Flexural strength and fracture toughness of two different lithium disilicate ceramics

Bogna STAWARCZYK1, Anja LIEBERMANN1, Martin ROSENTRITT2, Hubertus POVEL1, Marlis EICHBERGER1 and Nina LÜMKEMANN1

1 Department of Prosthetic Dentistry, University Hospital, Ludwig-Maximilians-University Munich, Germany
2 Department of Prosthetic Dentistry, University Hospital Regensburg, Germany

Corresponding author, Bogna STAWARCZYK; E-mail: bogna.stawarczyk@med.uni-muenchen.de

To test the impact of the pressing furnace on flexural strength and fracture toughness of the lithium-disilicate-ceramics HS10PC (HS) and IPS e.max Press (IP). Three hundred and sixty specimens (3×4×30 mm) were pressed (n=180/ceramic) using different pressing furnaces, namely Austromat 654 Press-i-dent (AUS), Programat EP5000 (PRO), and Vario Press 300 (VAR). Three-point flexural strength (n=30) and fracture toughness (n=30) were measured. Flexural strength (336–360 MPa) was not affected by pressing furnace or ceramic and showed comparable values between all groups. Fracture toughness (2.65–2.81 MPa√m) provided higher values for HS pressed using AUS compared to specimens pressed in PRO and VAR. For IP, no impact of the pressing furnace on fracture toughness was found. IP presented higher fracture toughness than HS when pressed using PRO. No correlations were found. Both lithium disilicate ceramics showed comparable flexural strength regardless of the pressing furnace. Fracture toughness depended on the ceramic and on the pressing furnace.

Keywords: Lithium disilicate ceramic, Glass-ceramic, Flexural strength, Fracture toughness, Pressing furnace

INTRODUCTION

Glass-ceramics show favorable mechanical and biological properties, such as flexural strength, fracture load, low thermal conductivity and minimal plaque accumulation1-5. Ceramics differ in their composition. Their mechanical and optical properties are influenced by their composition and crystalline structure5,9. For lithium disilicate, ceramics, the molar ratio of Li2O and SiO2 is essential for example for the formation of Li2SiO3, Li2Si2O5 or Li4SiO4. An increase in the crystalline structure of up to 60–70% through a reinforcement of lithium disilicate, lithium silicate or lithium orthophosphate (Li2Si2O5, Li2SiO3, Li3PO4) crystals, leads to glass-ceramics with a flexural strength about 2–3 times higher than that of unreinforced glass-ceramics1,2-5,7,10-12. Processing can influence the crystals share and amount, as well as the type and the orientation of the crystals, porosities, and shrinkage. This influence the mechanical properties such as flexural strength or fracture toughness. The variation of processing parameters such as temperature and holding time is used for controlling the crystal growth and content and type of crystals, allowing an individual adjustment of the mechanical properties of the ceramic. Therefore, variations of the processing parameters are supposed to affect the consistent material properties and variations.

The pressing of lithium disilicate ceramics with the lost wax technique combines a good marginal fit, an occlusal accuracy, low shrinkage, low porosity, good mechanical properties, and is above all, a simple and cost-effective fabrication method3,4,13-14. Pressed lithium disilicate ceramic resulted in superior fracture toughness compared to milled ceramics15,16. These observations might be traced back to different heating parameters that are known to possibly upset the driving force for growing lithium disilicate crystals and alter the overall percentage of residual glasses, which in turn might adversely impact several material properties including load-bearing capacity and fracture toughness17.

Glass-ceramics can be pressed with different pressing furnaces. Not every manufacturer has a complete system, including ceramic and pressing furnace. And not every ceramic manufacturer specifies the pressing program for all furnaces available on the market. Manufacturers are either focusing on furnace construction or material development. However, investigations analyzing the influence of the pressing furnace on the mechanical properties of lithium disilicate ceramics could not yet be found in literature.

