

Biaxial Flexural Strength and Microstructure Changes of Two Recycled Pressable Glass Ceramics

Mohammad Albakry, BSc;¹ Massimiliano Guazzato, BDS;²
and Michael Vincent Swain, BSc, PhD³

Purpose: This study evaluated the biaxial flexural strength and identified the crystalline phases and the microstructural features of pressed and repressed materials of the glass ceramics, Empress 1 and Empress 2.

Materials and Methods: Twenty pressed and 20 repressed disc specimens measuring 14 mm × 1 mm per material were prepared following the manufacturers' recommendations. Biaxial flexure (piston on 3-ball method) was used to assess strength. X-ray diffraction was performed to identify the crystalline phases, and a scanning electron microscope was used to disclose microstructural features.

Results: Biaxial flexural strength, for the pressed and repressed specimens, respectively, were E1 [148 (SD 18) and 149 (SD 35)] and E2 [340 (SD 40), 325 (SD 60)] MPa. There was no significant difference in strength between the pressed and the repressed groups of either material, Empress 1 and Empress 2 ($p > 0.05$). Weibull modulus values results were E1: (8, 4.7) and E2: (9, 5.8) for the same groups, respectively. X-ray diffraction revealed that leucite was the main crystalline phase for Empress 1 groups, and lithium disilicate for Empress 2 groups. No further peaks were observed in the X-ray diffraction patterns of either material after repressing. Dispersed leucite crystals and cracks within the leucite crystals and glass matrix were features observed in Empress 1 for pressed and repressed samples. Similar microstructure features—dense lithium disilicate crystals within a glass matrix—were observed in Empress 2 pressed and repressed materials. However, the repressed material showed larger lithium disilicate crystals than the singly pressed material.

Conclusions: Second pressing had no significant effect on the biaxial flexural strength of Empress 1 or Empress 2; however, higher strength variations among the repressed samples of the materials may indicate less reliability of these materials after second pressing.

J Prostodont 2004;13:141-149. Copyright © 2004 by The American College of Prosthodontists.

INDEX WORDS: lithium disilicate, leucite, biaxial flexural strength, repressing

THE POSSIBILITY of producing more vibrant dental restorations using all-ceramic systems has gained considerable attention from many clinicians and patients, because of these materials'

unique features, including esthetics, low thermal conductivity, abrasion resistance, and biocompatibility.¹ However, the widespread application and reliability of these materials has been dictated, until recently, by the credibility imparted to traditional porcelains by the metallic substrates.² Furthermore, all-ceramic dental materials, like any other ceramics, are inherently fragile in tension, and may be affected by microcracking, flaws, and defects that may be introduced during thermal treatment or fabrication procedures.

All-ceramic restorations are submitted to intermittent forces during fabrication and mastication. It is, therefore, important to evaluate their behavior under load. Mechanical properties such as strength and fracture toughness are the first parameters assessed to understand the clinical potential and limits of a dental ceramic;³ however, other factors, including fatigue during

¹Doctoral Student, Biomaterials Science Research Unit, Faculty of Dentistry, University of Sydney, United Dental Hospital.

²Associate Lecturer, Biomaterials Science Research Unit, Faculty of Dentistry, University of Sydney, United Dental Hospital.

³Professor, Department of Aerospace, Mechanical and Mechatronic Engineering, Faculty of Engineering; Professor, Biomaterials Science Research Unit, Faculty of Dentistry, University of Sydney, United Dental Hospital.

Accepted January 27, 2004.

Correspondence to: Mohammad Albakry, BSc, Biomaterials Science Research Unit, Faculty of Dentistry, University of Sydney, United Dental Hospital, 2 Chalmers Street, Surry Hills, NSW, 2010 Australia. E-mail: albakrym@hotmail.com

Copyright © 2004 by The American College of Prosthodontists 1059-941X/04

doi: 10.1111/j.1532-849X.2004.04025.x

functioning, restoration design, precise fabrication process, and skills of individual dental technicians, may affect the reliability and clinical performance of all-ceramic restorations.⁴

A wide range of materials and systems is currently available for the construction of all-ceramic restorations. One class among these systems requires hot pressing by means of a special furnace to produce the required shape (pressable materials). During the last 10 years, heat pressing has become a common technique in dentistry for the fabrication of all-ceramic prostheses.⁵ In addition to its simplicity, this technique promotes better crystalline dispersion within a glass matrix,⁶ less porosity,^{7,8} and better marginal adaptation⁹ compared to other techniques, such as sintering. Empress 1 (E1; leucite reinforced glass-ceramic; Ivoclar-Vivadent, Schaan, Liechtenstein) and Empress 2 (E2; lithium disilicate glass-ceramic; Ivoclar-Vivadent, Schaan, Liechtenstein) are well known and increasingly utilized all-ceramic dental materials. The reliability of E1 as an all-ceramic material suitable for the fabrication of single units, such as inlays, onlays, and crowns, has been recommended by many mechanical and clinical investigations.^{8,10-22} According to the manufacturer's recommendations, E2 has been used as a core material suitable for the construction of 3-unit fixed partial dentures up to the second premolar. The improved mechanical properties of this material,²⁰⁻²⁵ compared to most other pressable ceramics, are attributed to its chemical composition, which is comprised of dense multilongated lithium disilicate crystals within a glass matrix. In such a structure, a crack would be trapped by these distributed crystals, resulting in an improved strength and fracture toughness.²¹ In previous studies, this material also showed good results in vivo and in vitro.²⁶⁻³⁰

