then pressed into a mould using the lost wax technique [26]. The pressed material can be used as a full contour restoration or used as a substructure for the conventional feldspathic porcelain buildup to improve translucency [27]. There are various types of pressable ceramics which are available; IPS Empress, IPS ProCAD, IPS Empress 2 and IPS e.max Press (Ivoclar Vivadent, Schaan, Liechtenstein). These systems showed different chemical compositions, crystallinity, strength and opacity [28, 29]. IPS Empress, a leucite ($KAlSi_2O_6$) crystal which is supplied in an ingot form, reinforces the glass matrix and prevents crack propagation [30]. It contains about 30–40 wt% leucite crystal to increase the strength of the ceramic core. High crystallinity results in high opacity in the core. Therefore, the crystalline content must be limited within this range to improve the strength over conventional feldspathic porcelain without changing the level of translucency that might compromise aesthetics [31]. The IPS Empress system is designed for the fabrication of single crowns, inlays, onlays, and veneers [11].

IPS ProCAD was introduced in 1998. This material is a leucite-reinforced ceramic similar to IPS Empress. It has a fine particle size, therefore it is designed to be used with the CEREC inLab system (Sirona Dental Systems, Bensheim, Germany) and is available in numerous shades, including a bleached shade and an aesthetic block line [32].

IPS Empress 2 comprises lithium disilicate ($Li_2Si_2O_5$) crystal-reinforced glass ceramic. It contains 60–70 wt% of crystalline $Li_2Si_2O_5$ fillers without loss of translucency, and the refractive index of the crystals is similar to that of the glass matrix [33]. The framework of IPS Empress 2 is veneered with the fluorapatite-based porcelain (IPS Eris; Ivoclar Vivadent) to produce a semi-translucent restoration and improves light transmission [34, 35]. Albakry et al. [36] measured the biaxial flexural strength of these two recycled pressable glass ceramics, and they found that IPS Empress can resist 148 MPa, whereas IPS Empress 2 can resist 340 MPa. Whereas, the fracture toughness of IPS Empress and IPS Empress 2 was 13 MPa ·$m^{1/2}$ and 33 MPa ·$m^{1/2}$ respectively. Hence, the IPS Empress 2 has been recommended for the construction of FPDs in the anterior and premolar regions [2].

Lastly, IPS e.max Press is developed in 2005 as an improved press-ceramic material compared to IPS Empress 2. It also consists of a lithium-disilicate pressed glass ceramic, but its physical properties and translucency are improved through a different firing process [37]. Therefore, IPS Empress 2 has now been replaced by IPS e.max Press.

Glass-infiltrated ceramics

The high failure rate for all-ceramic posterior crowns has resulted in the development of high alumina content ceramics reinforced with glass-infiltration to improve the fracture strength of the current all-ceramic fixed prostheses.

In-Ceram (Vita Zahnfabrik, Germany) and Turkom-Cera™-fused alumina (Turkom-Ceramic) are the main representatives of this system. In-Ceram core comprises porous insoluble particles that are made from alumina, spinell, or zirconia. These materials are mixed with water to form a suspension known as "slip." The slip mass is then sintered at 1120 °C for 10 h to produce a porous structure. It is then infiltrated with a low-viscosity lanthanum oxide glass during second sintering at 1100 °C for 4 h to remove the porosity (depending on the manufacturer's recommendation)[38]. These core materials are veneered with alumina blank (VITABLOCS) feldspathic porcelain to improve the aesthetic traits[39]. Glass-infiltrated oxide ceramics are commercially available in four different compositions as described below.

In-Ceram alumina

Vita In-Ceram alumina was first introduced in 1990[15]. This material consists of 75 wt% polycrystalline alumina and 25% infiltration glass. It has high strength and fracture toughness of 500 MPa and 3.1 MPa·$m^{1/2}$ respectively, with medium translucency, which makes it suitable for posterior crowns and anterior bridges[11, 40].

In-Ceram spinell

Vita In-Ceram spinell was developed in 1994[28]. This material consists of 78 wt% magnesium aluminum oxide ($MgAl_2O_4$) and 22 wt% infiltration glass. It exhibits the highest aesthetic requirements, but it shows the lowest level of mechanical properties compared with other In-Ceram materials. It has flexural strength and fracture toughness of 400 MPa and 2.7 MP $am^{1/2}$, respectively. Therefore, In-Ceram spinell is only recommended for inlays and anterior crowns[11].

