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Contributions of stress corrosion and cyclic fatigue to subcritical crack growth in a dental glass-ceramic

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Abstract

Objective—The objective of this study was to test the following hypotheses: 1. Both cyclic degradation and stress-corrosion mechanisms result in subcritical crack growth (SCG) in a fluorapatite glass-ceramic (IPS e.max ZirPress, Ivoclar-Vivadent). 2. There is an interactive effect of stress corrosion and cyclic fatigue to accelerate subcritical crack growth.

Methods—Rectangular beam specimens were fabricated using the lost-wax process. Two groups of specimens (N=30/group) with polished (15 μ m) or air-abraded surface were tested under rapid monotonic loading. Additional polished specimens were subjected to cyclic loading at two frequencies, 2 Hz (N=44) and 10 Hz (N=36), and at various stress amplitudes. All tests were performed using a fully articulated four-point flexure fixture in deionized water at 37°C. The SCG parameters were determined using the ratio of inert strength Weibull modulus to lifetime Weibull modulus. A general log-linear model was fit to the fatigue lifetime data including time to failure, frequency, peak stress, and the product of frequency and logarithm of stress in ALTA PRO software.

Results—SCG parameters determined were $n=21.7$ and $A=4.99 \times 10^{-5}$ for 2 Hz, and $n=19.1$ and $A=7.39 \times 10^{-6}$ for 10 Hz. After fitting the general log-linear model to cyclic fatigue data, the coefficients of the frequency term (α_1), the stress term (α_2), and the interaction term (α_3) had estimates and 95% confidence intervals of $\alpha_1 = -3.16$ (−15.1, 6.30), $\alpha_2 = -21.2$ (−34.9, −9.73), and $\alpha_3 = 0.820$ (−1.59, 4.02). Only α_2 was significantly different from zero.

Keywords

Dental ceramic; pressable ceramic; air abrasion; stress corrosion; cyclic fatigue

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Introduction

Subcritical crack growth (SCG) is crack propagation under a stress intensity factor lower than the critical stress intensity factor. In vitro evidence suggests that the strengths of *dental ceramics* in the simulated oral environment decrease over time due to SCG [1–4]. The environment can have a strong effect on crack growth with aqueous environments leading to *increased SCG* and hence lower strength than inert environments [5–7]. Subcritical crack growth data can be obtained by direct or indirect techniques. The direct methods measure crack growth velocity as a function of stress intensity factor on specimens that allow stable crack growth, such as in the double cantilever beam test. The indirect methods obtain crack propagation parameters using strength *values* from specimens that have undergone varying amounts of SCG prior to unstable crack growth [5]. These include constant stress or ‘static fatigue’ and constant stress-rate or ‘dynamic fatigue’ test methods [8].

Some ceramic materials show accelerated crack growth in the presence of cyclic loading. The time to failure under cyclic stress can be less or more than for a static load at the same maximum stress, depending on the contribution of cyclic degradation to the crack growth [9]. Evans and Fuller compared crack growth rates for cyclic and static loading, using the double torsion technique, for glass and porcelain and showed that there is no significantly enhanced effect of cycling on crack growth for these materials [10]. Twigg *et al* showed that there is no significant difference between crack growth parameters obtained from dynamic fatigue and cyclic fatigue for a model porcelain [11]. On the other hand, White *et al* used repeated loading with blunt indentation for different numbers of cycles in inert, ambient and wet environments, followed by strength testing of porcelain discs to prove that, both stress corrosion and cyclic loading significantly reduced the strength of porcelain, but a two-way ANOVA test did not show any interactive effect between stress corrosion and cyclic fatigue [12]. However, White *et al* placed the surface in tension under flexural loading after repeated loading with blunt indentation. Thus, they did not simulate a clinical situation. Consistent flexural or blunt loading until failure would have simulated a clinical situation.

