Machinable glass-ceramics forming as a restorative dental material

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MgO, SiO₂, Al₂O₃, MgF₂, CaF₂, CaCO₃, SrCO₃, and P₂O₅ were used to prepare glass-ceramics for restorative dental materials. Thermal properties, phases, microstructures and hardness were characterized by DTA, XRD, SEM and Vickers microhardness. Three-point bending strength and fracture toughness were applied by UTM according to ISO 6872: 1997(E). XRD showed that the glass crystallized at 892°C (second crystallization temperature+20°C) for 3 hrs consisted mainly of calcium-mica and fluorapatite crystalline phases. Average hardness (3.70 GPa) closely matched human enamel (3.20 GPa). The higher fracture toughness (2.04 MPa√m) combined with the hardness to give a lower brittleness index (1.81 μm^{-1/2}) which indicates that they have exceptional machinability. Bending strength results (176.61 MPa) were analyzed by Weibull analysis to determine modulus value ($m=17.80$). Machinability of the calcium mica-fluorapatite glass-ceramic was demonstrated by fabricating with CAD/CAM.

Keywords: CAD/CAM technique, Calcium mica-fluorapatite glass-ceramic, Restorative dental material, Brittleness index, ISO 6872: 1997(E)

INTRODUCTION

The use of all-ceramic materials for fixed restorations in dentistry has become increasingly important due to their aesthetics, biocompatibility, high abrasion resistance, high wear resistance, chemical inertness and both thermal and electrical insulation^{1,2}. However, their hardness and brittleness affect their fabrication capabilities. Due to the small size of dental restorations, it is necessary to be able to fabricate them with high accuracy and precision. Computer aided design and computer aided manufacturing (CAD/CAM) technology provides dentists with the ability to do this for the often complex shapes of these restorative dental ceramics. This technology is replacing the traditional lost wax casting technique with a resultant decrease in manufacturing time³. CAD/CAM systems, however, utilize abrasive (grinding and milling) processes, and therefore, ceramics used with this technique need to possess excellent machinability³.

Currently, most restorative ceramic materials used with CAD/CAM systems are based on leucite (K₂Al₂Si₄O₁₂). However, because of its high hardness and high abrasiveness, machining results in high tool wear and, in use, causes wear of the opposing teeth⁴.

Machinability is an important property of mica-based glass-ceramics. It arises from the weak bonding between the mica layers resulting in a perfect basal cleavage^{5,6}. Hence, mica-based glass-ceramics lend themselves for use with CAD/CAM systems. Alkali-containing trisilicic

and fluorophlogopite-type mica were first reported by Beall⁷. Macor[®] is a well known mica glass-ceramic developed by Corning Glass. Its chemical composition was based on K₂O-MgO-B₂O₃-Al₂O₃-SiO₂-F system, of which the main crystalline phase was fluorophlogopite, KMg₃(AlSi₃O₁₀)F₂⁷. Subsequently, Hoda and Beall⁸ investigated the different nonalkali mica glass-ceramics containing barium, calcium, and strontium in the system of alkali earth oxide-Al₂O₃-SiO₂-F. These glass-ceramics had excellent dielectric properties, high mechanical strength and refractoriness. The structural formula of mica is generally expressed as X_{0.5-1}Y₂₋₃Z₄O₁₀(OH,F)₂, where X, Y, and Z are cations in 12-, 6-, and 4-fold coordinations respectively⁹.

Uno *et al.*⁹ investigated glasses from the ternary system of Ba_{0.5}Mg₃(Si₃AlO₁₀)F₂-Ca₃(PO₄)₂-Mg₂Al₄Si₅O₁₈ and found that, in agreement with Chaysuwan *et al.*¹⁰, bending strength and fracture toughness were improved over that of Macor[®]. Hardness and biaxial flexural strength of these glass-ceramics were twice those of Macor[®], however, machinability was worse than that of Macor[®].