Therefore, the aim of this study was to elaborate the pressing parameters for the respective furnaces and two different lithium disilicate ceramics as a first step. The second aim was to examine the influence of three different pressing furnaces on flexural strength (3-point-flexural-strength) and fracture toughness (single-edge-V-notch-beam; SEVNB) of the ceramics. The first part of the hypothesis stated that both ceramics show similar flexural strength regardless of the pressing furnace while the second part stated that the fracture toughness results of both tested lithium disilicate ceramics are comparable irrespective of the pressing furnace used.
MATERIALS AND METHODS

Fabrication of specimen
Fully combustible templates (n=360) were milled from CAD/CAM wax discs (Dental Concept Milling Wax Press+Cast (grey), Dental Concept Systems, Ulm, Germany) using a CAD/CAM milling machine (DC 5 milling system, Dental Concept Systems). Specimens of two lithium disilicate ceramics (HS10PC SL; HS; estetic ceram, Triesen, Liechtenstein; IPS e.max Press LT; IP; Ivoclar Vivadent, Schaan, Liechtenstein) were pressed with three different pressing furnaces [i. AUS (Austromat 654 Press-i-dent, Dekema, Freilassing, Germany), ii. PRO (Programat EP5000, Ivoclar Vivadent) and iii. VAR (Vario Press 300e, Zubler Gerätebau, Ulm, Germany)]. Specimens were embedded (HS: HS-PC Speed Investment material for pressable ceramics, Zubler; IP: Speed Investment IPS PressVest Speed, Ivoclar Vivadent) and preheated in a furnace (Typ 5636, Kavo Ewl, Biberach, Germany) at 850°C for 60 min. The materials and pressing parameters used are listed in Tables 1 and 2 sorted by lithium disilicate ceramic (HS, IP) and pressing furnace (AUS, PRO, VAR). The differences existed in final temperatures, holding time and press level. Depending on the final pressing parameters, following criteria must be fulfilled to accept the pressing result: completely refilled templates without blisters or cavities/blowholes and sharp edges (Fig. 1).

After cooling down to room temperature, all specimens were uncovered and cleaned by air-particle abrasion (sandmaster FG3-92, Sandmaster, Zofingen, Switzerland) using 125 µm/0.4 MPa and 50 µm/0.2 MPa alumina powder (Orbis Dental, Orbis Dental Handelsgesellschaft, Münster, Germany). IP specimens were etched (IPS e.max Press Invex Liquid, Ivoclar Vivadent) to remove the reaction layer and then air-particle abraded with alumina powder at 50 µm/0.2 MPa. Casting sprues were cut with a coated diamond

Fig. 1 Uncovered ceramic specimens with pressing canal (left and middle: with pressing defects–rounded edges; right: successful pressing).

Table 1  The descriptions, materials, lot numbers (Lot No), manufacturers and composition of the materials tested

| Material                  | Lot No. | Manufacturer                  | Composition (wt%)                                      |
|---------------------------|---------|-------------------------------|-------------------------------------------------------|
| HS10PC (HS)               | 820615  | estetic ceram, Triesen, Liechtenstein | SiO₂: 65–80%, Al₂O₃: 0–11%, Li₂O: 11–19%, K₂O: 0–7%, Na₂O: 0–5%, CaO: 0–10%, P₂O₅: 1.5–7%, ZnO: 0–7%, others: 0–15% |
| Speed Investment          | 4-46956-59 | Zubler Gerätebau, Ulm, Germany  | SiO₂, MgO, NH₄H₂PO₄/water, colloidal silica            |
| HS-PC/Liquid              | T38832  | Ivoclar Vivadent              | SiO₂: 57–80%, Li₂O: 11–19%, K₂O: 0–13%, P₂O₅: 0–11%, ZrO₂: 0–8%, ZnO 0–8%, others: 0–10% |
| IPS e.max Press (IP)      | TL 3092 | Ivoclar Vivadent              | SiO₂, MgO and NH₄H₂PO₄/water: 70%, colloidal silica: 30% |

