The ceramic revolution

Brenda Baker and **David Reaney** look at composition, processing mechanisms and clinical performance in monolithic and bilayer all-ceramic systems

There has been a shift over the last three decades when it comes to favouring the use of metal-free restorations by patients and dentists, who have both demanded highly aesthetic, biocompatible and long-lasting restorations.

Thus, several types of all-ceramic systems have been developed.

This overview presents past and current knowledge of monolithic and bilayer all-ceramic systems and addresses composition, processing mechanisms and clinical performance. Table 1 and its accompanying Figure 1 are the reference points for the materials discussed.

REINFORCED GLASS CERAMICS

Increased strength in glassy ceramics can be achieved by adding fillers that are uniformly dispersed throughout the glass matrix. This is called dispersion strengthening.

Leucite is used as a reinforcing crystal at a concentration of 35-45% by volume. IPS Empress (Ivoclar Vivadent) is an example of a leucite-reinforced glass ceramic. The molding procedure of IPS Empress is conducted at 1,080°C in a special, automatically controlled furnace. Leucite crystals are formed through a controlled surface crystallisation process in the SiO_2-Al_2O_3-K_2O glass system.

On cooling, compressive stresses develop at a tangent around the crystals due to the difference in the coefficient of thermal expansion (CTE) between leucite crystals and the glassy matrix. These stresses contribute to crack deflection and improved mechanical performance. The material is suitable for fabrication of inlays, onlays, veneers, and crowns.

GLASS INFILTRATED CERAMICS

In-Ceram Alumina (Vita) was the first all-ceramic system available for single-unit restorations and three-unit anterior bridges with a high strength ceramic core fabricated with the slip-casting technique. A slurry of densely packed (70-80 weight percent) Al_2O_3 is applied and sintered to a refractory die at 1,120°C for 10 hours.

This process produces a porous skeleton of alumina particles. This is then infiltrated with lanthanum glass in a second firing at 1,100°C for four hours to eliminate porosity and increase strength. The core is veneered with feldspathic porcelain.

In-Ceram Zirconia (Vita) was a modification of the original In-Ceram Alumina system, with an additional 35% partially stabilised zirconia oxide to the slip composition to strengthen the ceramic. Traditional slip-casting techniques can be used, or the material can be copy-milled from prefabricated, partially sintered blanks and then veneered with feldspathic porcelain. As the core is opaque and lacks translucency, the use of this material for anterior regions becomes problematic.

LITHIUM DISILICATE GLASS CERAMICS

The use of leucite-reinforced glass ceramic declined because of the introduction of lithium disilicate glass ceramics with significantly improved mechanical and aesthetic properties.

A significantly higher strength of 350MPa was achieved with a glass ceramic of the SiO_2-Li_2O-K_2O-ZnO-P_2O_5-Al_2O_3-La_2O_3 system by precipitating lithium disilicate ($Li_2Si_2O_5$) crystals. The crystal content of up to 70 vol% is higher than that of leucite materials.

Both lithium metasilicate (Li_2SiO_3) and crystobalite form during the crystallisation process before the growth of lithium disilicate ($Li_2Si_2O_5$) crystals. The final microstructure consists of highly interlocked lithium disilicate crystals, 5μm in length and 0.8μm in diameter. Thermal expansion mismatch between lithium disilicate crystals and glassy matrix results in compressive stresses developing at a tangent around the crystals. Crystal alignment after heat pressing of the lithium disilicate glass ceramic leads to multiple crack deflections and an increase in strength.

The lithium disilicate ceramic was originally introduced as IPS Empress 2 (Ivoclar Vivadent). Clinical data revealed high survival rates for anterior and posterior IPS Empress 2 crowns (95.5% after 10 years).

