

RECENT ADVANCES IN CERAMICS FOR DENTISTRY

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ABSTRACT: For the last ten years, the application of high-technology processes to dental ceramics allowed for the development of new materials such as heat-pressed, injection-molded, and slip-cast ceramics and glass-ceramics. The purpose of the present paper is to review advances in new materials and processes available for making all-ceramic dental restorations. Concepts on the structure and strengthening mechanisms of dental ceramics are provided. Major developments in materials for all-ceramic restorations are addressed. These advances include improved processing techniques and greater mechanical properties. An overview of the processing techniques available for all-ceramic materials is given, including sintering, casting, machining, slip-casting, and heat-pressing. The most recent ceramic materials are reviewed with respect to their principal crystalline phases, including leucite, alumina, forsterite, zirconia, mica, hydroxyapatite, lithium disilicate, sanidine, and spinel. Finally, a summary of flexural strength data available for all-ceramic materials is included.

Key words. Ceramics, dental porcelain, crystalline phases.

Introduction

Since the first use of porcelain to make a complete denture by Alexis Duchâteau in 1774, numerous dental porcelain compositions have been developed. Porcelain compositions suitable for metal-ceramic restorations were introduced in 1962 (Weinstein and Weinstein, 1962) and led to the success of this technology. The development of aluminous core and veneer porcelains was first described in 1965 (McLean and Hughes, 1965). For the last ten years, the application of high-technology processes to dental ceramics allowed for the development of new materials such as heat-pressed, injection-molded, slip-cast ceramics, and glass-ceramics.

The purpose of the present paper is to review the new materials and processes available for all-ceramic dental restorations. The first part summarizes basic concepts on dental ceramics and methods for improving the fracture resistance. The second part covers the new materials and processing techniques used for making all-ceramic dental restorations and their mechanical properties.

BACKGROUND

Dental ceramics have a composite structure. Materials for metal-ceramic restorations contain a vitreous phase, also called glassy matrix, that represents 75 to 85% by volume and are reinforced by various crystalline phases

(Denry and Rosenstiel, 1995). The choice of the crystalline phase in compositions for metal-ceramic restorations was initially dictated by the need for matching the thermal contraction coefficient of the porcelain close to that of the metallic infrastructure in order to avoid the development of tensile stresses within the porcelain when cooled. Most ceramics for metal-ceramic restorations contain from 15 to 25 vol% leucite as their major crystalline phase, but changes in the leucite volume fraction can occur during thermal treatment of dental porcelains (Mackert and Evans, 1991a,b). Leucite is a potassium aluminosilicate with a high thermal expansion coefficient (Mackert *et al.*, 1986a). Materials for all-ceramic restorations use a wider variety of crystalline phases as reinforcing agents and contain up to 90% by volume of crystalline phase. The nature, amount, and particle size distribution of the crystalline phase directly influence the mechanical and optical properties of the material (Morena *et al.*, 1986b; Kon *et al.*, 1994). The match between the refractive indices of the crystalline phase and glassy matrix is a key factor for controlling the translucency of the porcelain. Similarly, the match between the thermal expansion coefficients of the crystalline phase and glassy matrix is critical in controlling residual thermal stresses within the porcelain (Mackert, 1988). Brittle materials such as ceramics contain at least two populations of flaws: fabrication defects and surface cracks.

Fabrication defects are created during processing and consist of voids or inclusions generated during sintering. Microcracks develop upon cooling in feldspathic porcelains and are due to thermal contraction mismatch between either the crystals and the glassy matrix (Mackert *et al.*, 1994) or between the porcelain and the metal substrate. Condensation of a ceramic slurry by hand prior to sintering may introduce porosity. Sintering under vacuum has been shown to reduce the amount of porosity in dental porcelains from 5.6 to 0.56% (Jones and Wilson, 1975). Porosity on the internal side of clinically failed Dicor glass-ceramic restorations has been shown to constitute a fracture initiation site (Kelly *et al.*, 1990).

Surface cracks are induced by machining or grinding. The average natural flaw size varies from 20 to 50 micrometers (Anusavice *et al.*, 1991). Usually, failure of the ceramic originates from the most severe flaw. The size and spatial distribution of the flaws justify the necessity of a statistical approach to failure analysis (Weibull, 1939).