The recent work of Chaysuwan *et al.*¹¹ described the introduction of Sr²⁺ to the interlayer ions of the mica structure instead of Ba²⁺, giving an initial composition close to a Sr_{0.5}Mg₃(Si₃AlO₁₀)F₂-Ca₃(PO₄)₃F-Mg₂Al₄Si₅O₁₈ stoichiometry. They found that the hardness of the crystallized glass-ceramics for the second crystallized temperature of heat treatments was similar to human enamel whilst the strength was also low. Keawsupsak *et al.*¹² introduced fluorapatite (Ca₅(PO₄)₃F) into this glass-ceramic system so as to increase the flexural strength

and found that both strength and fracture toughness increased with increasing amounts of fluorapatite up to a fluorapatite content of not more than 4 mol%. This investigation describes the fabrication of glass-ceramics based on this 4 mol% of fluorapatite (GCF 4.0) for restorative dental materials via CAD/CAM using CEREC 3 software.

MATERIALS AND METHODS

Glass preparation

The glasses were produced by melting MgO, SiO₂, Al₂O₃, MgF₂, CaF₂, CaCO₃, SrCO₃, and P₂O₅ in high density alumina crucibles at a temperature of 1,420°C in a high temperature furnace (Nabertherm, HT 16/18, Lilienthal, Germany, max. 1,800°C) for 2 hrs with heating rate of 10°C/min. A batch size of approximately 100 g was used. The resultant chemical composition of the glass batch prepared had a weight ratio close to 4 mol% of fluorapatite and 90 mol% of mica and is shown in Table 1^{11,12}. The melts were rapidly quenched into water to prevent phase separation and crystallization⁹. The obtained glasses (glass frit) were remelted and poured into a carbon mould to yield a glass rod or cylinder. The obtained glass rod was then immediately transferred to an annealing furnace (Linn High Therm, LM 512, Eschenfelden, Germany, max. 1,200°C) operating at approximately 50°C below their glass-transition temperature (T_g -50°C) for 2 hrs followed by slow cooling to room temperature in the furnace.

Glass characterization

1. Differential thermal analysis (DTA)

The glasses were characterized by differential thermal

analysis using a Perkin Elmer TAC7/DX (Perkin Elmer, DTA7, Massachusetts, USA). Glass frits were crushed and sieved through a 325 mesh (<45 micrometer) to obtain glass powder suitable for thermal analysis. Each scan was from ambient temperature to 1,200°C and α -Al₂O₃ powder was used as the reference material.

Optimum nucleation temperatures were determined by the Marrotta method¹³ with one hour holding for nucleation. Suitable heat treatment times were determined using these nucleation temperatures and were held at various length of times (0.5, 1, 2, 4, and 10 hours).

DTA was performed by heating samples at a heating rate of 5, 10, 15, and 20°C/min to the optimum nucleation temperature and held for one hour. Samples were also heated from ambient to 1,000°C in order to calculate the activation energy by the Kissinger equation¹⁴ in Eq. (1) and the Avrami exponent by Augis-Bennett equation¹⁵ in Eq. (2).

The Johnson-Mehl-Avrami equation (J.M.A.)¹⁶ was applied to describe the behavior of the non-isothermal crystallization kinetics of glass developed by Kissinger¹³ as Eq. (1):

$$\ln \frac{T_p^2}{\alpha} = \frac{E}{RT_p} + \text{constant} \quad (1)$$

where T_p is the crystallization peak (Fig. 2), α is the heating rate (K/min), E is the activation energy (J/mol) and R is the universal gas constant (8.314 J/mol.K).