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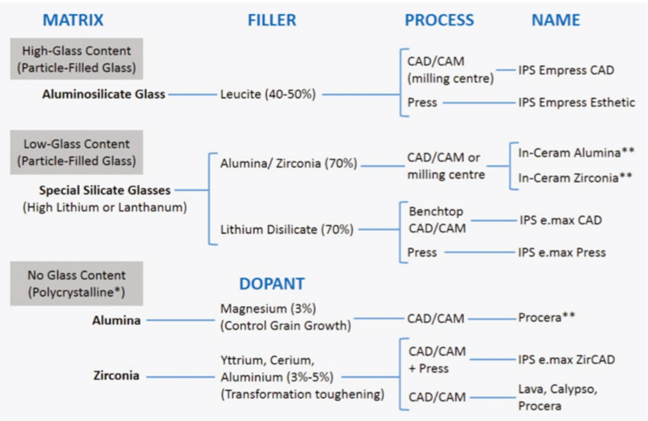

Figure 1: Compositional chart for all-ceramics; (**) earlier generation material, which is now outdated; (*) the fillers in polycrystalline ceramics are not particles but modifying atoms called 'dopants'

TABLE 1: MECHANICAL PROPERTIES OF DIFFERENT ALL-CERAMIC SYSTEMS

Material		Modulus (GPa)	Hardness (GPa)	Toughness (MPa m1/2)	Strength (MPa)	CTE°C X × 10–6	Firing (°C)
Porcelain	Lava ceram	78	5.3	1.1	100	10.5	810
	IPS E.max ceram	60–70	5.4	NA	90	9.5	750
	IPS E.max Zirpress (flourapatite)	65	5.4	NA	110	10.5–11	900–910
Glass ceramic	Empress Esthetic (leucite)	65–68	6.2	1.3	160	16.6–17.5	625
	IPS E.max Press (lithium disilicate)	95	5.8	2.75	400	10.2–10.5	915–920
	IPS E.max CAD (lithium disilicate)	95	5.8	2.25	360	10.2–10.5	840
Alumina	In-Ceram Alumina**	280	20	3.5	500	7.2	2,053 melting point
	Procera Alumina**	340	17	3.2	695	7.0	1,600
Zirconia	IPS E.max Zircad	210	13	5.5	900	10.8	1,500
	Lava	210	14	5.9	1,048	10.5	1,480
	Procera Zirconia	210	14	6	1,200	10.4	1,550
Tooth	Dentine	16	0.6	3.1	—	11–14	—
	Enamel	94	3.2	0.3	—	2–8	—

** earlier generation material, which is now outdated

THE PRESS TECHNIQUE

Pressable lithium disilicate glass ceramic (IPS E.max Press, Ivoclar Vivadent) has improved physical properties (flexural strength of 440MPa) and translucency through a different firing process that was developed in the SiO_2-Li_2O-K_2O-ZnO-P_2O_5-Al_2O_3-ZrO_2 system.

The press technique has two different types of ingots available: IPS E.max Press and IPS E.max Zirpress, which is a glass ceramic pressed onto zirconium oxide (Figures 1 and 2); E.max Zirpress ingots combine the press and CAD/CAM technique as the fluorapatite glass ceramic ingots are used to press onto IPS E.max Zircad frameworks.

The pressable lithium disilicate is produced according to a bulk casting method, which involves a process based on glass technology (melting, cooling, simultaneous nucleation of two different crystals, and growth of crystals) that aims to prevent defect formation. Following the glass formation, the ingots are then nucleated and crystallised in one heat treatment to produce the final ingots. These ingots are then pressed at approximately 920°C for five to 15 minutes to form a 70% crystalline lithium disilicate restoration.

The pressable lithium disilicate ceramic can be used in monolithic application for inlays, onlays, and posterior crowns or as a core for crowns and three-unit bridges anteriorly. E.max Ceram is a nano-fluorapatite layering ceramic that can veneer all IPS E.max components – be they glass ceramic or zirconium oxide.

Clinical data revealed high survival rates on IPS E.max Press onlays (100% after three years), crowns (96.6% after three years), monolithic inlay-retained bridges (100% after four years) and full crown retained bridges (93% after eight years).