Previous studies have investigated SCG in dental ceramics under cyclic loading in water [4, 13, 14]. However, the individual contributions of stress corrosion, cyclic fatigue or the interaction between the two have not been established. Hence, in this study, the general log-linear model was used to determine the individual contributions of stress corrosion and cyclic fatigue as well as the interaction between the two. The general log-linear model in ALTA PRO software is based on more widely known Log-Linear model and is formulated for the Weibull and Log-normal distributions. The model is based on two assumptions: (1) Statistically independent covariates (2) similar mode of failure for all specimens. The general log-linear relationship describes characteristic life, as a function of simultaneous causes of damage accumulation, which may include environmental factors, mechanical loading, categorical factors, and interaction between these factors having a variety of relations with lifetime, including Arrhenius and inverse power law [15].

The objective of this study was to test the hypotheses: (1) Cyclic degradation has an additional effect on subcritical crack growth in the fluorapatite glass-ceramic IPS e.max

ZirPress. (2) There is an interactive effect of stress corrosion and cyclic fatigue to accelerate subcritical crack growth.

Materials and methods

Specimen preparation

This study was performed on a pressable fluorapatite glass-ceramic (IPS e.max ZirPress, Ivoclar Vivadent, Schaan, Liechtenstein). It is available in the form of prefabricated ingots, which must be injection molded into phosphate-based investment material via the lost wax method. The composition of IPS e.max ZirPress, as provided by the manufacturer, is as follows (in wt %): 57–62 SiO₂, 12–16 Al₂O₃, 7–10 Na₂O, 6–8 K₂O, 2–4 CaO, 1.5–2.5 ZrO₂, 1–2 P₂O₅, 0.5–1 F, and 0–6 other oxides. Rectangular beam specimens were fabricated to dimensions of 25 mm × 4 mm × 1.2 mm according to the ISO 6872 standard [16].

Rectangular bars of the abovementioned dimensions were cut from casting wax sheets (Kinco dental waxes, Kindt-Collins Company, Cleveland, OH, USA). *Spruing*, investing in the investment material (IPS PressVEST Speed, Ivoclar-Vivadent, Schaan, Liechtenstein), and preheating at 850°C were performed following the manufacturer's instructions. Immediately after wax burnout, ingots were placed into the open end of the mold, followed by an alumina plunger, and the whole assembly was placed into a press furnace (Multimat Touch & Press, Dentsply, Tulsa, OK, USA). The mold was heated to 920°C and held for 15 minutes, followed by a press time of 6 minutes at an air pressure of 2 bar (0.2 MPa). After cooling the investment ring to room temperature, divesting was carried out by airborne particle abrasion with glass beads (100 µm) at 4 bar (0.4 MPa) pressure (for rough divestment) followed by 2 bar pressure (for fine divestment) in an air abrasion unit (Quattro IS, Renfert, St.Charles, Illinois, USA).

Specimens for cyclic loading were ground to the final desired dimensions using a 30-µm diamond wheel and 200 g pressure with a polishing machine (Techprep, Allied High Tech, Rancho Dominguez, CA, USA). Then, specimens were polished to a 15-µm surface finish using the circular rotating motion of diamond lapping films (30 µm film followed by a 15 µm film). Specimens with an air-abraded surface finish were treated by immersing in Invet liquid (Ivoclar-Vivadent) and cleaning in a sonicator (Aquasonic 150T, VWR Scientific Products, Radnor, PA) for 5 minutes, according to the manufacturer's instructions. Subsequently, specimens were cleaned in running water and blown dry. The white reaction layer was removed by air abrasion with Al₂O₃ particles (100 µm) at 2 bar pressure. The edges of all specimens were chamfered (0.11 mm) parallel to the long axis of specimens with the help of a custom-made apparatus to minimize stress concentration and consequent failure from the edges during mechanical testing.

Mechanical testing

Specimens for cyclic fatigue were tested at two different frequencies, 2 Hz and 10 Hz, and at different peak stress levels ranging from 40 to 60 MPa. These stress levels were determined using fast fracture data in conjunction with ALTA PRO software (Reliasoft, Tucson, AZ,