Both E1 and E2 are available in ingots of several different shades and transparencies to match various clinical situations. These ingots are pressed into a mold by an Alumina plunger under pressure from a pneumatic press furnace. After pressing and cooling, the sprues are removed, along with the remaining material (button). The buttons should be discarded and a new ingot should be used for a new pressing. However, it has been reported that these materials are recycled in some dental laboratories; sufficient knowledge about the safety and con-

sequences of such treatment is not available. Whether these buttons can be repressed and recycled successfully has been questioned. Concerns have also been expressed regarding the change in the microstructure and possible degradation of the mechanical properties of these materials, as a result of multiple processing and subsequent heat firing.

The aim of the present study was to appraise the biaxial flexural strength and describe the microstructural features and crystalline phases of repressed materials of E1 and E2, and to compare them to those of singly pressed materials.

Materials and Methods

Twenty perspex disc samples measuring 14 mm (diameter) \times 1.1 mm (thickness) were sprued and attached to muffle bases with surrounding paper cylinders. The samples were then invested using a total of 200 g investment powder and 52 ml of liquid, 40 ml special investment liquid and 12 ml of distilled water. Mixing was carried out for 60 seconds manually and 60 seconds under vacuum, then the mixtures were poured into a cylinder under vibration to prevent the formation of air bubbles. The cylinders were allowed to set for 30 minutes. The refractory molds with the E1 ingots and the Alumina plunger were heated at a rate of 9°C/min from room temperature to 850°C; this temperature was held for 90 minutes. When the preheating cycle was complete, the ingots were inserted into the molds, and the preheated plunger was placed on top and then transformed to the pressing furnace (Programat EP 500, Ivoclar-Vivadent) and the pressing cycle was started. The pressing was performed at a temperature of 1,175°C and a pressure of 5 bars, with a 20 minute hold and 40 minute pressing. After pressing, the investment molds were removed from the furnace and allowed to air cool. The specimens were then carefully devested using an air abrasion unit (Kavo EWL, Type 5423; Kavo, Biberach, Germany) with 50 μ m glass beads at a pressure of 3 bars. The sprues were separated from the disks using a diamond-cutting wheel saw (Isomet, Buehler Ltd., Lake Bluff, IL). E2 disk specimens were prepared following the same procedure utilized for E1. However, E2 ingots were not preheated along with the moulds, but inserted at room temperature into the preheated refractory mould and the pressing cycle was started at 920°C and pressure of 5 bars with a 20 minute hold and 30 minute pressing. To remove the reaction layer of the E2 specimens, they were immersed in invex liquid (Invex liquid, Ivoclar-Vivadent) in an ultrasonic unit (Ultrasonic cleaner; Unisonics, Manly Vale, New South Wales, Australia) for 10 minutes and then rinsed and

dried; this was followed by aluminum oxide sandblasting 50 μm at 1 bar pressure. The remaining buttons of E1 and E2 were adjusted by grinding to allow proper insertion into the refractory moulds. The same procedures were then followed to press these buttons.

All specimens were serially wet ground with 220, 320, 500, and 600 grade silicon carbide paper mounted on a metallographic lapping machine (RotoPol-22, Struers A/S, Rodovre, Denmark). All specimens were cleaned using an ultrasonic bath for 15 minutes at 90°C, followed by washing in detergent and boiling water. Specimen dimensions were 14 mm (diameter) \times 1 mm (thickness). All specimens were fired in a porcelain furnace (Programat P100; Ivoclar-Vivadent) according to the manufacturer's recommended firing cycles to simulate laboratory procedures and release all stresses associated with polishing procedures.

For microstructure investigations, 2 specimens of E1 and E2, pressed and repressed, were finely polished further using 4, 2, and 1 μm diamond paste, cleaned in ethanol, etched with HF acid, 0.1% for E1 and 10% for E2, and coated with platinum 20 nm. A field emission (scanning electron microscope; JSM 6000 FSEM, Joel, Tokyo, Japan) was used for the microstructural examination.