Using the value of the activation energy, the Avrami exponent (n) was calculated by the Augis-Bennett equation¹⁵ as in Eq. (2):

Table 1 The composition of the glass^{11,12}

Compound	MgO	SiO ₂	Al ₂ O ₃	MgF ₂	CaF ₂	CaCO ₃	SrCO ₃	P ₂ O ₅
Concentration (mol%)	26.09	40.76	7.74	12.23	x	y	6.11	z

Fig. 1 Schematic of heat treatment process

Fig. 2 DTA curve of the glass-ceramic

$$n=2.5 \frac{RT_p^2}{\Delta TE} \quad (2)$$

where ΔT is the interval temperature on the half height point of crystallization peak. The value of the Avrami exponent (n) is a parameter related to the crystallization mechanisms: for $n=1$, the crystallization mechanism is one of surface crystallization; for $n=2$, the mechanism is two-dimensional growth; and for $n=3$, three-dimensional growth¹⁷.

Glass-ceramics preparation

Both the glass rods and frit were crystallized via a heat treatment process outlined by Marotta¹³. The heat treatment process converts glass to glass-ceramics by two individual processes, nucleation and crystal growth¹³. Glass rods were heated at the constant heating rate of 10°C/min to the optimum nucleation temperature and held there for 3 hrs (Fig. 1). They were then heated up at the same heating rate to allow crystal growth at the second peak of crystallization plus 20°C ($T_{p2}+20^\circ\text{C}$) and held for 3 hrs heat treatment time. The obtained glass-ceramics based on this 4.0 mol% of fluorapatite was called GCF 4.0. Fig. 2 shows two exothermic peaks, denoted by T_{p1} and T_{p2} , representing the first crystallization temperature and the second crystallization temperature, respectively.

Characterization techniques

1. X-ray powder diffraction (XRD)

A Philips powder diffractometer (Philips, X'pert PW 3040/00, Eindhoven, The Netherlands) was used with Cu K_α X-rays. Heat-treated frits were ground to a fine powder for analysis by X-ray diffraction. Scan parameters were a step size of 0.05°, a count time of 0.5 s, and operating at 40 kV and 30 mA.

2. Scanning electron microscopy (SEM)

Microstructure was observed on surfaces which were polished to 1 micrometer and fracture surfaces of mechanical-tested specimen by scanning electron microscope (Philips, XL30&EDAX, Eindhoven, the Netherlands). Prior to SEM analysis, surfaces were chemically etched using 10% hydrofluoric acid solution for 20 s then rinsed with water and sonicated to remove debris. No etching was performed on fracture surfaces. After cleaning, the samples were gold sputtering.

Mechanical testing

1. Vickers hardness

Vickers microhardness (Shimadzu, HMV-2000, Kyoto, Japan) was performed with a pyramid-shaped diamond indenter at a load of 500 g for 15 s. The thickness of specimens was 3 mm.

2. Three point bending strength

Glass-ceramic rods were cut into bars of 4×3×40 mm³. The edge chamfer specified for strength test was ignored¹⁷. They were then ground and polished to 1 micrometer. Ten bar specimens of each were tested by a universal testing machine (Instron, 8872, Massachusetts,

USA) according to ISO 6872: 1997(E)¹⁸ using three-point geometry. A cross-head speed of 0.5 mm/min was used in order to avoid subcritical crack growth during the experiment. The strength distribution was analyzed by Weibull distribution (ISO 6872: 1997(E)¹⁸), using the following equation:

$$\ln \ln \left(\frac{1}{1-P_f} \right) = m \ln \sigma_c - m \ln \sigma_{c,0} \quad (3)$$

where P_f is the probability of failure, σ_c is the strength, $\sigma_{c,0}$ is the characteristic strength (at 63% failure probability) and m is the Weibull modulus.

The failure probability was calculated assuming the following relation: $P_f = (i-0.5)/N$ where P_f is the failure probability of the i^{th} specimen (ranked in order of ascending strength) and N is the total number of specimens tested.

3. Fracture toughness

Fracture toughness (K_{IC}) values were obtained using Single Edge V-Notch Beam (SEVNB) method. Ten bar specimens in size of 3×2×25 mm³ in accordance with ISO 6872: 1997(E)¹⁸ were tested by a universal testing machine (Instron, 8872, Massachusetts, USA) applying cross-head speed of 0.5 mm/min.