Table 2  Press parameters for both lithium disilicate ceramics depending on the pressing furnace

| Ceramic | Pressing furnaces | Start temperature (°C) | Heating rate (°C/min) | Final temperature (°C) | Holding time (min) | Pressure |
|---------|-------------------|------------------------|-----------------------|------------------------|--------------------|----------|
| HS      | AUS               | 700                    | 60                    | 938                    | 15                 | pressing level 7 |
|         | PRO               | 700                    | 60                    | 910                    | 20                 | no information |
|         | VAR               | 700                    | 60                    | 880                    | Adv. press 200/6*  | low      |
| IP      | AUS               | 700                    | 60                    | 930                    | 25                 | pressing level 6 |
|         | PRO               | 700                    | 60                    | 917                    | 25                 | no information |
|         | VAR               | 700                    | 60                    | 920                    | 25                 | low      |
Three-point flexural strength measurement

The 3-point flexural strength was measured according to ISO 6872:2015. After placement in the sample holder, the specimens were loaded in the universal testing machine (14450 Zwick/Roell; Zwick, Ulm, Germany) at a cross-head speed of 1 mm/min until fracture. The 3-point flexural strength was calculated according to the following formula:

$$\sigma = \frac{3F l_0}{2w h^2}$$

\(\sigma\): flexural strength (N/mm²=MPa), \(F\): force at fracture of the specimen (N), \(l_0\): Distance between the counterfort (mm), \(w\): width of the specimen (mm), \(h\): height of the specimen (mm)

Three-point fracture toughness measurement

Fracture toughness was measured by SEVNB method according to ISO 6872:2015. Three specimens were placed on the narrow side (3.0±0.2 mm) and fixed upright, side by side and centered in an adapted specimen holder. A saw cut was inserted in center using a universal cutting machine (Secotom-50; Struers) with a diamond charged cut-off wheel (102 mm dia. ×0.3 mm, Diamond cut-off wheel M1D10, Struers, Fig. 2).

The depths of the saw cuts were more than 0.5 mm according to the standard. The specimen holder was placed in a specially constructed notching machine (SD Mechatronik) and specimens were notched and sharpened using a razor blade (0.3 mm David combi & finisher blades, Shapero manufacturers, Currumbin, QLD, Australia) with polishing diamond paste of 6 and 1 µm (DP-Suspension M 6 µm/DiaPro Nap R1 1 µm, Struers). The depth of the saw cut together with the depth of the notching ranged between 0.8 and 1.2 mm. The cycles of the movement of the machine varied as well as the pressing force of the movement via weights. Specimens were ultrasonically cleaned (Sonorex RK102H; Bandelin electronic, Mörfelden-Walldorf, Germany) in 80% alcohol (Alkopharm 80; Brüggemann Alcohol, Heilbronn, Germany), and air-dried for at least 24 h. The saws and notches were measured using a microscope (Zwick/Roell Z 2.5; Zwick, Fig. 3). Specimens were exposed to loading in the universal testing machine (14450 Zwick/Roell) at a crosshead speed of 0.5 mm/min until fracture. The fracture toughness was calculated according to the following formula:

$$K_{IC} = \frac{F}{b}\sqrt{w} \cdot (s_1 - s_2) / w \cdot (3\sqrt{\alpha} / (2(1-\alpha)^{1.5}))Y$$

\(K_{IC}\): fracture toughness (MPa√m), \(F\): fracture load (N), \(b\): thickness of specimen (m), \(w\): width of specimen (m), \(s_1\): bearing range (m), \(s_2\): inner range (m), \(\alpha\): relative depth of the V-notch, \(Y\): form factor of stress intensity.

SEM images

SEM images were recorded for both ceramics (HS and IP) pressed in each pressing furnace (either AUS, PRO or VAR) to investigate the ceramic microstructure. Images were recorded using a scanning electron microscope (Phenom, FEI, Hillsboro, OR, USA) at magnifications up to ×10,000 at a working distance <11.1 mm (low vacuum, 10.0 kV, SE).

Statistical analyses

The measured data were analyzed statistically with SPSS Version 23.0 (IBM, SPSS Statistics). For quantitative variables, the assumption of normality was tested with the Kolmogorov-Smirnov test. The general linear model analysis was performed. Data were tested with non-parametric tests, such as Kruskal-Wallis and Mann-Whitney U tests. Weibull modulus (m) were calculated using the maximum likelihood estimation method at 95% confidence level. Correlations
between flexural strength and fracture toughness were measured using Spearman test. The results of statistical analyses with $p<0.05$ were interpreted as statistically significant.