Biaxial Flexure Strength

Piston on 3-ball test was utilized to determine the biaxial flexure strength. The test was carried out using a universal testing machine (Shimadzu Autograph AG-G, Kyoto, Japan) at a crosshead speed rate of 0.5 mm/min until failure occurred. The disk specimens were supported on 3 symmetrically spaced balls (6 mm distant from the center of the jig). A thin plastic sheet (0.05 mm thick) was placed between the piston (1.5 mm diameter) and the specimen to facilitate even load distribution. Testing was performed at room conditions (22°C, and 66% relative humidity). The maximum tensile stress, which corresponds to the biaxial flexure strength, was calculated according to the equation suggested by the test standard (ASTM F 394-78)³¹ as follows:

$$S = -0.2387P(X - Y)/d^2$$

where S is the maximum tensile stress, P is the load at fracture and d is the specimen thickness at fracture origin. X and Y were determined as follows:

$$X = (1 + \nu) \ln(B/C)^2 + [(1 - \nu)/2](B/C)^2$$

$$Y = (1 + \nu)[1 + \ln(A/C)^2] + (1 - \nu)(A/C)^2$$

where ν is the Poisson's ratio, A is the radius of the support circle, B is the radius of the tip of the piston, and C is the radius of the specimen. Poisson's ratio for both materials, 0.23 and 0.24 for E1 and E2, respectively, was taken from a previous investigation.²⁰

Weibull Modulus

Strength variation among each group was evaluated by calculating the Weibull modulus (m). A computer was used to rank the biaxial strength data in ascending order and appoint a rank over the range 1 to N (N is the number of specimens); a straight line was then fitted through the points using the median rank regression method. The following equation was used to calculate the Weibull modulus:

$$P_f = 1 - \exp[-(\sigma/\sigma_0)^m] \quad (1)$$

where P_f is the failure probability, σ is the strength at a given P_f , σ_0 is the characteristic strength, and m is the Weibull modulus. However, since P_f can be identified by the following relation:

$$P_f = j/(N - 1) \quad (2)$$

where j is the rank in strength and N is the number of specimens, equation no (1) can be rewritten as follows:

$$1/(1 - P_f) = 1/\exp[-(\sigma/\sigma_0)^m] \quad (3)$$

Accordingly, plotting $\ln[1/(1 - P_f)]$ against $\ln(\text{strength})$ will provide a slope with the value of the Weibull modulus.^{2,32}

X-ray Diffraction

X-ray diffraction (Diffractometer D5000, Siemens, Germany) was carried out to investigate and determine the crystalline phases in the pressed and repressed samples of both materials. Samples measuring 14 mm (diameter) \times 1 mm (thickness) were placed in the holder of a Siemens diffractometer and scanned using Cu $K\alpha$ X-ray from 20° to 40° 2θ degrees; a step size of 0.04° and 5 s-step interval was used.

Statistics

One-way analysis of variance (ANOVA) was used for the result comparisons. Pairwise t -tests were also carried out at overall significance level 0.05 respecting the Bonferroni adjustment.

Results

Biaxial flexural strength results, Weibull modulus, standard deviation, and coefficient of variation for the 2 materials are listed in Table 1. The biaxial strength results were: E1: [148 (SD 18), 149 (SD 35)], and E2 [340 (SD 40), 325 (SD 60)] MPa for the pressed and repressed groups, respectively. One-way ANOVA revealed no significant difference between the 2 tested pressed and repressed groups for the 2 materials E1 and E2 ($p > 0.05$).

All biaxial strength data were ranked in an ascending order and the resultant Weibull modulus for E1 and E2 specimens was tested as pressed and repressed, respectively were: E1 (8, 4.7) and E2 (9, 5.8). Probability of survival for all data was plotted versus the ranked strength values (in ascending order) for the 2 groups of each material (Figs 1A and B).

X-ray diffraction patterns of E1 groups showed that leucite was the main crystalline phase, with the background intensity signals indicating the presence of an amorphous phase, the glass matrix. The main leucite peaks were detected at 2θ values of 25.89° , 27.22° , 30.41° , and 31.36° with the main peak at 27.22° matching the (400) crystallographic plane of the tetragonal phase (Fig 1C). After repressing, peaks remained unchanged and no further peaks were detected, which denotes no change in the crystalline phase.

Lithium disilicate was the main crystalline phase for E2 groups. The major peaks of the lithium disilicate crystals ($\text{Li}_2\text{Si}_2\text{O}_5$) were observed at 2θ values of 23.79° , 24.33° , and 24.84° , with the dominant peak (highest intensity) at 24.33° , which corresponds to the (040) crystallographic plane of the monoclinic phase, as predicted from the X-ray diffraction standards file (40-0376), lithium silicate. The lithium orthophosphate (Li_3PO_4) peaks were detected at 2θ values of 22.3 and 23.1. X-ray diffraction patterns of the pressed and repressed materials are shown in Figure 1D.

Scanning electron microscopic observations of the E1 pressed material show a dispersal of various shapes and sizes (0.5 to 3.5 μm in diameter) of tetragonal leucite crystals in a glass matrix (Fig 1E). Microfracturing was frequently seen in the glass matrix, and in areas of larger leucite crystals (Fig 1F). Twinning of the leucite crystals

was repeatedly observed in both small and large leucite crystals (Fig 1E). The repressed material demonstrated similar microstructural features to those of the pressed material (Fig 2A). Both materials also demonstrated a similar distribution of crystals within the glass matrix, which indicates that a better crystal distribution was not achieved following second pressing (Figs 2B and C). However, the presence of microcracking damage, associated with scratching that was not completely eliminated by polishing, was noticed within a glass matrix in both pressed and repressed materials (Fig 1F).