Surface crystallization of leucite can be induced by seeding the surface of a feldspathic glass with leucite particles (Höland *et al.*, 1995). Ceramic materials for all-ceramic restorations are in contact with refractory die materials during firing or pressing at high temperatures. Surface reactions have also been reported between glass-ceramics and the refractory embedment used during the crystallization process, thereby modifying the mechanical properties of the final product (Campbell and Kelly, 1989; Denry and Rosenstiel, 1993). Diffusion processes are temperature-dependent, and surface reactions are likely to occur between the porcelain and the refractory die material.

OVERVIEW OF PROCESSING METHODS

Dental ceramics are usually processed by sintering, but in the last few years, processing techniques used for high-technology ceramic materials have been applied to dental ceramics, leading to the development of glass-ceramics, slip-cast ceramics, and heat-pressed ceramics.

When applied to ceramic materials, the sintering process is defined as the "transformation of an originally porous compact to a strong, dense ceramic" (Kingery *et al.*, 1976). It can be described as a complex sequence of high-temperature reactions occurring above the softening point of the porcelain and leading to partial melting of the glassy matrix, with coalescence of the powder particles. During sintering, the density of the porcelain greatly increases and is associated with a volume shrinkage of between 30 and 40%. As mentioned earlier, sintering under vacuum helps reduce the amount of porosity in the porcelain (Meyer *et al.*, 1976; Claus and Rauter, 1989). Clinically, the amount of shrinkage still constitutes a problem in metal-ceramic restorations with all-porcelain

margins, decreasing the marginal fit.

Slip-casting has long been used in the ceramic industry to make sanitary ware. Slip-casting involves the condensation of an aqueous porcelain slip on a refractory die. The porosity of the refractory die helps condensation by absorbing the water from the slip by capillary action. The piece is then fired at high temperature on the refractory die. Usually, the refractory shrinks more than the condensed slip, and the piece can be separated easily after being fired. The fired porous core is later glass-infiltrated, a unique process in which molten glass is drawn into the pores by capillary action at high temperature. Materials processed by slip-casting tend to exhibit reduced porosity, fewer defects from processing, and higher toughness than conventional feldspathic porcelains.

The first glass-ceramics were developed in the late 1950s (Stookey, 1959). "Glass-ceramics are polycrystalline solids prepared by the controlled crystallization of glasses" (McMillan, 1979). The crystallization is achieved when the glass is submitted to a heat treatment during which crystal nucleation and growth are thermodynamically possible. Proper control of the crystallization heat treatment is necessary to ensure the nucleation of a sufficient number of crystals and their growth to an effective size. The dual nature of glass-ceramic materials confers upon them the esthetic, mechanical, and chemical qualities of ceramics as well as the ability to be cast and processed as glasses. These characteristics are of great interest for dental applications. Machinability is another property desirable for the maximum utility of glass-ceramics as dental materials. The ability of glass-ceramics to be machined is closely related to the nature and particle size of the crystalline phase that develops during the crystallization heat treatment (Utsumi and Sakka, 1970). Machinable glass-ceramics for industrial as well as dental applications often contain mica as a major crystalline phase.

Hot-pressed ceramics constitute another application of high technology to dentistry. This process relies on the application of external pressure at elevated temperatures to obtain sintering of the ceramic body. Hot-pressed ceramics are also called "heat-pressed" ceramics. Hot-pressing classically helps avoid large pores caused by non-uniform mixing. It also prevents extensive grain growth or secondary crystallization, considering the temperature at which sintering is obtained. The mechanical properties of many ceramic systems are maximized with high density and small grain size. Therefore, optimum properties can be obtained by hot-pressing techniques (Kingery *et al.*, 1976).

In spite of their excellent esthetic qualities and their good biological compatibility, dental ceramics, like all ceramic materials, are brittle. They are susceptible to fracture at the time of placement or during function.