4. Machinability

The machinability can be simply measured when a material is cut, however, quantitative measurement is difficult depending on various criteria such as measuring tool wear, surface roughness and cutting force^{19,20}. Boccaccini²⁰ determined a brittleness index (B) as a parameter for estimating the machinability of glass-ceramics given by the ratio of hardness (H_v) to fracture toughness (K_{IC}) (Eq. (4)):

$$B = \frac{H_v}{K_{IC}} \quad (4)$$

The lower the brittleness index, the higher the machinability.

CAD/CAM Fabrication

Prior to sand milling of glass-ceramic blocks, they were cut from glass-ceramic rods to a size of 10×12×15 mm³ and ground with grit size 8.4 μm of SiC paper. Consequently, they were then adhered to stainless steel abutments by Super-Bond C&B which is a self-cure dental adhesive resin cement²¹. The CEREC 3D software (V2.10 R1500) is used for designing inlay, veneer, premolar crown and molar crown restorations. The default milling mode and the default milling burs (CEREC Cone-shaped Cylinder Diamond 1.6, Art.No.58 55734 D3329, CEREC Cylinder Diamond 1.6, Art. No. 5466193b D3268, Sirona Dental Systems GmbH, Bensheim, Germany) were used to mill the glass-ceramic blocks.

Roughness measurement by stylus profiler

After fabricating, specimens were sonicated with acetone to remove debris. Then, for each specimen, the roughness

Fig. 3 (a) measured location along occlusal margins, (b) measured location along interproximal margins, (c) SEM of occlusal surface and (d) interproximal surface

was measured three times by a stylus profiler (Taylor-Hobson, Leicester, United Kingdom). The surface contact length was 3.2 mm in orthogonal directions.

Margin gap size of occlusal and interproximal surface of inlay

Fit at the margin of the inlay was evaluated in terms of the average marginal gap of the occlusal surface and interproximal surface. The margin gaps were measured in 10 locations along the occlusal margins (Fig. 3a) and 6 locations along interproximal margins (Fig. 3b). The photographs were taken perpendicular to the surface along the margin gap using scanning electron microscopy (Figs. 3c and 3d).

RESULTS

Thermal analysis

1. Differential thermal analysis (DTA)

The DTA curve of the as-quenched glass is shown in Fig.

2. The glass transition temperature, T_g , was given by the

endothermic shoulder at approximately 630°C. The two exothermic peaks at 767°C and 872°C are crystallization peaks which were denoted by T_{p1} and T_{p2} , respectively. The endothermic peaks above 1,000°C are the result of the decomposition, softening, and, probably, melting processes of the different crystalline phases.

Previous investigations^{11,12)} indicated that the glass-ceramics crystallized at a temperature of 20°C above the second peak of crystallization ($T_{p2}+20^\circ\text{C}$) showed hardness resembling human enamel and that the crystallization was complete. Hence, for this research, $T_{p2}+20^\circ\text{C}$ was used.

2. Determination of the optimum nucleation temperature and time of heat treatment outlined by Marotta method¹³⁾ Differential thermal analysis was performed to determine the optimum nucleation temperature and time by collecting T_{p1} from each isothermal hold for an hour at $T_g-30^\circ\text{C}$, $T_g-15^\circ\text{C}$, $T_g^\circ\text{C}$, $T_g+15^\circ\text{C}$ and $T_g+30^\circ\text{C}$. Then the graph of holding temperature against ($T_{p2}^{\text{original}} - T_{p2}^*$), i.e. the difference temperatures between T_{p2} of as-quenched glass and T_{p2}^* of the other holding

Fig. 4 (a) $T_{p2} - T_{p2}^*$ plotted against heat treatment temperature
(b) $T_{p2} - T_{p2}^*$ plotted against time of heat treatment