Scanning electron microscopic observations of E2 also showed similar microstructural features in the pressed and repressed materials (Figs 2D and E). Numerous elongated lithium disilicate crystals were present within a glass matrix after the first pressing, measuring approximately 3 to 5 μm long (Fig 2D). However, the lithium disilicate crystals of the repressed material appeared larger than those of the pressed material; these were in the range of approximately 7.5 to 8.5 μm in length (Fig 2E).

Discussion

Microstructural investigations revealed a continuous glassy matrix, which did not appear to change following repressing, in E1 materials. The size and shape of the tetragonal leucite crystals were also very similar in both materials, pressed and repressed. Microcracking was present within the glass matrix and more prominent surrounding larger leucite crystals. Such damage has been linked to the significant difference in the coefficient of thermal expansion between leucite crystals and the glass matrix. This creates internal tension within the crystals and compensating compressive stresses within the glass matrix upon cooling. Furthermore, cracks are deflected around the leucite crystals as a result of these radial tensile and compensating hoop stresses.^{25,33} The effect of larger leucite crystals on the degree of microcracking has been addressed previously by Mackert et al. (2001).³⁴ These investigators reported that the microcracking in leucite containing porcelain could be minimized by decreasing the mean leucite crystals. Shareef et al. (1994) noted that smaller particle size enhanced a homogenous distribution of the leucite crystals

Table 1. Biaxial Flexural Strength, Standard Deviation, Coefficient of Variation, and Weibull Modulus of E1 and E2

Material	Biaxial Strength (SD)	Coefficient of Variation %	Weibull Modulus
Empress 1	—	—	—
Pressed	148 (18)	13.5	8
Repressed	149 (35)	25	4.7
Empress 2	—	—	—
Pressed	340 (40)	12	9
Repressed	325 (60)	20	5.8