RESULTS

All collected data of flexural strength and fracture toughness, including Weibull modulus, are summarized in Tables 3 and 4. The fracture strength values ranged between 336 and 360 MPa with Weibull modulus between 5.5 and 9.7. The fracture toughness values ranged between 2.65 and 2.81 MPa $\sqrt{m}$.

Influence of pressing furnace

No impact of pressing furnace on the flexural strength results ($p=0.428$) and flexural strength Weibull modulus was found. No impact of pressing furnace on the fracture toughness was observed within IP ($p=0.595$), while HS showed significantly higher fracture toughness when pressed using AUS compared to specimens pressed using the two other pressing furnaces (PRO and VAR) ($p=0.001$).

Influence of ceramic

No impact of lithium disilicate ceramic on the flexural strength results was found ($p=0.844$). Within specimens pressed in VAR, HS ($m=9.7$) showed significantly higher flexural strength Weibull modulus than IP ($m=5.5$). For both ceramics pressed using AUS ($p=0.294$) and VAR ($p=0.114$), the fracture toughness values were in the same values range. Within lithium disilicate ceramics pressed using PRO, IP showed significantly higher fracture toughness than HS ($p=0.009$). No correlations between flexural strength and fracture toughness values were found ($p=0.333$).

SEM images

SEM images of HS and IP pressed in each furnace (AUS, PRO, VAR) are depicted in Fig. 4. Within each ceramic and in direct comparison of both ceramics pressed in the same furnace, certain differences were visible. Within HS, the crystal structure appears more regular and denser when pressed using furnace AUS. Also, the orientation of the crystals appears more consistent and aligned. Within IP, the crystals appear larger and less equally oriented when pressed using VAR. Comparing the crystal structure of both ceramics pressed using PRO, the crystals appeared more regular and more distinct and denser for IP.

Table 3 Descriptive statistics of flexural strength (MPa) for all tested ceramic groups depending on the pressing furnace

| Pressing furnace | HS mean±SD (95% CI) | Weibull modulus (95% CI) | IP mean±SD (95% CI) | Weibull modulus (95% CI) |
|------------------|---------------------|--------------------------|---------------------|--------------------------|
| AUS              | 350±61 (325;373)$^{aA}$ | 6.6 (4.4;9.7)           | 360±54* (338;380)$^{aA}$ | 7.1 (4.7;10.4)           |
| PRO              | 340±50 (320;359)$^{aA}$ | 7.7 (5.1;11.2)          | 344±56 (321;365)$^{aA}$ | 6.9 (4.6;10.1)          |
| VAR              | 354±45 (336;371)$^{aA}$ | 9.7 (6.5;14.1)          | 336±64* (310;360)$^{aA}$ | 5.5 (3.7;8.1)           |

* not normally distributed  
$^{aA}$ different letters show significantly differences between groups pressed using different pressing furnaces within one lithium disilicate ceramic.  
$^{A}$ different letters show significantly differences between the lithium disilicate ceramics within specimens pressed in one pressing furnaces.

Table 4 Descriptive statistics of fracture toughness (MPa $\sqrt{m}$) for all tested ceramic groups depending on the pressing furnace

| Pressing furnace | HS mean±SD (95% CI) | Weibull modulus (95% CI) | IP mean±SD (95% CI) | Weibull modulus (95% CI) |
|------------------|---------------------|--------------------------|---------------------|--------------------------|
| AUS              | 2.79±0.12 (2.74;2.84)$^{bA}$ |                      | 2.73±0.26 (2.62;2.83)$^{bA}$ |                      |
| PRO              | 2.65±0.16 (2.58;2.72)$^{bA}$ |                      | 2.81±0.22 (2.71;2.90)$^{bB}$ |                      |
| VAR              | 2.65±0.28 (2.52;2.76)$^{bA}$ |                      | 2.75±0.21 (2.65;2.83)$^{bA}$ |                      |