Fig. 5 Plot of $\ln(T_{p2}^2/a)$ vs $1/T_{p2}$

Fig. 6 XRD patterns of: (a) as-received glass (b) a glass-ceramic crystallized at 892°C

temperatures, were plotted. Fig. 4(a) shows the plots of $(T_{p2} - T_{p2}^*)$ versus holding temperatures for glass ceramic GCF 4.0. The maxima, from where two straight lines drawn through the points intersected provided the optimum nucleation temperature of 643°C for this material. Thus, the samples were held for various times at this temperature in order to evaluate optimal time for nucleation duration for the heat treatment¹³⁾. In Fig. 4(b), plots of $T_{p2} - T_{p2}^*$ against the times of heat treatments are presented. It shows that the nuclei number increases rapidly with increasing heat treatment time, similar to that found by Marotta's¹³⁾. It was found that the maximum number of nuclei occurred at approximate used as the time of heat treatment.

The activation energy (E) for crystallization, derived

from the slope (E/R) of the plot of $\ln(T_{p2}^2/a)$ against $1/T_{p2}$, was 175.47 kJ/mol as shown in Fig. 5. From Eq. (2), the Avrami exponent was approximately 3 indicating that the dominant crystallization mechanism was three-dimensional in the bulk.

Crystallization process

1. X-ray diffraction analysis (XRD)

The changes in intensity of XRD patterns of an as-quenched glass and the glass-ceramic crystallized at $T_{p2} + 20^{\circ}\text{C}$ (892°C) are shown in Fig. 6. The pattern of the as-received glass shows a fully amorphous material as in Fig. 6(a) whereas Fig. 6(b) shows the patterns of heat-treated sample heated up to a temperature of 892°C and soaked at that temperature 3 hrs. The predominant

Fig. 7 Microstructures of the polished and etched surface of glass-ceramics crystallized at 892°C, (a) grains of Ca-mica and glassy phase at grain boundaries, (b) mica grew radially (the fingers indicated interlocking structure), microstructures of the fracture surface without etching (c) the fingers pointed plate-like of Ca-mica microstructure and (d) plate-like microstructures in the bulk

crystalline phases are calcium-mica ($\text{Ca}_{0.5}\text{Mg}_3\text{AlSi}_3\text{O}_{10}\text{F}_2$), fluorapatite ($\text{Ca}_5(\text{PO}_4)_3\text{F}$) mixed with strontiumapatite ($\text{Ca}_5(\text{PO}_4)_3\text{Sr}$) and anorthite ($\text{CaAl}_2\text{Si}_2\text{O}_8$). In addition, forsterite (Mg_2SiO_4), stishovite (SiO_2) and silicon oxide (SiO_2) were the minor crystalline structures. Cordierite ($\text{Mg}_2\text{Al}_4\text{Si}_5\text{O}_{18}$) was not observed in specimens of this research. The absence of cordierite is beneficial as it is hard and may result in increased tool wear and is considered an undesirable phase in a machinable glass-ceramic⁴⁾.

2. Microstructural analysis

The SEM micrograph of the polished and etched surface of optimally heat treated GCF 4.0 is shown in Fig. 7(a). The microstructure is composed of two phases, a glassy phase and a calcium-mica phase. The equiaxed grains of calcium-mica grew radially out from the centre of each grain until meeting at the grain boundaries. An interlocking microstructure of mica was then formed²²⁾ as shown in Fig. 7(b). The grain boundaries had a remnant glassy phase, depicted by the chemically attacked area due to the etching with HF. The average grain size of calcium-mica was between 4.0 and 5.7

Fig. 8 Weibull distribution for flexural strength

Table 2 Mechanical properties of the resultant glass-ceramic and human enamel

	$\sigma_{c,0}$ (MPa)	m	H_v (GPa)	K_{IC} (MPa $\sqrt{m}$)	B ($\mu\text{m}^{-1/2}$)	Machinability
GCF 4.0	176.61	17.80	3.70 $\pm$ 0.24	2.04 $\pm$ 0.30	1.81 $\pm$ 0.29	○
Human enamel ³⁾	—	—	3.20 $\pm$ 0.40	0.77 $\pm$ 0.05	4.15 $\pm$ 0.58	○
2A8M ²²⁾	139	—	2.8	—	—	○
3A7M ²²⁾	204	—	4.8	—	—	×

Remark: A and M are the stoichiometric fluorapatite and calcium-mica, respectively.
○ stands for “good machinability”; × stands for “no good machinability”.