In-Ceram zirconia

In-Ceram zirconia was introduced in 1999. This material is based on In-Ceram alumina of 67 wt% with the addition of CeO_2 stabilized zirconia of 33 wt%. It consists of 56 wt% polycrystalline alumina, 24 wt% polycrystalline zirconia, and 20 wt% infiltration glass[41]. It is currently the strongest material of the In-Ceram range with a flexural strength and fracture toughness of 600 MPa and 4.8 MPa·$m^{1/2}$ respectively. The material is also opaque, so it is recommended for crowns, posterior three-unit bridges and possibly masking discolored teeth[11, 42].

Turkom-Cera™

Turkom-Cera™ fused alumina (Turkom-Ceramic, Puchong, Selangor, Malaysia) consists of two components, namely, alumina gel (99.98% Al_2O_3) and the crystal powder of lanthanum oxide-based glass. The alumina gel is sintered into a porous structure, and the crystal powder of lanthanum oxide-based glass is infiltrated to the porous structure. Turkom-Cera™ crowns show an acceptable clinical behavior and adequate strength (equal to or higher than currently available alumina-based In-Ceram). It has flexural strength and hardness of 506 MPa and 10 GPa, respectively. These properties favour its use as a core material for all-ceramic anterior and posterior crowns[43, 44].

Machinable (CAD/CAM) ceramics

Machinable ceramics are provided as ceramic ingots in various shades. Both precision copy-milling concept and CAD/CAM systems are commercially available. Machining has become a viable option in the fabrication of all-ceramic restorations because ceramic templates do not require high temperatures for processing[45]. Dental prostheses can be fabricated in different ways depending upon the requirement of material and extent of the clinical problem. Fabrication method can be either centralised, chair-side, or it can involve laboratory processing[46].

CAD/CAM (Cerec system)

Ceramic restorations are milled from the industrial blocks of ceramic materials that are synthesized under optimum and controlled conditions. Since its development in 1980, Cerec system (Sirona Dental Systems, Bensheim, Germany) has undergone several technical modifications. The first generation system was Cerec 1 (2D image), which was developed by Mçrmann and Brandestini (1987) using a chair-side fabrication of intra-oral restorations such as onlays, inlays, and/or veneers[14]. Subsequently, Cerec 2 (2D image) was introduced in 1994 with the software and hardware designed to fabricate complete crowns and intra-coronal restorations[47]. In 2003, the development of the Cerec 3 system showed remarkable improvement compared with the Cerec 2 system as an enhanced intra-oral optical

Table 1. Different types of dental ceramics based on their composition, processing techniques, properties and clinical applications

Material	Phase	Processing technique	Physical properties	Clinical applicatins
Feldspathic porcelain	Amorphous glassy phase	Powder slurries for layering and sintering technique	σ: 60-70 MPa; K_{IC}: 0.9-1.2 MPa·$m^{1/2}$ E:70 GPa; H:6 GPa;	Resin-bonded laminate, metal and ceramic
CTE:vary, depends on application		veneer cores		
Reinforced felds pathic porcelain	Alumina, leucite, fibers glass dominated phase	Powder slurries for layering and sintering technique or hot press	σ:120-150 MPa; K_{IC}: 1.5 MPa·$m^{1/2}$; CTE: vary, depends on type of core materials	Resin-bonded laminate, crown and bridges veneers
Leucite glass ceramic (IPS) veneer,	$KAlSi_2O_6$ Tetragonal phase	Hot press CAD/CAM	σ:160 MPa; K_{IC}: 1.3 MPa·$m^{1/2}$ E:65 GPa;	Resin-bonded laminate,
Empress			H: 6.2 GPa; CTE: 16.6-17.5×10^{-6} K^{-1} (100-500°C)	crown, onlays and inlays
Lithium disilicate glass-ceramic veneer,	$Li_2Si_2O_5$	Hot press	σ: 360-400 MPa;	Resin-bonded laminate,
Empress 2	Long needle-like crystals	CAD/CAM	K_{IC}: 2.2-2.7 MPa·$m^{1/2}$ E: 95 GPa; H: 5.8 GPa; CTE: 10.5×10^{-6} K^{-1} (100-500°C)	onlays inlays, crown and anterior bridge
Fluormica glass-ceramic (Dicor)	$K_2Mg_5Si_8O_{20}F_4$ Glass dominated phase	Castable CAD/CAM	σ:150 MPa; K_{IC}: 1.4-1.5 MPa·$m^{1/2}$ E:68 GPa; H: 3.3-3.5 GPa; CTE: 6.4-7.2×10^{-6} K^{-1}	Resin-bonded laminate, anterior crown and posterior inlays