TABLE 1**Influence of Crystalline Phase Characteristics Compared with Those of the Glassy Phase (GP) on the Fracture Probability of Two-phase Ceramic Materials**

<u>Thermal Contraction Coefficient</u>	<u>Modulus of Elasticity</u>	<u>Toughness</u>	<u>Effect on the Ceramic</u>
Matches that of glassy phase (GP)	Higher than that of GP	Higher than that of GP	Low fracture probability
Matches that of GP	Lower than that of GP	Lower than that of GP	High fracture probability
Higher than that of GP	Higher than that of GP	Higher than that of GP	Debonding of the crystals from the matrix
Lower than that of GP	Lower or higher than that of GP	Lower or higher than that of GP	Radial cracks, very high fracture probability

Several methods are used to improve the strength and clinical performance of dental ceramics, including crystalline reinforcement, chemical strengthening, and thermal tempering.

Strengthening by crystalline reinforcement involves the introduction of a high proportion of the crystalline phase into the ceramic to improve its resistance to crack propagation. However, the crystalline phase must be carefully selected. Important selection criteria include the coefficient of thermal contraction, toughness, and the modulus of elasticity. The influence of these crystalline-phase characteristics compared with those of the glassy matrix on the fracture probability of two-phase ceramic materials is summarized in Table 1.

Chemical strengthening is another method used to increase the strength of glasses and ceramics. The principle of chemical strengthening relies on the exchange of small alkali ions for larger ions below the strain point of the ceramic. Since stress relaxation is not possible in this temperature range, the exchange leads to the creation of a compressive layer at the surface of the ceramic (Dunn *et al.*, 1977). Finally, any applied load must first overcome this built-in compression layer before the surface can be placed into tension, resulting in an increase in fracture resistance. This technique involves the use of alkali salts with a melting point lower than the glass transition temperature of the ceramic material. Ion-exchange strengthening has been reported to increase the flexural strength of feldspathic dental porcelain up to 80%, depending on the ionic species involved and the composition of the porcelain (Seghi *et al.*, 1990a; Denry *et al.*, 1993). The depth of the ion-exchanged layer has been shown to be greater than 50 micrometers (Anusavice *et al.*, 1994a). However, this technique is diffusion-driven, and its kinetics are limited by factors such as time, temperature, and ionic radius of the exchanged ions.

Thermal tempering is commonly used to strengthen glasses and is based on the creation of temperature gradients between the surface and the bulk part of the glass

piece. The technique involves heating of the glass to a temperature above the glass transition region and below the softening point. It is then cooled to room temperature in a jet of air or, in some cases, in an oil bath. The residual stresses arise from differences in cooling rates for surface and interior regions. The result is similar to that obtained with chemical strengthening with the formation of a surface compressive layer that results in increased strength. This technique has been successfully applied to feldspathic dental porcelain and resulted in mean flexure strength values 2.6 times greater than the corresponding value for slow-cooled specimens (Anusavice and Hojjatie, 1991). The stress relaxation behavior of dental porcelain when reheated can be characterized by stress relaxation testing under compression at high temperature (DeHoff *et al.*, 1994) or by acoustic emission techniques (Asaoka *et al.*, 1992). The principal effect of tempering is the inhibition of crack formation rather than the retardation of crack growth (Anusavice *et al.*, 1991; DeHoff and Anusavice, 1992; Hojjatie and Anusavice, 1993). However, the combination of thermal tempering and subsequent ion-exchange does not lead to a significant increase in the mean biaxial flexural strength values (Anusavice *et al.*, 1992).

One last method commonly used to strengthen ceramics is the glazing procedure. The principle is the formation of a low-expansion surface layer formed at high temperature. When cooled, the low-expansion glaze places the surface of the ceramic in compression and reduces the depth and width of surface flaws. However, glazing does not significantly improve the biaxial flexure strength of feldspathic dental porcelain (Fairhurst *et al.*, 1992; Griggs *et al.*, 1995).

REVIEW OF NEW MATERIALS AND PROCESSES

Within the last ten years, an increasing number of ceramic materials for all-ceramic restorations has been developed. Each of these materials uses a different approach in attempting to improve the mechanical properties

without being detrimental to the esthetic qualities of the ceramic. They can be classified first according to the processing technique and second according to their major crystalline phase.