Fig. 9 (a) SEM of crown (15 $\times$) with magnification of strip lines, (b) reveals the designed inlay and (c) the duplicated inlay

micrometer (Intercept method ASTM E112 standard²³⁾). Ca-mica crystals on the fracture surface consist of layers of plates as shown in Fig. 7(c). This material had approximately 80 vol% of randomly interlocking crystals of mica. Generally, the bulk microstructures consisted of plate-like structures as shown in Figs. 7(c) and 7(d).

Mechanical properties and machinability

The three-point bending strength data were analyzed in

a double-logarithmic Weibull plot (Fig. 8), where the slope and x-axis intersection of the fitting curve corresponds to the Weibull modulus, m , and the characteristic strength, $\sigma_{c,0}$, respectively. The characteristic strength is 176.61 MPa and Weibull modulus of 17.80 as shown in Table 2. Three-point bending strength and Vickers hardness of GCF 4.0 is higher than 2A8M²²⁾, however, lower than that of 3A7M²²⁾.

Table 3 Marginal gap width of inlay of GCF 4.0

Location	Marginal gap width (μm)
Occlusal	88.37 $\pm$ 35.45
Interproximal	109.85 $\pm$ 59.21

For acceptable machinability of a glass-ceramic, the brittleness index (B) of the material should be less than $4.3 \mu\text{m}^{-1/2}$ (20). From Table 2, it can be seen that GCF 4.0 is within this range and can be machined by conventional dental tools. The hardness of GCF 4.0 is 3.70 GPa and is similar to that of human enamel (3.2 GPa), thus, it should not induce increased wear of the opposing contact tooth. Due to the large number of fine calcium-mica crystals and their interlocking microstructures, resistance to crack growth results in a relatively high K_{IC} (2.04 MPa $\sqrt{\text{m}}$). On the other hand, K_{IC} of enamel (0.77 MPa $\sqrt{\text{m}}$) is low resulting from easy fracture along the weak boundaries between the enamel rods⁵.

Fabrication

The restoration was designed with the aid of a computerized design (CAD) by CEREC 3D software. The glass-ceramic blocks were then milled via a computer-controlled milling machine (CAM), for example, veneers, inlays, and crowns (Fig. 9(a)). The fracture behavior of GCF 4.0 allows this glass-ceramic to be machinable because the cleavage allows propagation of cracks to follow a path determined by the cutting tool (diamond bur). No microcracking was observed away from the cutting surface, however, strip lines (Fig. 9(a)) from the diamond bur were present on the machined surface were due to incomplete surface finishing. The mean surface roughness as described by the arithmetic mean roughness (R_a) was $1.95 \pm 0.03 \mu\text{m}$. The successive deformation caused by cutting was attributed to the degree of plasticity of the Ca-mica phase more like a ductile metal than a brittle ceramic²⁴. Moreover, the appearance of the restoration was an exact replica as the design shown in Figs. 9(b) and 9(c). The average gap sizes of the inlay were calculated for the occlusal surfaces ($88.37 \pm 35.45 \mu\text{m}$) and interproximal surfaces ($109.85 \pm 59.21 \mu\text{m}$) as shown in Table 3. Both the mean marginal gap size along the occlusal surfaces and the interproximal surfaces of the GCF 4.0 were within clinically accepted standards ($<120 \mu\text{m}$)²⁵.

DISCUSSION

This mica layers are connected to each other by alkaline earth ions. The weak bonding of these alkaline earth interlayer ions determine the mechanical properties of these layered structures⁵. For this reason, mica crystals possess excellent cleavages perpendicular to the c -axis. By contrast, fracture propagation across the basal plane is more difficult inducing fractures to the cleavage

planes or mica-glass interfaces²⁶.