Material	phase	Processing technique	Physical properties	Clinical applicatins
Glass infiltrated spinell (vita In-Ceram spinell)	$MgAl_2O_4$ Crystalline-dominated phase	Slip casting CAD/CAM	σ: 400 MPa; K_{IC}: 2.7 MPa·$m^{1/2}$ E:185 GPa; CTE: 7.7× 10^{-6} K^{-1}	Inlays and anterior crowns
Glass infiltrated alumina (vita In-Ceram alumina)	Al_2O_3 Hexagonal phase	Slip casting CAD/CAM	σ: 500 MPa; K_{IC}: 3.9 MPa·$m^{1/2}$ E:280 GPa; CTE: 7.4× 10^{-6} K^{-1}	Laminate cores, crowns, abutments and anterior bridges
Glass infiltrated zirconia (vita In-Ceram zirconia)	ZrO_2 Yttria- stabilized tetragonal phase	Slip casting CAD/CAM	σ: 600 MPa; K_{IC}: 4.4 MPa·$m^{1/2}$ E:258 GPa; CTE: 7.8× 10^{-6} K^{-1}	Anterior and posterior crowns and bridges
Turkom-Cera™ fused alumina	alumina gel (99.98% Al_2O_3) & crystal powder of lanthanum oxide-based glass	Glass-infiltration	σ: 506 MPa; H: 10 GPa	anterior and posterior crowns
Pure alumina	Al_2O_3 Hexagonal phase	CAD/CAM	σ: 500-700 MPa; K_{IC}: 4.5 MPa·$m^{1/2}$ E: 270-380 GPa; H: 12 GPa; CTE: 7× 10^{-6} K^{-1}	Laminate cores, crowns, 4-unit bridges
Yttria-stabilized tetragonal zirconia (3Y-TZP)	ZrO_2 Yttria- stabilized tetragonal phase	CAD/CAM	σ: 900-1400 MPa; $K_{IC:}$ 6-10MPa·$m^{1/2}$ E: 205-210 GPa; H: 13.9 GPa; CTE: 10.5 × 10^{-6} K^{-1}	Laminate cores, anterior and posterior crowns and bridges and implant bridges

Abbreviations: σ: Flexural strength, K_{IC}: Fracture toughness, H: Hardness,
E: Youngs s modulus, CTE: Coefficient of thermal expansion

Table 2. Shows the effect of nano-composites on the mechanical properties of dental ceramic

Nano-composite alumina/ceramic	The ratio of nano-particle	Flexural strengthMPa	Fracture toughnessMPa ·m$^{1/2}$
Al_2O_3/SiC	5 wt% of SiC	1000	4.7
Al_2O_3/ZrO_2	10-15 wt% of Y_2O_3-stabilized ZrO_2	1000	10
Al_2O_3/Ni	5wt% of Ni	1000	3.5
Al_2O_3/Fe_3Al	5 wt% of Fe_3Al	832	7.96
Al_2O_3/Mo	0.69 wt% of Mo	700	2.62

camera was utilised to reproduce fine details and improve software capability for recording 3D images for fast preparation [46].

Later, Cerec inLab MC XL CAD/CAM system (InLab 3D software, Sirona Dental GmbH, Germany) was established in 2005. It was used to fabricate a variety of restorations including crown copings, long-span bridge frameworks, full-contoured crowns, inlays, onlays, temporaries and veneers with a high-end milling machine [48]. According to the manufacturer, this machine could significantly reduce fabrication times of crown copings, fully fabricated crowns and (up to) 10-unit frameworks.

Currently, a highly translucent zirconia VITA YZ-Cerec (VITA Zahnfabrik, Bad Säckingen, Germany) was utilized using partially-stabilized zirconia blocks with yttrium oxide. YZ-Cerec system was designed to fabricate single crown, multi-unit substructures and fully anatomical dental restorations in the anterior and posterior regions. This system also possesses flexural strength of approximately 1200 MPa, Weibull modulus of 14 and excellent light refraction properties which makes it suitable for monolithic restorations. VITA YZ-Cerec showed minimal marginal discrepancy with significantly smaller marginal gap values before cementation when compared from the Digitising computer and Procera systems [49].