Sintered porcelains

Leucite-reinforced feldspathic porcelain

Optec HSP material (Jeneric/Pentron, Inc.) is a feldspathic porcelain containing up to 45 vol% tetragonal leucite (Schmid *et al.*, 1992; Piché *et al.*, 1994; Denry and Rosenstiel, 1995). The greater leucite content of Optec HSP porcelain compared with conventional feldspathic porcelain for metal-ceramics leads to a higher modulus of rupture and compressive strength (Vaidyanathan *et al.*, 1989). The large amount of leucite in the material contributes to a high thermal contraction coefficient (Katz, 1989). In addition, the large thermal contraction mismatch between leucite (22 to $25 \times 10^{-6}/^{\circ}\text{C}$) and the glassy matrix ($8 \times 10^{-6}/^{\circ}\text{C}$) results in the development of tangential compressive stresses in the glass around the leucite crystals when cooled. These stresses can act as crack deflectors and contribute to increase the resistance of the weaker glassy phase to crack propagation. After heat treatment of Optec HSP for one hour at temperatures ranging from 705 to 980°C , a second metastable phase identified as sanidine (KAlSi_3O_8) forms at the expense of the glassy matrix (Vaidyanathan *et al.*, 1989). The crystallization of sanidine is associated with a modification of the optical properties of the material from translucent to opaque. However, sanidine does not appear when the porcelain is heated to 980°C , since sanidine is metastable in the temperature range 500 - 925°C . The precipitation of sanidine has been reported as well upon isothermal heat treatment of conventional feldspathic porcelain for metal-ceramics (Mackert *et al.*, 1986b; Mackert, 1988; Barreiro *et al.*, 1989). An isothermal time-temperature-transformation diagram that makes it possible to predict the amount of leucite and sanidine in samples subjected to different thermal histories has been established (Barreiro and Vicente, 1993).

Alumina-based porcelain

Aluminous core porcelain is a typical example of strengthening by dispersion of a crystalline phase (McLean and Kedge, 1987). Alumina has a high modulus of elasticity (350 GPa) and high fracture toughness (3.5 to 4 $\text{MPa}\cdot\text{m}^{0.5}$). Its dispersion in a glassy matrix of similar thermal expansion coefficient leads to significant strengthening of the core. The first aluminous core porcelains contained 40 to 50% alumina by weight (McLean and Hughes, 1965). The core was baked on a platinum foil and later veneered with matched-expansion porcelain. Hi-Ceram (Vident, Baldwin Park, CA) is a more recent development of this technique. Aluminous

core porcelain is now baked directly onto a refractory die (McLean *et al.*, 1994).

Magnesia-based core porcelain

Magnesia core ceramic was developed as an experimental material in 1985 (O'Brien, 1985). Its high thermal expansion coefficient ($14.5 \times 10^{-6}/^{\circ}\text{C}$) closely matches that of body and incisal porcelains designed for bonding to metal ($13.5 \times 10^{-6}/^{\circ}\text{C}$). The flexural strength of unglazed magnesia core ceramic is twice as high (131 MPa) as that of conventional feldspathic porcelain (65 MPa). The core material is made by reacting magnesia with a silica glass within the 1100 - 1150°C temperature range. This treatment leads to the formation of forsterite (Mg_2SiO_4) in various amounts, depending on the holding time. The proposed strengthening mechanism is the precipitation of fine forsterite crystals (O'Brien *et al.*, 1993). The magnesia core material can be significantly strengthened by glazing, thereby placing the surface under residual compressive stresses that have to be overcome before fracture can occur (Wagner *et al.*, 1992).

Zirconia-based porcelain

Mirage II (Myron International, Kansas City, KS) is a conventional feldspathic porcelain in which tetragonal zirconia fibers have been included. Zirconia undergoes a crystallographic transformation from monoclinic to tetragonal at 1173°C . Partial stabilization can be obtained by using various oxides such as CaO , MgO , Y_2O_3 , and CeO , which allows the high-temperature tetragonal phase to be retained at room temperature. The transformation of partially stabilized tetragonal zirconia into the stable monoclinic form can also occur under stress and is associated with a slight particle volume increase. The result of this transformation is that compressive stresses are established on the crack surface, thereby arresting its growth. This mechanism is called transformation toughening. The addition of yttria-stabilized zirconia to a conventional feldspathic porcelain has been shown to produce substantial improvements in fracture toughness, strength, and thermal shock resistance (Morena *et al.*, 1986a; Kon *et al.*, 1990). However, other properties, such as translucency and fusion temperature, can be adversely affected. The modulus of rupture of commercially available zirconia-reinforced feldspathic dental porcelain (Mirage II) is not significantly different from that of conventional feldspathic porcelain (Seghi *et al.*, 1990b).