* not normally distributed  
$^{bA}$ different letters show significantly differences between groups pressed using different pressing furnaces within one lithium disilicate ceramic.  
$^{AB}$ different letters show significantly differences between the lithium disilicate ceramics within specimens pressed in one pressing furnaces.
DISCUSSION

The first part of the hypothesis, stating that both lithium disilicate ceramics show comparable results for flexural strength regardless of pressing furnaces used, was rejected. The second part of the hypothesis assuming that both lithium disilicate ceramics show comparable values of fracture toughness irrespective of the pressing furnace used, was accepted since differences between both tested lithium disilicate ceramics were found in dependence on the pressing furnace.

Lithium disilicate ceramic

The SEM images presenting the microstructure of both tested lithium disilicate ceramics show differences regarding the size, density, morphology and the orientation of the crystals with no specific characteristic that can be assigned to one certain pressing furnace (Fig. 4). For example, IP revealed a more regular, distinct and denser crystal structure compared to HS when pressed using PRO (Fig. 4). This observation might be caused by differences in the chemical compositions between the lithium disilicate ceramics. But based on the results, the differences in the microstructure might be neglectable regarding the results of flexural strength. The overall results of 3-point flexural strength for IP were comparable with previous results[19], while no data on the flexural strength of HS were found in published scientific literature. Regarding to fracture toughness results a noticeable impact of the pressing furnace was observed. HS revealed higher values when pressed in AUS compared with the other pressing furnaces, and resulted in lower values compared to IP when pressed in PRO. Even though, the fracture toughness values are in concurrent dependence of the pressing furnace, the obtained values of both lithium disilicate ceramics are in accordance with the specifications provided by the manufacturer (2.5–3 MPa*m^-1/2). Fracture toughness also differs from ceramic material tested. In general, the lithium disilicate ceramic IP presented higher fracture toughness values (4.20±1.23) compared to polymer-based materials (1.96±0.42) and the polymer-infiltrated ceramic VITA Enamic (2.02±0.39) in a further investigation with similar test method[20].

There are several test methods to evaluate fracture toughness of ceramic materials like the single-edge-V-notch-beam (SEVNB), single edge precracked beam (SEPB), chevron notch beam (CNB), and surface crack in flexure (SCF). The SEVNB is generally the recommended method for the fracture toughness of the ADM guidance for ceramic with its main advantage of the ease of producing the notch via a cutting disk and was therefore used in the present investigation[21,22].

The good results of flexural strength and fracture toughness for both lithium disilicate ceramics might be explained by the fact that the pressing parameters were individually determined in pilot tests ensuring optimal pressing results for each lithium disilicate ceramic in dependence on the pressing furnace. The individualization of the pressing parameters could also be seen as a limitation of the study, described at the end of the discussion.

Differences between the developed pressing parameters might not only be based on differences between the pressing furnaces but could also be associated with differences in the chemical composition between the ceramics. Further relevant parameters that differed between the lithium disilicate ceramics were the investment materials that were chosen according to the manufacturer’s instructions. In this context, the difference between the reaction layers on both lithium disilicate ceramics after the pressing procedure was...
Fig. 5  a: IP specimen directly after pressing with reaction layer as example (left: after pre-treatment with Invex liquid; middle: cleaned by air-particle abrasion using 125 µm alumina powder; right: cleaned by air-particle abrasion using 50 µm alumina powder).

b: HS specimen cleaned by air-particle abrasion using 50 and 125 µm alumina powder without any reaction layer.

particularly remarkable (Fig. 5). The reaction layer was obviously thicker for IP and was removed by additional acid etching. HS was only treated by air-particle abrasion. However, since all specimens were polished equally after the individual removal of the reaction layer, no impact of the thickness of the reaction layer and the removal process on the mechanical properties of both lithium disilicate ceramics could be assumed. Thus, all observed differences mainly depend on the impact of the pressing furnace.