A lithium disilicate glass ceramic (IPS E.max CAD, Ivoclar Vivadent) has been designed for CAD/CAM technology (Figure 4). The milled lithium disilicate block is exposed to a two-stage crystallisation process:

1. Lithium metasilicate crystals are precipitated during the first stage. The resulting glass ceramic has a crystal size range of 0.2-1.0μm with approximately 40 vol% lithium metasilicate crystals. At this pre-crystallised state, the CAD/CAM block exhibits a flexural strength of 130-150MPa, which allows the material to be easily milled without excessive bur wear
2. The final crystallisation process occurs after milling of the restoration at 850°C in vacuum. The metasilicate crystal phase is dissolved completely, and the lithium disilicate crystallises.

This process also converts the blue shade of the pre-crystallised block to the selected tooth shade with more chroma, and results in a glass ceramic with a crystal size of 1.5μm and a 70% crystal volume incorporated in a glass matrix. CAD/CAM processed lithium disilicate glass ceramic has a flexural strength of 360MPa. The translucency and available shades can be used for monolithic restorations with subsequent staining characterisation, or as a core material with

Figure 2: These E.max restorations demonstrate the exceptional aesthetics that can be achieved

Figure 3: E.max Zirpress

Figure 4: This ingot is suitable for CAD/CAM

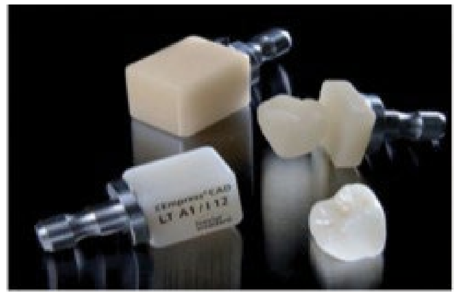

Figure 5: This state-of-the-art milling technology delivers superb dimensional accuracy and guarantees consistency

Figure 6: This Lava posterior bridge provides strength and beauty

subsequent coating with veneering ceramics.

CAD/CAM processed lithium disilicate can be used for anterior or posterior crowns, implant crowns, inlays, onlays, and veneers. Clinical data revealed high survival rates on single crowns (100% after two years).

Thus, IPS E.max Press material is produced similarly to the IPS E.max CAD as far as the formation of the initial glass ingots, as they are composed of different powders that are melted and cooled to room temperature to produce glass ingots.

NEW GENERATION MATERIALS

Lithium silicate ceramic

Lithium silicate ceramic is a new glass high strength monolithic ceramic that has improved durability and chipping. Lithium silicate exceeds the ISO strength requirements for all-ceramic restorations with a flexural strength of 373MPa, and combines aesthetics and strength.

Lithium silicate can be used for anterior and posterior crowns, three-unit bridges having only one pontic with the second bicuspid as the most distal abutment, as well as inlays, onlays and veneers.

Veneers are recommended when they can be combined with adjacent lithium silicate crowns or bridges, providing sufficient reduction is achieved. The use of this material is contra-indicated in patients with parafunctional activities such as bruxers or clenchers and should not be used as abutments for cast partials or for Maryland-type bridges.

Lithium silicate can be conventionally cemented or adhesively bonded. If adjustment is required, use of a fine diamond with water and polishing with a ceramic polishing wheel is advised.

Lithium silicate has medium translucency when compared to other monolithic ceramics and is available in all Vita classical and bleached shades.

The porcelain should not be fired, as the ceramic requires specific stains and glaze, as well as precisely calibrated ovens at specific temperatures and vacuum settings. The crown should be returned for a re-glaze firing to the laboratory. This technology is very new and somewhat unproven as only short-term evidence exists for its use.

Lava Ultimate

Lava Ultimate is a CAD/CAM material that is aesthetic, versatile and durable. Lava Ultimate contains three ceramic filler particles – silica particles of 20nm, zirconia particles of 4-11nm and agglomerated nanoparticles of silica and zirconia, which are all embedded in a highly cross-linked polymer matrix. The flexural strength of Lava Ultimate is 200MPa.

As a resin nano-ceramic with an elastic modulus comparable to dentine, it can better absorb chewing forces. Less wear to opposing enamel occurs with Lava Ultimate than with other glass ceramics.