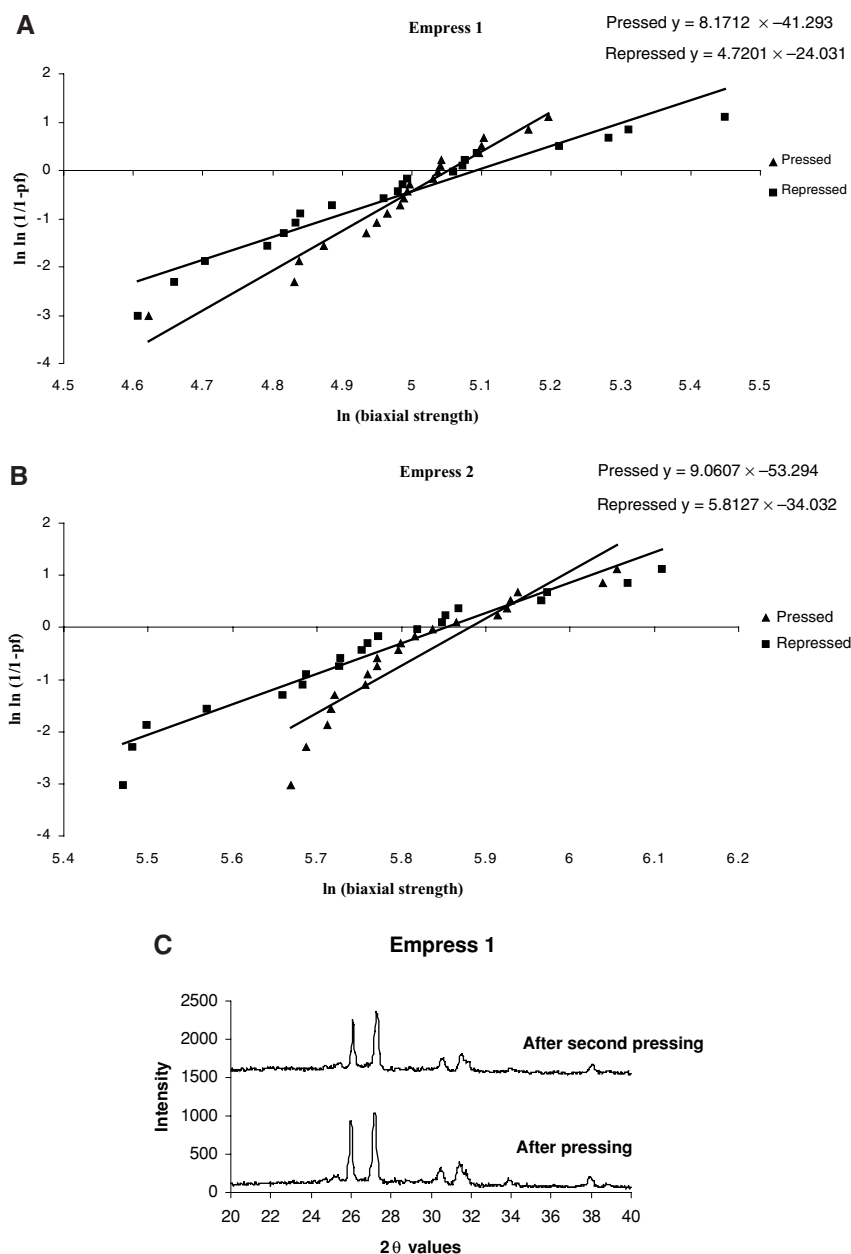


Figure 1. (A) Illustration of the Weibull plots of E1 pressed and repressed material. (B) Illustration of the Weibull plots of E2 pressed and repressed material. (C) X-ray diffraction traces of E1, showing similar patterns for the pressed and repressed samples, with the main leucite peaks occurring at approximately the same positions and heights. (D) X-ray diffraction traces of E2, showing similar patterns for the pressed and repressed samples, where the main lithium disilicate peaks occurred at approximately the same positions and heights. (E) SEM photomicrograph of E1 after pressing, showing various shapes and sizes of dispersed leucite crystals in a glass matrix, and twinned crystals. (F) SEM photomicrograph of E1 after pressing, showing areas of accumulated cracks surrounding the leucite crystals.

within the glass matrix, and consequently there was less evidence of glass matrix microcracking.³⁵

Twinning of leucite crystals was observed in both pressed and repressed specimens. This

was attributed to the shear deformation associated with relief of the shear strains during the transformation from the cubic to tetragonal phase at 625°C.⁵ No leucite crystal agglomerates were

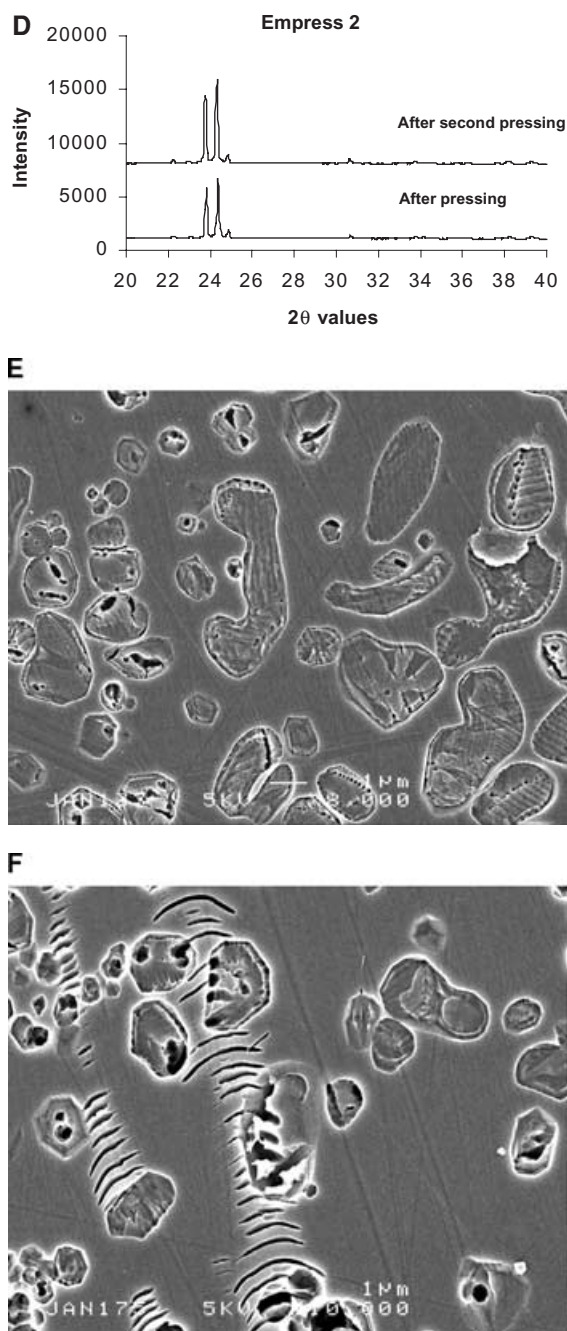


Figure 1. continued

noticed, and similar crystal dispersion within the glass matrix can be seen. These microstructural features may signify that repressing did not noticeably affect the microstructure of the repressed samples.

The main crystalline phase of E2 material, pressed and repressed samples, is lithium disili-

cate. These elongated crystals were present in the glass matrix, and appeared to form an interlocking pattern in some sites; however, the lithium disilicate crystals in the repressed material were seen to be larger than those of the pressed samples. This behavior is called Ostwald ripening³⁶ and is common for all precipitated materials. It takes place when the microstructure coarsens and liberates surface energy excess due to the solubility of small particles. As a consequence, larger grains are expected to grow at the expense of those small particles. The present results are similar to previously reported findings by Oh et al. (2000),³⁷ who noticed that the lithium disilicate crystals, after pressing, were approximately double the size of those before pressing. No further homogenous crystal distribution was noticed after repressing; however, crystal alignment can be observed in some sites. The orientation of lithium disilicate crystals of E2 material, as a result of viscous deformation of the glass matrix phase, occurred during sprue extrusion as previously reported.²¹ This preferred crystal orientation was less prominent in the repressed materials, which showed a more interlocking pattern than the pressed material. Another crystalline phase, lithium orthophosphate, could not be identified in the SEM images, perhaps due to its greater solubility upon acidic etching.