Glass-ceramics

Mica-based

As described earlier, glass-ceramics are obtained by controlled devitrification of glasses with a suitable composition including nucleating agents. Depending on the composition of the glass, various crystalline phases can

nucleate and grow within the glass. The advantage of this process is that the dental restorations can be cast by means of the lost-wax technique, thus increasing the homogeneity of the final product compared with conventional sintered feldspathic porcelains.

Dicor (Dentsply Inc., York, PA) is a mica-based machinable glass-ceramic. The machinability of Dicor glass-ceramic is made possible by the presence of a tetrasilicic fluormica ($\text{KMg}_{2.5}\text{Si}_4\text{O}_{10}\text{F}_2$) as the major crystalline phase (Grossman and Johnson, 1987). Micras are classified as layer-type silicates. Cleavage planes are situated along the layers, and this specific crystal structure dictates the mechanical properties of the mineral itself. Crack propagation is not likely to occur across the mica crystals and is more probable along the cleavage planes of these layered silicates (Daniels and Moore, 1975). In the glass-ceramic material, the mica crystals are usually highly interlocked within the glassy matrix, achieving a "house of cards" microstructure (Grossman, 1972). The interlocking of the crystals is a key factor in the fracture resistance of the glass-ceramic, and their random orientation makes fracture propagation equally difficult in all directions.

After being cast, the Dicor glass is converted into a glass-ceramic by means of a single-step heat treatment with a six-hour dwell at 1070°C. This treatment facilitates controlled nucleation and growth of the mica crystals. However, it is critical to re-invest the cast glass restoration prior to the crystallization heat treatment, to prevent sagging or rounding of the edges at high temperature. The match in the thermal expansion coefficients of the glass and the investment is achieved by use of a leucite-based gypsum-bonded investment. The interaction of the glass-ceramic and the investment during the crystallization heat treatment leads to the formation of calcium magnesium silicate at the surface of the glass-ceramic (Denry and Rosenstiel, 1993). This crystalline phase could be formed by decomposition of the mica into magnesium silicate that later reacts with the gypsum-bonded investment. This surface layer, called the "ceram layer", has been reported to decrease the strength of glass-ceramic crowns significantly (Campbell and Kelly, 1989; Kelly *et al.*, 1989). The effects of alumina and zirconia additions on the bending strength of Dicor glass-ceramic have been investigated. It was found that alumina additions successfully increase the bending strength of Dicor glass-ceramic, whereas zirconia additions had no effect (Tzeng *et al.*, 1993).

Hydroxyapatite-based

Ceraparl (Kyocera, San Diego, CA) is a castable glass-ceramic in which the main crystalline phase is oxyapatite, transformable into hydroxyapatite when exposed to moisture (Hobo and Iwata, 1985).

Lithia-based

Glass-ceramics can be obtained from a wide variety of compositions, leading to a wide range of mechanical and optical properties, depending on the nature of the crystalline phase nucleating and growing within the glass. Experimental glass-ceramics in the system $\text{Li}_2\text{O}-\text{Al}_2\text{O}_3-\text{CaO}-\text{SiO}_2$ are currently the object of extensive research work. The choice of adequate additives is critical in the development of tougher and higher-strength glass-ceramics (Anusavice *et al.* 1994b). Differential thermal analysis can be efficiently used to determine the heat treatment leading to the maximum lithium disilicate crystal population in the shortest amount of time, thereby optimizing the nucleation and crystallization heat treatment of this type of glass-ceramic (Parsell and Anusavice, 1994).