Copy-milling technique (Celay system)

The milling technique is a central and important aspect of CAD/CAM technology. High milling accuracy reduces the time needed to adapt the work-piece, and provides restorations with better longevity and aesthetic aspect [50]. The Celay system (Mikrona Technologies, Spreitenbach, Switzerland) is a divergence of the direct–indirect restoration concept, but a dental technician is not needed. After completing tooth preparation, a precision imprint chemical or light-cured dental composite is loaded directly in the prepared teeth or indirectly on the master cast. This mould is adjusted for the occlusal relationship and marginal integrity, thereby making the material cured. The mould is then removed from the patient's mouth and mounted on one side of the Celay (the scanning side). This serves as a prototype model, whereas the ceramic blocks are reproduced on the other side using the milling duplicating technique [44].

In the Celay system, the type of ceramic blocks used is similar to those available for the CAD/CAM system [4]. In-Ceram alumina and spinell blocks can also be used to fabricate single and multiple units of In-Ceram cores to produce all-ceramic crowns and bridges[18]. The milling technique for In-Ceram material is dramatically better than that for glass-infiltrated In-Ceram restorations. This result is due to the shorter time needed to produce prosthesis by eliminating slip fabrication, reducing sintering cycle, and decreasing the glass infusion time. The Celay core needs 40 min for glass infiltration compared with the 4 h required by the conventional In-Ceram prosthesis [51]. Hwang and Yang [52] showed that the fracture strength of copy-milled In-Ceram prosthesis is 10% higher than that of conventional glass-infiltrated In-Ceram restorations.

Procera all-Ceram CAD/CAM system

The Procera system utilizes the concept of the CAD/CAM system to fabricate all-ceramic prostheses [29]. The ceramic core consists of more than 99.9% of pure Al_2O_3 that is sintered at 1600 °C to produce a dense translucent material. The burning process leads to a large shrinkage of alumina of about 15%–20% [2]. Alumina shrinkage is compensated by scanning the original master die with a stylus, and the information can then be stored in the computer, and the computer enlarges this die to accommodate the burning shrinkage. The enlarged die is milled with the CAD/CAM system to fabricate accurate restoration [29]. The densely sintered, high purity of 99.9% Al_2O_3 facilitates densification during melting and solidification. Most of the porosities will be eliminated, which leads to the improved strength of the materials [17]. The flexural strength and fracture toughness of Procera AllCeram material are 687 MPa and 4.48 MPa$\cdot$m$^{1/2}$ respectively. However, it is only indicated for single-unit restorations because the currently available system is unable to compensate the complex shrinkage of a multi-unit prosthesis [18]. The special veneering porcelain (all-Ceram Porcelain, Ducera) has a coefficient of thermal expansion of 7×10^{-6} K^{-1}, which is adjusted to correspond to the Al_2O_3 core [29].

Strengthening of dental ceramics

Several attempts have been made over the last few years to enhance the strength of dental ceramics and improve their clinical applications as dental cores for anterior and posterior restorations [11]. There are different typical methods for reinforcing dental ceramics through the creation of residual compressive stresses within the surface of the restorations that deflect and arrest crack propagation in the ceramic frameworks.

Chemical or ion exchange strengthening

This is a process that creates a thin surface layer of high compressive stress by exchanging the small glass monovalent ions with the larger ones. When the temperature is elevated, large ions enter the glass matrix by diffusional exchange from a molten salt bath. During cooling, the larger ions trapped in the ceramic surface takes more space because of higher molar volume. This leaves the superficial layer in compressive status[53]. For instance, the exchange of lithium ions with the small sodium ions on the surface layer resulted in the production of lower coefficient of thermal contraction glasses with enough stress release during cooling. Moreover, the exchange of large potassium ions for surface sodium ions in feldspathic porcelain will increase the viscosity during cooling stresses that are generated in the surface layer due to the congestion of potassium ions in place of the smaller sodium ions [54]. A range of porcelains has been significantly strengthened using commercially available ion exchange paste (Ceramicoat, GC Inc, Tokyo, Japan). This obviates the necessity for a potentially dangerous molten salt bath [55, 56]. Ion exchange produces a state of compression to a limited depth from the surface varying from 30 to 100 µm and this will lead to a small improvement in biaxial strength of the materials [54].

Thermal treatment strengthening

One of the advantages of thermal treatment is the stress profiles that extend much deeper in the ceramic materials to a depth of 150 µm, when compared to chemical treatment [57]. During sintering, the outer layer solidifies first and then cools rapidly due to poor thermal conductivity of the material. However the inner part of the material shrinks and remains liquid for some time. Consequently, it introduces a compressive stress in the outer layer. This method of strengthening can occur during the initial firing of the ceramic or during subsequent heat treatment. Therefore, difficulty in the cooling rate control is one of disadvantages of thermal strengthening method [13, 45].