Lava Ultimate can be used for implant-supported crowns and other single unit situations including crowns, onlays, inlays and veneers. It is also easily adjusted. If access is needed to an abutment and implant at any time, an access cavity can be created, resealed with composite and then repolished.

Lava Ultimate restorations must be bonded with an adhesive resin cement. There are eight shades and two translucencies. Lava Ultimate has excellent stain resistance for colour stability and demonstrates a less brittle nature, which allows for easy milling and no need for post-firing.

High strength ceramics

High strength ceramics in dentistry include alumina and zirconia, although zirconia has superior mechanical properties compared with alumina.

Chemically, zirconia is an oxide and, technologically, it is a ceramic. Zirconia is characterised by a dense, monocrystalline homogeneity, possesses low thermal conductivity, low corrosion potential and is radiopaque. It has high biocompatibility and low bacterial surface adhesion and advantageous optical properties.

Zirconia in its pure form is a polymorph that has three temperature-dependant phases:

1. Monoclinic (room temperature to 1,170°C)
2. Tetragonal (1,170–2,370°C)
3. Cubic (2,370°C to melting point).

With the addition of stabilising oxides such as magnesia, ceria, yttrium, and calcium to zirconia, the tetragonal phase is retained in a metastable condition at room temperature, enabling a phenomenon called 'transformation toughening' to occur.

In response to mechanical stimuli, the partially stabilised crystalline tetragonal zirconia transforms to the more stable monoclinic phase, with a volume increase of approximately 4%. This increase in volume counteracts further crack propagation by compression at the tip of the crack.

Zirconia can be used for root canal posts, frameworks for posterior teeth, implant-supported crowns and multi-unit bridges, with current recommendations allowing spans of up to six units (four pontics anteriorly and three pontics posteriorly), which depends on the manufacturer's recommendation for its own material.

Custom-made bars can be made to support fixed and removable dental prostheses, implant abutments, and implants. Porcelain fused to zirconia should be avoided in bruxers or patients with parafunctional activities.

Zirconia and CAD/CAM technology

Some CAD/CAM systems machine fully sinter zirconia blocks, which have been processed by hot isostatic pressing. Due to the hardness and poor machinability of fully sintered zirconia, a robust milling system and extended milling periods are required (Figure 5).

Most of the available CAD/CAM systems shape blocks of partially sintered zirconia. Milling from partially sintered blocks involves machining enlarged frameworks in a so-called 'green state'. These blocks are then sintered to full strength for five to six hours, which is accompanied by shrinkage of the milled framework by approximately 25% to the desired dimensions. This shrinkage must be compensated for during milling. Examples of these systems are Lava (3M Espe), Procera (Nobel Biocare) and Cerec (Sirona) (Figure 6).

Zirconia is as opaque as metal if used at certain core thicknesses. Cores should be 0.5mm thick buccally; for Procera zirconia, this can be 0.6mm. Studies have shown that 0.5mm

Figure 7: Several crowns milled from CAD/CAM

Figure 8: Final fully milled zirconia (FMZir) crowns showing excellent occlusal detail

of zirconia is too opaque for incisors. Most manufacturers use a white form of zirconia for cores. The chroma and translucency of natural teeth can be matched if the correct shaded core is chosen as opposed to using the white zirconia core material.

Translucent liners or shoulder powders can be used as the bonding layer and to assist with core colour. Base dentines are now available to replace former opaque dentines. Sintered zirconia can now be immersed in specifically coloured dye, which minimises the high value of the material and more closely matches the abutment colour.

Studies have shown that bridge connector heights and widths of at least 3-4mm considerably reduce stress levels in the connector and provide adequate strength. The zirconia coping design must give good support for veneering porcelain. Ceramic copings are frequently milled in a standardised manner with thicknesses between 0.4-0.7mm based on experimental guidelines.

The core to veneering porcelain thickness ratio is optimal at 1:1 for aesthetics and function. The core must be thick enough and be sufficiently stiff. The aim is to produce coping and framework designs that reduce the tensile loading of the veneering porcelain. This, in turn, will reduce mechanical failure. Porcelain fused to zirconia needs more additional support in proximal areas than porcelain fused to metal (PFM). Cohesive fracture within the veneering ceramic has been the most frequent reason for failures.