Pressing furnace
The use of different pressing furnaces only affected the fracture toughness results for the tested lithium disilicate ceramics. The fact that IP showed significantly higher fracture toughness values than HS when pressed using PRO might be explained on the basis that IP and the pressing furnace PRO are coordinated to each other by the manufacturer being one system. The SEM images clearly reveal a more regular, distinct and denser crystal structure for IP compared to HS when pressed using PRO (Fig. 4). Further, the result that HS obtained higher fracture toughness values when pressed in AUS is also presented in a more regular and denser crystal structure as well a more consistent and aligned orientation of the crystals (Fig. 4). But as already mentioned above, a certain specific microstructural characteristic of the lithium disilicate ceramic cannot be assigned to one of the pressing furnaces. In addition, the crystal growth be the cause of changes in fracture toughness instead of the furnace even though the fracture toughness is an intrinsic material property.

The few differences observed, could be caused by the pressing procedure that differ between the pressing furnaces. Pressing furnace AUS was the only one based on an upward pressing movement, while VAR has an engine technology using compressed air. For both lithium disilicate ceramics tested, no impact of the pressing furnace on flexural strength was observed. This in accordance to previous results that found no impact of extended temperature ranges and protracted holding times during crystallizing of lithium disilicate ceramic on flexural strength and fracture toughness. However, since information on the furnaces are limited, further in-vitro investigations are necessary to understand and explain the observed effects.

Fracture toughness
Fracture toughness is an intrinsic material property describing the material’s ability to withstand unstable crack propagation and correlating with clinical performance. For determination of fracture toughness, SEVNB method is well-established and widely used. SEVNB is easy to implement and is considered as suitable for glass-ceramics. A comparison of fracture toughness values between IPS e.max Press and IPS e.max CAD revealed superior results for IPS e.max Press when the fracture toughness was determined via notchless triangular prism specimens. With respect to the present results, latter cited literature represents significantly lower fracture toughness values \(K_{IC} = 2.50 \pm 0.31 \text{ MPa}\cdot\text{m}^{1/2}\) which might be explained by the different test methods. It is generally known that the variety of existing test methods for the determination of fracture toughness is overwhelming and that the fracture toughness values of one and the same material depends on the testing method employed.

While IP is a well-researched ceramic in vitro and in vivo, further studies and especially clinical studies are needed for HS. Since the mechanical properties of both ceramics tested in this study are comparable, it can be assumed that HS will also show good long-term clinical results.

As limitation of the present investigation it is to mention, that the pressing parameter used were developed for both lithium disilicate ceramic in each of the pressing furnaces in order to obtain optimal pressing results regarding to completely refilled templates without blisters or cavities and sharp edges. It is assumed that further optimizations of the pressing parameters could have a significant effect on the tested parameters of flexural strength and fracture toughness.
CONCLUSIONS
Within the limitations of the present investigation, the following conclusions can be drawn:
1. Both tested lithium disilicate ceramics showed comparable results of flexural strength irrespective of the pressing furnace used.
2. Fracture toughness varied depending on the lithium disilicate ceramic and the pressing furnace used.
3. Fracture toughness of IP can be improved by using the coordinated pressing furnace provided by the manufacturer.

ACKNOWLEDGMENTS
The authors would like to thank estetic ceram, Zubler Gerätebau and Dekema for supporting this study. This research did not receive any specific grant from funding agencies in the public, commercial, or not-for-profit sectors.