Machinable ceramics

Cerec system

The evolution of CAD-CAM systems for the production of machined inlays, onlays, and crowns led to the development of a new generation of machinable porcelains. There are two popular systems available for machining all-ceramic restorations. The best-known is the Cerec system (Siemens, Bensheim, Germany). It has been marketed for several years, and two materials can be used with this system: Vita Mark II (Vident, Baldwin Park, CA) and Dicor MGC (Dentsply International, Inc., York, PA). Vita Mark II contains sanidine (KAlSi_3O_8) as a major crystalline phase within a glassy matrix. As explained earlier, the presence of sanidine could explain the lack of translucency of this material. Dicor MGC is a machinable glass-ceramic similar to Dicor, with the exception that the material is cast and cerammed by the manufacturer. Colorants have been added to match tooth color. The glass-ceramic contains 70 vol% of the crystalline phase (Grossman, 1991). Manufacturer's control over the processing of this material and the higher volume percent of the crystalline phase could explain the improved mechanical properties of Dicor MGC compared with conventional Dicor glass-ceramic. The use of adhesive resin-based cements has been shown to improve the fracture resistance of all-ceramic crowns (Eden and Kacicz, 1987; Grossman and Nelson, 1987). Other studies have shown that the overall fracture resistance of Dicor MGC was independent of cement film thickness (Scherrer *et al.*, 1994). Presently, the main identified weakness of the Cerec system is the marginal fit of the restorations (Anusavice, 1993).

Celay system

The Celay system (Mikrona Technologie, Spreitenbach, Switzerland) uses a copy-milling technique to manufac-

ture ceramic inlays or onlays from resin analogs. The Celay system is a mechanical device based on pantographic tracing of a resin inlay or onlay fabricated directly onto the prepared tooth or onto the master die (Eidenbenz *et al.*, 1994).

As with the Cerec system, the starting material is a ceramic blank available in different shades. One ceramic material currently available for use with the Celay system is Vita-Celay (Vident, Baldwin Park, CA). This material contains sanidine as the major crystalline phase within a glassy matrix. Recently, In-Ceram pre-sintered slip-cast alumina blocks (Vident, Baldwin Park, CA) have been machined with the Celay copy-milling system used to generate copings for crowns and fixed partial dentures (McLaren and Sorensen, 1995). The alumina copings were further infiltrated with glass following the conventional In-Ceram technique, resulting in a final marginal accuracy within 50 μm .

Slip-cast ceramics

Alumina-based (In-Ceram)

In-Ceram (Vident, Baldwin Park, CA) is a slip-cast aluminous porcelain. The alumina-based slip is applied to a gypsum refractory die designed to shrink during firing. The alumina content of the slip is more than 90%, with a particle size between 0.5 and 3.5 micrometers. After being fired for four hours at 1100°C, the porous alumina coping is shaped and infiltrated with a lanthanum-containing glass during a second firing at 1150°C for four hours. After removal of the excess glass, the restoration is veneered with matched expansion veneer porcelain (Pröbster and Diehl, 1992). This processing technique is unique in dentistry and leads to a high-strength material due to the presence of densely packed alumina particles and the reduction of porosity.

Two modified porcelain compositions for the In-Ceram technique have been recently introduced. In-Ceram Spinel contains a magnesium spinel (MgAl_2O_4) as the major crystalline phase with traces of alpha-alumina, which seems to improve the translucency of the final restoration. The second material contains tetragonal zirconia and alumina. A variety of alumina-glass dental composites can be prepared by the glass-infiltration process. However, research has shown that the fracture toughness of the composites is relatively insensitive to the volume fraction of alumina in the range investigated (Wolf *et al.*, 1993).

Hot-pressed, injection-molded ceramics

Leucite-based

IPS Empress (Ivoclar USA, Amherst, NY) is a leucite-containing porcelain. Ceramic ingots are pressed at 1150°C (under a pressure of 0.3 to 0.4 MPa) into the refractory