Dispersion strengthening

Moderate strengthening of dental ceramics can be achieved with appropriate fillers added and uniformly dispersed throughout the glass. In 1965, McLean and Hughes [8] developed the first successful strengthened ceramic substructure by the addition of 55 wt% of aluminum oxide particles and uniformly dispersed throughout the feldspathic glass. Leucite fillers (at concentrations of around 40-55 wt%) are also used for dispersion strengthening of all-ceramic restorations by Empress technique into moulds at high temperature [30].

Fine microstructures strengthening

Numerous methods or techniques were developed to reinforce feldspathic dental ceramics by using fine microstructure materials that are beneficial to machinability, strength, and translucency of the dental ceramics. These materials include; alumina-leucite fibers, leucite glass ceramics ($KAlSi_2O_6$), fluorapatite glass ceramics **(**$Ca_5(PO_4)_3F$**)**, fluormica glass ceramics ($K_2Mg_5Si_8O_{20}F_4$), and lithium disilicate glass ceramics ($Li_2Si_2O_5$). In addition, other materials are glass infiltrated oxide ceramics; glass infiltrated spinell ($MgAl_2O_4$), glass-infiltrated alumina (Al_2O_3) or the glass infiltrated zirconia polycrystals (3y-Tzp) [11].

Nano-composite strengthening

Nano-composite ceramics materials have been receiving much attention due to their significantly enhanced mechanical properties. In this regard, there are several models dealing with different aspects of strengthening and toughening mechanisms for ceramic materials are shown in **Table 2**. Niihara [58] revealed that a dispersion of 5 wt% of silicon carbide (SiC) nano-particles into alumina will improve the strength and toughness of Al_2O_3/SiC composite from 350 MPa to over 1000 MPa, and from 3.2 to 4.7 MPa ·$m^{1/2}$, respectively. These improvements occurred due to the reduction in the interparticle spacing, whereas the average internal stresses remain unaffected [59]. In another instance, alumina/zirconia nano-composite ceramics were prepared from nanoscale Y_2O_3-stabilized ZrO_2 (10-15 wt%) and nanoscale Al_2O_3 powders. The results show that ZrO_2 particles inhibit the densification and also retard the matrix alumina grain growth. Y_2O_3-stabilized ZrO_2 powder in the Al_2O_3/ZrO_2 nano-composites is a strengthening and toughening agent, where the maximum strength and toughness of the composites were 1000 MPa and 10 MPa ·$m^{1/2}$, respectively [60]. Evidently, Sekino et al. [61] prepared high-density Al_2O_3/Ni nano-composite ceramic (containing 5 wt% nickel metal) by reducing and hot pressing technique under 30 MPa at 1450 °C for 1 h. They demonstrated that the fracture toughness and fracture strength were 3.5 MPa ·$m^{1/2}$ and 1000 MPa, respectively. Similarly, Gong et al. [62] fabricated Al_2O_3/Fe_3Al nano-composite ceramic (containing 5 wt% Fe_3Al) by sintering process at 1530 °C. The study reveals that the bending strength and fracture toughness were 832 MPa and 7.96 MPa ·$m^{1/2}$, respectively. The improvement in the mechanical properties of the nano-composite was attributed to the change in the fracture mode from intergranular fracture to transgranular fracture. Also, D1´az et al. [63] synthesized Al_2O_3/Mo nano-composite ceramic (containing 0.69 wt% molybdenum metal) by colloidal processing method. They observed an improvement in the mechanical behavior of the ceramic material. For example, the flexural strength and fracture toughness were 700 MPa and 2.62 MPa ·$m^{1/2}$, respectively. This result reveals that the toughening mechanism activated in the Al_2O_3/Mo nano-composite was not due small size of the particles, but it is a result of stresses generated by mismatch of thermal expansion coefficient between Al_2O_3 and Mo metal.

CONCLUSION

Historical review of the development of all-ceramic restorative materials and their applications shows the current limitations and the revealing the many challenges which still need to be tackled. As seen, there is no single material and/or system that possess all the characteristics of ceramic existing in clinical situations. The choice of one specific type of ceramic, rather than the latest system, should be dependent on the careful assessment of the indications and contraindications of the system related to the specific dental application. Such assessment depends on laboratory investigations, clinical data associated with proper scientific evidence, and real aesthetic needs of the patient.

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