The strength value of E1 obtained in this study was not significantly affected by repressing the material. This result supports the insignificance of changes found in the microstructures of these materials. It is also comparable to results achieved in previous studies;⁷⁻⁹ however, some areas showed severe glass cracking and damage (Fig 1F). Such damage is thought to result from sliding deformation and damage of individual particles of the SiC grit paper with E1 surface. This creates relatively small partial Hertzian cone cracks, which became more visible with the aid of acidic etching, behind the sliding grit contacts.³⁸ The significant residual stress accrual in E1 material during cooling, due to the prominent thermal expansion mismatch between leucite crystals and the glass matrix, can also cause localized damage within the glassy matrix surrounding these crystals. For larger leucite crystals, these defective sites may become detrimental to the strength and could be sites of catastrophic failure, especially when they are in areas of high tensile stresses.

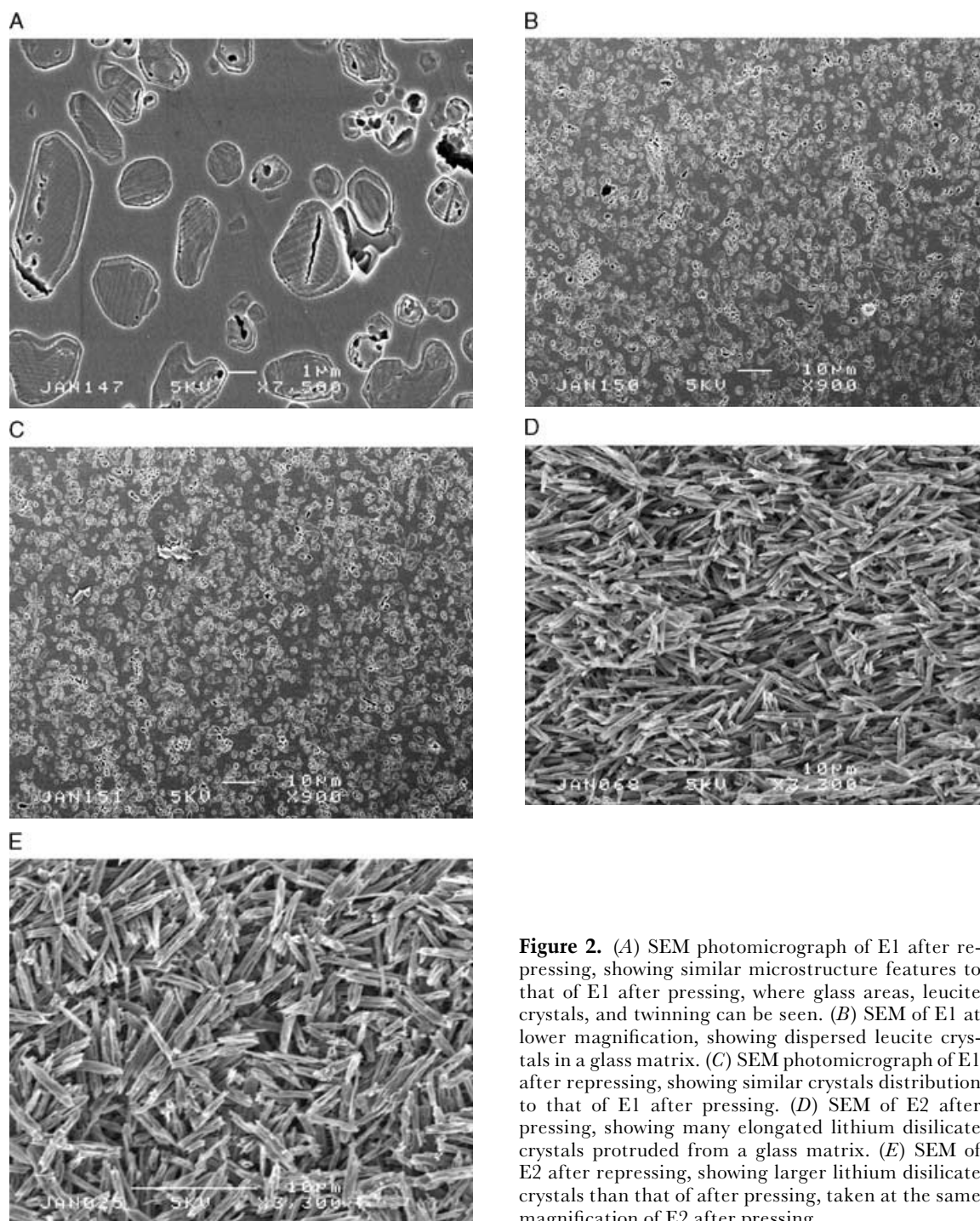


Figure 2. (A) SEM photomicrograph of E1 after repressing, showing similar microstructure features to that of E1 after pressing, where glass areas, leucite crystals, and twinning can be seen. (B) SEM of E1 at lower magnification, showing dispersed leucite crystals in a glass matrix. (C) SEM photomicrograph of E1 after repressing, showing similar crystals distribution to that of E1 after pressing. (D) SEM of E2 after pressing, showing many elongated lithium disilicate crystals protruded from a glass matrix. (E) SEM of E2 after repressing, showing larger lithium disilicate crystals than that of after pressing, taken at the same magnification of E2 after pressing.