REFERENCES
1) Sadowsky SJ. An overview of treatment considerations for esthetic restorations: A review of the literature. J Prosthet Dent 2006; 96: 433-442.
2) Kelly JR, Nishimura I, Campbell SD. Ceramics in dentistry: Historical roots and current perspectives. J Prosthet Dent 1996; 75: 18-32.
3) Conrad HJ, Seong WJ, Pesun IJ. Current ceramic materials and systems with clinical recommendations: A systematic review. J Prosthet Dent 2007; 98: 389-404.
4) Albakry M, Guazzato M, Swain MV. Biaxial flexural strength, elastic moduli, and x-ray diffraction characterization of three pressable all-ceramic materials. J Prosthet Dent 2003; 89: 374-380.
5) Pollington S. Novel glass —Ceramics for dental restorations. J Contemp Dent Pract 2011; 12: 60-67.
6) Haselton DR, Diaz-Arnold AM, Hillis SL. Clinical assessment of high-strength all-ceramic crowns. J Prosthet Dent 2000; 83: 396-401.
7) Holand W, Schweiger M, Frank M, Rheinberger V. A comparison of the microstructure and properties of the IPS Empress 2 and the IPS Empress glass-ceramics. J Biomed Mater Res 2000; 53: 297-303.
8) Emslander A, Reise M, Eichberger M, Uhrenbacher J, Edelhofer D, Stawarczyk B. Impact of surface treatment of different reinforced glass-ceramic anterior crowns on load bearing capacity. Dent Mater J 2015; 34: 585-604.
9) Brewer JD, Garlapo DA, Chipps EA, Tedesco LA. Clinical discrimination between autoglazed and polished porcelain surfaces. J Prostheth Dent 1996; 64: 631-634.
10) Drummond JL, King TJ, Bapna MS, Koperski RD. Mechanical property evaluation of pressable restorative ceramics. Dent Mater 2000; 16: 226-233.
11) Seghi RR, Denry IL, Rosenstiel SF. Relative fracture toughness and hardness of new dental ceramics. J Prosthet Dent 1995; 74: 145-150.
12) Wölfart S, Eschbach S, Scherrer S, Kern M. Clinical outcome of three-unit lithium-disilicate glass-ceramic fixed dental prostheses: Up to 8 years results. Dent Mater 2009; 25: e63-e71.
13) Gorman CM, McDevitt WE, Hill RG. Comparison of two heat-pressed all-ceramic dental materials. Dent Mater 2000; 16: 389-395.
14) Goldin EB, Boyd NW III, Goldstein GR, Hittelman EL, Thompson VP. Marginal fit of leucite-glass pressable ceramic restorations and ceramic-pressed-to-metal restorations. J Prosthet Dent 2005; 93: 143-147.
15) Gerogianni P, Lien W, Bompelaki D, Verrett R, Haney S, Mattie P, et al. Fracture resistance of pressed and milled lithium disilicate anterior complete coverage restorations following endodontic access preparation. J Prosthodont 2019; 28: 163-170.
16) Alkadi L, Ruse ND. Fracture toughness of two lithium disilicate dental glass ceramics. J Prosthet Dent 2016; 116: 591-596.
17) Lien W, Roberts HW, Platt JA, Vandewalle KS, Hill TJ, Chu TM. Microstructural evolution and physical behavior of a lithium disilicate glass-ceramic. Dent Mater 2015; 31: 928-940.
18) Bütikofer L, Stawarczyk B, Roos M. Two regression methods for estimation of a two-parameter Weibull distribution for reliability of dental materials. Dent Mater 2015; 31: e33-e50.
19) Fabian FR, Carrabba M, Sedda M, Ferrari M, Goracci C, Vichi A. Flexural resistance of heat-pressed and CAD/CAM lithium disilicate with different translucencies. Dent Mater 2017; 32: 63-70.
20) Porto TS, Roperto RC, Akkus A, Akkus O, Teich S, Faddoul FF, et al. Effect of thermal cycling on fracture toughness of CAD/CAM materials. Am J Dent 2018; 31: 205-210.
21) Cesar PF, Della Bona A, Scherrer SS, Tholey M, van Noort R, Vichi A, et al. ADM guidance-ceramics: Fracture toughness testing and method selection. Dent Mater 2017; 33: 573-584.
22) Della Bona A, Corazza PH, Zhang Y. Characterization of a polymer-infiltrated ceramic-network material. Dent Mater 2014; 30: 564-569.
23) Cesar PF, Yoshimura HN, Miranda WG Jr, Miyazaki CL, Mutal LM, Rodrigues Filho LE. Relationship between fracture toughness and flexural strength in dental porcelains. J Biomed Mater Res B 2006; 75: 265-273.
24) Belli R, Wendler M, Zorzin J, Lohbauer U. Practical and theoretical considerations on the fracture toughness testing of dental restorative materials. Dent Mater 2018; 34: 97-119.