USA). ALTA PRO predicted that these stress levels corresponded to a small probability of fast fracture and achieved fatigue fracture of all specimens within the study timeline. To compare the effect of frequency on lifetime, two groups of 30 specimens each were tested at 2 Hz and 10 Hz frequencies and a peak stress level of 45 MPa. The sinusoidal cyclic loading (Stress ratio, $R = 0.1$) was applied using a custom-made fully articulated four-point ¼-point flexure fixture [17] in deionized water at 37°C, and the number of cycles to failure and the lifetime were recorded for each specimen. Another group of 30 specimens with airabraded surface finish and a group of 30 polished specimens were tested in oil under monotonic loading at a stressing rate of 1 MPa/s to determine the inert strength. These specimens were tested in oil to eliminate the SCG due to moisture in environment. The target stressing rate for monotonic loading or target peak stress level for cyclic loading was attained using servohydraulic load frames in load-controlled mode. The load necessary to reach the target stress was determined using the following equation:

$$P = \frac{4\sigma}{3L}wd^2 \quad (1)$$

where P is the load, σ is the target stress, L is the outer support span of the fixture, w is the specimen width, and d is the specimen thickness.

The width and thickness of each specimen were measured adjacent to the fracture surface to determine the flexural strength, σ_f of each specimen according to the following equation:

$$\sigma_f = \frac{3P_{max}L}{4wd^2} \quad (2)$$

where P_{max} is the maximum load recorded during testing.

Weibull analysis

The strength and lifetime data obtained from inert strength and cyclic fatigue testing were analyzed using Weibull statistics [18]. The inert strength data from polished specimens were fit to a Weibull distribution using Maximum Likelihood Estimation (MLE) [19]. They were also fit using the rank regression method with the following equations:

$$P_f = \frac{x - 0.5}{n_T} \quad (3)$$

$$\ln \ln \left(\frac{1}{1 - P_f} \right) = m \ln \sigma - m \ln \sigma_0 \quad (4)$$

where P_f is probability of failure of “ x^{th} ” specimen after ranking the specimens in ascending order according to their failure strength σ , n_T is the total number of specimens tested, m is the Weibull modulus and σ_0 is the characteristic strength. The cyclic fatigue data were fit to Weibull distributions using the following equation,

$$\ln \ln \left(\frac{1}{1 - P_f} \right) = m^* \ln N_f - m^* \ln N_{f,0} \quad (5)$$

where P_f is the failure probability of the “x” specimen after ranking the specimens in ascending order according to their number of cycles to failure (N_f), $N_{f,0}$ is the characteristic number of cycles to failure at 63.21% failure probability, and m^* is the lifetime Weibull modulus. The lifetime for each specimen was calculated using the frequency and number of cycles to failure. The cyclic lifetime data were also fit to Weibull distributions to determine the characteristic lifetime, η , for each frequency.

Subcritical crack growth (SCG) parameters

SCG parameters A and n were calculated from the paired Weibull distributions of inert strengths and cyclic fatigue lifetimes of the test specimens using the statistical approach described by Munz and Fett [20]. This method is applicable if (1) the group of specimens submitted to the strength tests has the same flaw size distribution as that of specimens submitted to the lifetime experiments and (2) cracks initiate from surface flaws in both tests. These are reasonable assumptions in this study, since most of the specimens used for determining SCG parameters failed from surface flaws [21].

SCG parameters A and n were calculated using following equations:

$$n = \left(\frac{m}{m^*} \right) + 2 \quad (6)$$

$$A = \frac{2(K_{Ic})^2 - n(\sigma_0)^{n-2}}{N_{f,0} Y^2 (n-2)(\sigma_{max})^n} \quad (7)$$

where K_{Ic} and Y are the means of estimates determined from the fractographic analysis of specimens as published previously [21], and σ_{max} is the peak stress for cyclic loading. The stress intensity shape factor, Y , was determined for both the deepest point on the critical flaw and at the tensile surface using an equation developed by Newman and Raju, and the greater of the two values was used [22]. The critical flaw dimensions and failure stress were used to calculate the fracture toughness using the following equation.

$$K_{Ic} = Y \sigma_f \sqrt{a} \quad (8)$$

where K_{Ic} is the fracture toughness of material, σ_f is the failure stress, and a is the depth of the critical flaw.

The subcritical crack growth curves were calculated using the SCG parameters. The crack velocity, v , was plotted against the maximum stress intensity factor, K_{Imax} .