The improved mechanical properties of E2 material over that of E1 are attributed to the unique interlocking microstructure of densely packed high content of lithium disilicate crystals, 70%.²⁴ A recent study reported higher crystalline content

of E2 material, reaching 90%.²³ It is well known that higher crystalline content tends to improve the mechanical properties of ceramic materials;³⁹ however, the behavior of the crystals during either heat treatment or external forces can also play

a major role in the mechanical properties. In a previous study by the present investigators, it was shown that a preferred orientation of these crystals after pressing may occur and cause fracture toughness anisotropy. This alignment may also result in overestimation of the fracture toughness and strength if stresses, during testing, are applied parallel to these aligned elongated crystals.²¹

X-ray diffraction was used in this study to evaluate the effect of second heat pressing on the crystalline phases of both materials. The results for both E1 and E2 showed similar X-ray diffraction traces for the pressed and repressed samples of each material. These results support other findings, namely mechanical testing and the microstructure features, which suggest that repressing did not cause a significant change in the studied materials, E1 and E2.

Flaws and microcracks may develop during the processing of brittle materials or may occur as a result of residual stresses within the microstructure during heat treatment. The influence of these flaws and defects on strength measurements can cause large variations in the strength data. Weibull modulus is used to describe the variation of the strength results. The lower the value of Weibull modulus, the greater the variability of the strength data which, in turn, points to more flaws and defects of the material, and unreliability.³² In fact, Weibull modulus values are also affected by the method adopted to finish specimens and test environment, because of possible influences on residual flaw sizes and subcritical crack growth. In this study, both materials demonstrated lower Weibull modulus values after repressing. During repressing, flaws might have developed as a result of occasional porosity entrapment between the remnant buttons used for repressing. This may create large pores or cracks that significantly degrade strength; however, since the mean strength value was not significantly affected, this indicated that only a few specimens, among those tested, were affected.

Conclusion

Within the limitations of the present study, it may be concluded that second pressing of both materials did not affect their mechanical strength; however, greater strength scatter of the repressed samples of both materials may indicate less reliability of these materials after repressing. Further

studies and/or testing of other mechanical properties, such as Elastic modulus or fracture toughness, may provide a better understanding of the effect of repressing on the mechanical properties of the pressable materials, E1 and E2.

Acknowledgments

We would like to acknowledge Ivoclar-Vivadent, Schaan, Liechtenstein for providing the materials and the following people for their technical advice: Dr. Kaarel Proos, Mr. Adel Fadel, Mr. Mossa Alfify, and Mr. Hamad Al-Dwais.

References

1. Xiao-ping L, Jie-mo T, Yun-long Z, et al: Strength and fracture toughness of MgO-modified glass infiltrated alumina for CAD/CAM. *Dent Mater* 2002;18:216-220
2. Cattell MJ, Clarke RL, Lynch EJ: The transverse strength, reliability and microstructural features of four dental ceramics. Part I. *J Dent* 1997;25:399-407
3. Guazzato M, Albakry M, Swain MV, et al: Mechanical properties of In-Ceram Alumina and In-Ceram Zirconia. *Int J Prosthodont* 2002;15:339-346
4. Chen HY, Hickel R, Setcos JC, et al: Effects of surface finish and fatigue testing on the fracture strength of CAD-CAM and pressed-ceramic crowns. *J Prosthet Dent* 1999;82:468-475
5. Denry IL, Holloway JA, Colijn HO: Phase transformations in a leucite-reinforced pressable dental ceramic. *J Biomed Mater Res* 2001;54:351-359
6. Dong JK, Luthy H, Wohlwend A, et al: Heat-pressed ceramics: technology and strength. *Int J Prosthodont* 1992;5:9-16
7. Gorman CM, McDevitt WE, Hill RG: Comparison of two heat-pressed all-ceramic dental materials. *Dent Mater* 2000;16:389-395
8. Probst L, Geis-Gerstorf J, Kirchner E, et al: In vitro evaluation of a glass-ceramic restorative material. *J Oral Rehabil* 1997;24:636-645
9. Cattell MJ, Knowles JC, Clarke RL, et al: The biaxial flexural strength of two pressable ceramic systems. *J Dent* 1999;27:183-196
10. Neiva G, Yaman P, Dennison JB, et al: Resistance to fracture of three all-ceramic systems. *J Esthet Dent* 1998;10:60-66
11. Strub JR, Beschnidt SM: Fracture strength of 5 different all-ceramic crown systems. *Int J Prosthodont* 1998;11:602-609
12. Chai J, Takahashi Y, Sulaiman F, et al: Probability of fracture of all-ceramic crowns. *Int J Prosthodont* 2000;13:420-424
13. Esquivel-Upshaw JF, Anusavice KJ, Yang MC, et al: Fracture resistance of all-ceramic and metal-ceramic inlays. *Int J Prosthodont* 2001;14:109-114
14. Ohyama T, Yoshinari M, Oda Y: Effects of cyclic loading on the strength of all-ceramic materials. *Int J Prosthodont* 1999;12:28-37