mold made by the lost-wax technique. This temperature is held for 20 minutes in a specially designed automatic press furnace (Dong *et al.*, 1992). The ceramic ingots are available in different shades. They are produced by sintering at 1200°C and contain leucite crystals obtained by surface crystallization (Höland *et al.*, 1995). The leucite crystals are further dispersed by the hot-pressing step. The final microstructure of IPS Empress exhibits 40% by volume of tetragonal leucite. The leucite crystals measure 1-5 μm and are dispersed in a glassy matrix. Two finishing techniques can be used with IPS Empress: a staining technique or a layering technique involving the application of veneering porcelain. The two techniques lead to comparable mean flexure strength values for the resulting porcelain composite (Luthy *et al.*, 1993). The thermal expansion coefficient of the IPS Empress material for the veneering technique ($14.9 \times 10^{-6}/^\circ\text{C}$) is lower than that of the material for the staining technique ($18 \times 10^{-6}/^\circ\text{C}$) to be compatible with the thermal expansion coefficient of the veneering porcelain. The flexural strength of IPS Empress material was significantly improved after additional firings (Dong *et al.*, 1992). The strength increase is attributed to a good dispersion of the fine leucite crystals as well as the tangential compressive stresses arising from the thermal contraction mismatch between the leucite crystals and the glassy matrix.

Spinel-based

Alceram (Innotek Dental Corp, Lakewood, CO) is a material for injection-molded technology and contains a magnesium spinel (MgAl_2O_4) as the major crystalline phase (McLean and Kedge, 1987). This system was initially introduced as the "shrink-free" Cerestore system, which relied on the conversion of alumina and magnesium oxide to a magnesium aluminate spinel. One of the recognized advantages of this system was the excellent marginal fit of the restorations (Wohlwend *et al.*, 1989).

MECHANICAL PROPERTIES

Test methods

Numerous test methods are available to evaluate the mechanical properties of ceramics. The influence of the test method on the failure stress of brittle dental materials has been investigated (Ban and Anusavice, 1990). Important test parameters are the specimen thickness, the contact zone at loading, the homogeneity and porosity of the material, and the loading rate. It was concluded that "the bi-axial flexure test is a reliable method for determinations of the strength of brittle dental materials since it is relatively insensitive to test conditions" such as piston or specimen dimensions and specimen geometry. Yet the ISO standard (ISO, 1984) is used by many researchers and requires a three-point bending test for the evaluation of the modulus of rupture of dental porce-

TABLE 2**Comparative Flexural Strength Values for All-ceramic Materials**

<u>Material</u>	<u>Product</u>	<u>Modulus of Rupture (MPa)</u>	<u>Reference</u>
Aluminous core (Pt foil)	Vitadur-N™ core	123	Seghi <i>et al.</i> , 1990b
Aluminous core	Hi-Ceram	139	Seghi <i>et al.</i> , 1990b
Zirconia-reinforced	Mirage II™	70	Seghi <i>et al.</i> , 1990b
Injection-molded aluminous	Alceram®	162	Wohlwend <i>et al.</i> , 1989
Heat-pressed, leucite-reinforced	IPS Empress	97	Seghi and Sorensen, 1995
		160-180	Dong <i>et al.</i> , 1992
Leucite-reinforced	Optec HSP™	104	Seghi <i>et al.</i> , 1990b
Slip-cast alumina	In-Ceram®	446	Seghi and Sorensen, 1995
Slip-cast alumina	In-Ceram Spinel®	378	Seghi and Sorensen, 1995
Slip-cast alumina	In-Ceram Zirconia	604	Seghi and Sorensen, 1995
Mica glass-ceramic	Dicor™	125	Seghi <i>et al.</i> , 1990b
Hydroxyapatite glass-ceramic	Cerapearl®	150	Hobo and Iwata, 1985
Lithia-based glass-ceramic	Experimental	188	Anusavice <i>et al.</i> , 1994b
Machinable glass-ceramic	Dicor MGC™	229	Seghi and Sorensen, 1995
Machinable ceramic	Vita Mark II®	122	Seghi and Sorensen, 1995
Magnesia core (glazed)	Experimental	269	Wagner <i>et al.</i> , 1992

lain. Other researchers use devices that try to simulate dental morphology (Pröbster, 1992). However, the experimental variables can become extremely complex and difficult to reproduce in this latter type of testing. Finite Element (FE) Analysis constitutes another approach to the simulation of clinical conditions. Failure predictions of ceramic inlays by the FE technique successfully matched fractographic analyses of clinically failed restorations (Peters *et al.*, 1993).