The commercial mica glass-ceramic materials used for CAD/CAM, such as Dicor (tetrasilicic mica: $\text{KMg}_{2.5}\text{Si}_4\text{O}_{10}\text{F}_2$) and Macor (fluorophlogopite: $\text{KMg}_3\text{AlSi}_3\text{O}_{10}\text{F}_2$) contain K^+ as the interlayer ions²⁷. The glass-ceramic in this work contains Ca^{2+} as the interlayer ions and exhibits a higher strength than the K^+ interlayer glass ceramics due to the divalency of these interlayer alkaline earth ions.

Taruta *et al.*²² investigated calcium-mica and fluorapatite glass-ceramic and found that 3A7M²², composed of a large amount of fluorapatite crystals and with a finer calcium-mica microstructure, gave higher bend strengths and hardness than those of GCF 4.0 (0.4A9M) and 2A8M²². Its machinability is inferior to the other materials because of the incomplete interlocking microstructure²². The interlocking of the randomly orientated mica crystals is a crucial characteristic in developing good machinability in glass-ceramics⁵.

Since the crystals are in mutual contact, a series of deflections, branching and often blunting of cracks absorb energy²⁶ allowing for good machining. GCF 4.0 contains the highest amount of mica resulting in the highest degree of interlocking.

The Weibull modulus (m) describes the relative spread of strength values in an asymmetric distribution. The Weibull modulus of this glass-ceramic material approaches a value of 18 exhibited a large m value. This good value of Weibull modulus demonstrates the greater clinical reliability and the small flaw size distribution in this material²⁸. The characteristic strength of this glass-ceramic is appropriate for a single unit of anterior or posterior prostheses (*e.g.* veneers, inlays, onlays and crowns) according to ISO 6872 : 1997(E). Nevertheless, the chemical solubility must be investigated to determine long term durability¹⁸.

Boccaccini²⁰ has proposed the brittleness index as a parameter for machinability evaluation. The brittleness index was given by the ratio of the hardness (H_v), which quantifies the resistance to deformation, to the fracture toughness (K_{IC}), which quantifies the resistance to fracture. The correlation of both of these phenomena is preferred over hardness and toughness considered separately in order to predict the machinability of glass-ceramics. The machinability of restorative dental materials should be similar to that of human enamel. The GCF 4.0 can be machined comparable to human enamel according to this index.

The CAD/CAM system is an ideal system for producing highly accurate dimensions needed for dental restorations. This system offers one solution for the production of restorations by machining industrially fabricated ceramic blocks to reduce number of bulk defects²⁷. The fine grain size allows for good resolution in machining⁵ for this material, although as with any machining processes, the dental burs initiate surface damage that could reduce the potential strength. To overcome this smooth surface finishing by polishing should be used as a final step to remove the larger surface flaws, reducing surface imperfections, including grooves

and fissures²⁹⁾ and thereby increasing reliability.

In order to produce acceptable colors for restorative dental glass-ceramics, colorants should be yellow to yellow-red in the crystallized product³⁰⁾. The control of translucency and color shade needs to be addressed. Long term durability should also be studied in accordance with ISO 6872 : 1997(E)¹⁸⁾. This standard indicates that core ceramic materials must have a chemical solubility less than 2000 µg/cm² and for a body ceramic that is in direct contact with oral environment, it should be less than 100 µg/cm².

CONCLUSION

The GCF 4.0 glass-ceramic containing calcium mica and fluorapatite crystal as dominant crystalline phases was found to be appropriate for the application of a machinable dental ceramic due to its good machinability and appropriate strength. A large Weibull modulus (*m*) value suggests a reliable structural material. These properties, along with a useful fracture toughness, allowed for the material to be used with CAD/CAM to produce a prosthesis. According to ISO 6872 : 1997(E), the mechanical properties are proper for single unit anterior or posterior prostheses.

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