A major drawback of zirconia restorations is aging observed in the presence of moisture. This is called low temperature degradation, which can affect the mechanical properties.

Meticulous attention to the occlusion is needed, particularly pre-cementation when using zirconia-based restorations. In many clinical studies, veneer failures were associated with roughness in the veneering ceramic due to occlusal function or occlusal adjustment. Any occlusal adjustments should be performed with copious irrigation and polishing, as intense heat is generated when tungsten carbide or diamond burs are used.

Fully milled zirconia

Fully milled zirconia (FMZir) is a new generation, fully milled monolithic solid zirconia crown or bridge restoration with no veneering ceramic (Figures 7 and 8).

It is designed and milled using CAD/CAM technology, and then soaked in a dyeing liquid to approximate the requested shade. Techniques have been introduced for colouring of FMZir restorations that have involved a three-zone colouring system. The unsintered restoration is brushed with the final colour around the cervical area of the proposed crown. The desired body shade is then applied.

Effect shades are finally added to the occlusal aspect of the crown. Once the milled crown has had the shade adjusted in the colouring solution, sintering occurs in an oven for 6.5 hours at 1,560°C. Sintering changes the tetragonal zirconia to a monolithic phase. This makes the milled crown less likely to fracture and break. During sintering, zirconia shrinks and becomes denser. The use of a computer program increases the crown size during milling, which makes up for the shrinkage that takes place during sintering.

The final FMZir solid zirconia crown or bridge emerges nearly 'bulletproof' with reported compressive strengths of more than 1,200MPa.

There is no danger of delamination of the traditional porcelain veneer layer as with some porcelain fused to zirconia crowns, and acceptable aesthetics can be achieved when inserted in lieu of metal occlusal porcelain fused to metal and full cast metal restorations posteriorly.

FMZir crowns or bridges are indicated for bruxers and grinders when PFM occlusal or full cast restorations are not desired; and where the antagonist is metallic, zirconia, but no dentine, is exposed. FMZir is ideally suited for posterior molar crowns when the patient desires a tooth coloured restoration but lacks the preparation space for, or has broken, a PFM crown in the past due to bruxing.

Cases where the dentine is exposed on the antagonist preoperatively should be precluded from FMZir and full gold or PFM options are preferred. To ensure the bridge will not fracture, each connector must have a calculated number of 27 or more. The number is determined by measuring the connector areas' height, width, and depth in millimetres, and the numbers are multiplied to obtain the final result. With adequate connector size, three, four and even six unit bridges are dimensionally predictable using FMZir.

The following factors need to be carefully considered:

- Although the restorations are fabricated using a colour dip that is prepared to mimic the Vita shade guide selection system, some units can appear to be a higher value than the shade requested. Thickness of the restoration is an issue that impinges on the aesthetic outcome greatly: too much reduction leads to zirconia, which is simply too thick and opaque, with no chance of light transmission. Replacing a PFM with a FMZir should not be considered as the copious axial wall reduction means an aesthetic zone value that is far too high
- The fitting surface of a zirconia restoration cannot be etched in the way that materials like E.max or Procera can be, and so cannot rely on micro-mechanical retention
- Incorrect and insufficient polishing creates an even more abrasive finish, which can wreak havoc with the opposing dentition. If dentine is exposed on the antagonist after adjustment, this wear is exacerbated even further.

ENHANCE AND EXPAND

Glass ceramics are used for all-ceramic cores to enhance form and aesthetics. In monolithic applications, inlays, onlays, veneers and crowns are fabricated.

High strength ceramics evolved as cores for crowns and bridges suitable for high load bearing areas. Monolithic zirconia is suitable for single crown and full mouth reconstructions, and especially suitable for situations where parafunctional activity is evident.

With the advent of CAD/CAM, the clinical applications have become even more expansive as full-arch zirconia frameworks, as well as implant abutments and complex implant superstructures, can be created for fixed and removable prostheses. ID