15. Sorensen JA, Choi C, Fanuscu MI, et al: IPS Empress crown system: three-year clinical trial results. *J Calif Dent Assoc* 1998;26:130-136
16. Tidehag P, Gunne J: A 2-year clinical follow-up study of IPS Empress ceramic inlays. *Int J Prosthodont* 1995;8:456-460
17. Myers ML, Ergle JW, Fairhurst CW, et al: Fatigue failure parameters of IPS-Empress porcelain. *Int J Prosthodont* 1994;7:549-553
18. Krejci I, Krejci D, Lutz F: Clinical evaluation of a new pressed glass ceramic inlay material over 1.5 years. *Quintessence Int* 1992;23:181-186
19. Wagner WC, Chu TM: Biaxial flexural strength and indentation fracture toughness of three new dental core ceramics. *J Prosthet Dent* 1996;76:140-144
20. 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
21. Albakry M, Guazzato M, Swain MV: Fracture toughness and hardness evaluation of three pressable all-ceramic dental materials. *J Dent* 2003;31:181-188
22. van Dijken JW, Ormin A, Olofsson AL: Clinical performance of pressed ceramic inlays luted with resin-modified glass ionomer and autopolymerizing resin composite cements. *J Prosthet Dent* 1999;82:529-535
23. Cattell MJ, Palumbo RP, Knowles JC, et al: The effect of veneering and heat treatment on the flexural strength of Empress 2 ceramics. *J Dent* 2002;30:161-169
24. Holand W, Schweiger M, Frank M, et al: 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
25. Albakry M, Guazzato M, Swain MV: Fracture toughness, microstructure and toughening mechanism of leucite and lithium disilicate glass ceramics. *Bioceramic 15, Proceedings of the 15th International Symposium on Ceramics in Medicine, the Annual Meeting of the International Society for Ceramics in Medicine, 2002:955-958*
26. Sorensen JA, Cruz M, Mito WT, et al: A clinical investigation on three-unit fixed partial dentures fabricated with a lithium disilicate glass ceramic. *Pract Periodontics Aesthet Dent* 1999;11:95-106
27. Kheradmandan S, Koutayas SO, Bernhard M, et al: Fracture strength of four different types of anterior 3-unit bridges after thermo-mechanical fatigue in the dual-axis chewing simulator. *J Oral Rehabil* 2001;28:361-369
28. Tinschert J, Natt G, Mautsch W, et al: Fracture resistance of lithium disilicate-, alumina-, and zirconia-based three-unit fixed partial dentures: a laboratory study. *Int J Prosthodont* 2001;14:231-238
29. Fischer H, Rentzsch W, Marx R: R-curve behavior of dental ceramic materials. *J Dent Res* 2002;81:547-551
30. Nakamura T, Ohyama T, Imanishi A, et al: Fracture resistance of pressable glass-ceramic fixed partial dentures. *J Oral Rehabil* 2002;29:951-955
31. ASTM: F394-78. Standard test method for biaxial flexure strength (modulus of rupture) of ceramic substrates, 1996:1-5
32. Ban S, Anusavice KJ: Influence of test method on failure stress of brittle dental materials. *J Dent Res* 1990;69:1791-1799
33. Esquivel-Upshaw JF, Chai J, Sansano S, et al: Resistance to staining, flexural strength, and chemical solubility of core porcelains for all-ceramic crowns. *Int J Prosthodont* 2001;14:284-288
34. Mackert JR, Twigg SW, Russell CM, et al: Evidence of a critical leucite particle size for microcracking in dental porcelains. *J Dent Res* 2001;80:1574-1579
35. Shareef MY, Van Noort R, Messer PF: The effect of microstructural features on the biaxial flexural strength of leucite reinforced glass-ceramics. *J Mater Sci Mater Med* 1994; 5:113-118
36. Martin JW, Doherty RD, Cantor B: *Stability of Microstructure in Metallic Systems* (ed 2). Cambridge, MA, Cambridge University Press, 1997, pp 239-259
37. Oh SC, Dong JK, Luthy H, et al: Strength and microstructure of IPS Empress 2 glass-ceramic after different treatments. *Int J Prosthodont* 2000;13:468-472
38. Lawn BR: *Fracture of Brittle Solids* (ed 2). Cambridge, MA, Cambridge University Press, 1993, pp 249-306
39. Seghi RR, Sorensen JA: Relative flexural strength of six new ceramic materials. *Int J Prosthodont* 1995;8:239-246

Copyright of Journal of Prosthodontics is the property of Blackwell Publishing Limited. The copyright in an individual article may be maintained by the author in certain cases. Content may not be copied or emailed to multiple sites or posted to a listserv without the copyright holder's express written permission. However, users may print, download, or email articles for individual use.