Fractography is well-established as a means of failure analysis in the field of glasses and ceramics. It has been recognized as a powerful analytical tool in den-

tistry. *In vivo* failure stress of clinically failed all-ceramic crowns can be determined by fractography (Kelly *et al.*, 1989). A protocol for retrieval and fractographic analysis of failed ceramic restorations has been proposed (Thompson *et al.*, 1994) from which critical flaw sizes and failure stresses can be calculated.

It is well-established that glasses and ceramic materials are susceptible to stress corrosion and slow crack growth (Michalske and Freiman, 1982). The fatigue parameters of an all-ceramic material (IPS Empress) compared with those of feldspathic porcelain have recently been investigated (Myers *et al.*, 1994). The results showed that

TABLE 3**Product Information**

<u>Material</u>	<u>Product</u>	<u>Manufacturer</u>	<u>Reinforcing Component</u>
Aluminous core (Pt foil)	Vitadur-N™ core	Vident, Baldwin Park, CA	Alumina
Aluminous core	Hi-Ceram	Vident, Baldwin Park, CA	Alumina
Zirconia-reinforced	Mirage II™	Myron International, Kansas City, KS	Zirconia fibers
Injection-molded aluminous	Alceram®	Innotek Dental Corp, Lakewood, CO	Alumina
Heat-pressed, leucite-reinforced	IPS Empress	Ivoclar North America, Inc., Amherst, NY	Leucite
Leucite-reinforced	Optec HSP™	Jeneric/Pentron, Inc., Wallingford, CT	Leucite
Slip-cast alumina	In-Ceram®	Vident, Baldwin Park, CA	Alumina
Slip-cast alumina	In-Ceram Spinel®	Vident, Baldwin Park, CA	Spinel
Slip-cast alumina	In-Ceram Zirconia	Vident, Baldwin Park, CA	Zirconia, alumina
Mica glass-ceramic	Dicor™	Dentsply International, Inc., York, PA	Tetrasilicic fluormica
Hydroxyapatite glass-ceramic	Cerapearl®	Kyocera, San Diego, CA	Hydroxyapatite
Lithia-based glass-ceramic	Experimental	N/A	Lithium disilicate
Machinable glass-ceramic	Dicor MGC™	Dentsply International, Inc., York, PA	Tetrasilicic fluormica
Machinable ceramic	Vita Mark II®	Vident, Baldwin Park, CA	Sanidine
Magnesia core (glazed)	Experimental	N/A	Forsterite

the all-ceramic material had a 12-year failure stress (39 MPa) higher than that of conventional feldspathic porcelain (24 MPa). The study of the fatigue parameters of dental porcelains appears to be a key in lifetime prediction of all-ceramic restorations, and more research is definitely needed in this direction.

COMPARATIVE DATA

Extensive reviews on the qualities and mechanical properties of dental ceramics have been carried out by Wohlwend *et al.* (1989), Hondrum (1992), Wall and Cipra (1992), Anusavice (1993), and McLean *et al.* (1994). The mean flexural strength values of all-ceramic materials from several references are summarized in Table 2. Among the currently available materials, slip-cast ceramics exhibit the highest values compared with all other products (378-604 MPa). The mean flexural strength of alumina or leucite-based materials, whether sintered or heat-pressed, is between 70 and 180 MPa. Among the machinable ceramic materials, the mica-based material (Dicor MGC) has the highest flexural strength value (229 MPa). The product type, brand name, manufacturer, and type of reinforcing component for all ceramic materials reviewed in this paper are listed in Table 3. As mentioned previously, the nature of the crystalline phase present in the ceramic material strongly influences the mechanical properties of the final product.

FUTURE DIRECTIONS

The future of ceramics for dentistry is clearly open to new technologies. However, the greatest challenge in developing all-ceramic compositions or processing methods suitable for dental applications is satisfying strength as well as esthetics, while ceramic materials for industrial applications generally do not need to meet esthetic requirements.

As pointed out earlier, research is now focusing on fractographic analysis of clinically failed restorations, measure of fatigue parameters, and lifetime prediction of ceramic restorations. It is now established that at least a five-year evaluation period has to be completed before a long-term prognosis can be proposed. The metal-ceramic technique is still the most commonly used procedure in restorative dentistry, and the success of new all-ceramic systems will depend as much on developmental as on analytical research.

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