General log linear model

Data from cyclic fatigue testing were fit to the general log-linear model using ALTA PRO software.

$$\eta = e^{\alpha_0 + \alpha_1 f + \alpha_2 \ln \sigma_{max} + \alpha_3 f \ln \sigma_{max}} \quad (9)$$

where η is the characteristic lifetime, $\alpha_0, \alpha_1, \alpha_2, \alpha_3$ are regression coefficients and f is the frequency of cycling. The first term in the equation is the intercept. The second term gives the effect of cycling on lifetime, as it contains the frequency. The third term indicates the effect of stress corrosion as a power law function, while the fourth term gives the interaction between stress corrosion and cyclic fatigue. The confidence intervals for the statistical model parameters were determined by Monte Carlo simulation using the Simumatic tool of ALTA PRO software.

Results

Rapid monotonic loading

The Weibull parameters for rapid monotonic loading of airabraded specimens and polished specimens are summarized in Table 1. There was no significant difference in Weibull modulus, m , and characteristic strength, σ_0 , for the two groups, since the 95% confidence intervals for these parameters overlap. Figure 1 shows a Weibull plot of probability of failure vs. strength for both groups.

Fatigue testing

The Weibull parameters for fatigue lifetime data for specimens tested at the frequencies, 2 Hz and 10 Hz, and a peak stress level of 45 MPa are summarized in Table 2. There was no significant difference in characteristic lifetime, η , for the two groups. The lifetime Weibull moduli, m^* , were less than one for both groups. Lifetime Weibull moduli are always smaller than strength Weibull moduli [4, 14, 23].

SCG parameters

Equations 6 and 7 were used to calculate SCG parameters for groups tested at frequencies of 2 Hz and 10 Hz. The mean values for K_{IC} and Y , and SCG parameters are presented in Table 3. This method does not provide the confidence intervals for the SCG parameter estimates. Figure 2 presents the SCG curves for the specimens tested at both frequencies. The SCG curves for the two frequencies almost overlapped each other. The confidence bounds could not be calculated for these curves, since the confidence intervals for the SCG parameters are not provided by the method of Munz and Fett.

General log-linear model

Fatigue lifetime data were fit to a general log-linear model (Equation 9) in ALTA PRO software. The values of parameters obtained with their 95% confidence intervals are summarized in Table 4. As seen in the table, only α_0 and α_2 are significantly different from zero because their confidence intervals do not include zero. Since the values are negative, the third term (stress corrosion) in Equation 9 has a significantly negative effect on lifetime. The confidence intervals for α_1 and α_3 include zero indicating no significant effect of the second term (frequency of cycling) and fourth term (interaction) on lifetime.

Discussion

The present study showed that an increase in the frequency of cycling did not cause a decrease in the lifetime. Although the specimens tested at 10 Hz survived for a higher number of cycles than the specimens tested at 2 Hz, both groups showed similar characteristic lifetimes ($\eta_{2\text{Hz}}=10800$ s, $\eta_{10\text{Hz}}=11600$ s). This proves that there was no additional effect of cyclic loading on the crack growth. Thus, the first hypothesis was rejected. The parameters of the general log-linear model showed that, besides the intercept term (α_0), only α_2 was significantly different from zero, ranging from -35 to -10 . The confidence intervals for α_1 ($-15.1, 6.30$) and α_3 ($-1.59, 4.02$) included zero. Thus, only stress corrosion had a significant effect on the lifetime. There was no significant effect of frequency of loading as well as the interaction between the stress corrosion and cyclic loading. Hence, the second hypothesis was also rejected.

These results support the findings of a previous study, which showed no significant difference between crack growth parameters obtained from dynamic fatigue and cyclic fatigue for a model porcelain [11]. In that study, disk specimens of a model porcelain were tested under biaxial loading at different stressing rates to determine the crack growth parameters. Another study by White *et al*/reported contradictory findings [12]. They used repeated cyclic loading with a blunt indenter to prove that both stress corrosion and cyclic fatigue significantly reduced the strength of porcelain. However, White *et al*/induced Hertzian cone cracks produced using a blunt indenter, which is different from the types of initial flaws observed in the specimens that were investigated in the present study [21]. Also, repeated loading with blunt indentation, followed by flexural loading did not simulate a clinical situation.

The subcritical crack growth curves (Figure 2) showed that the crack velocity ranged approximately from 10^{-20} m/cycle to 10^{-6} m/cycle. These values could not be compared to the values in literature because sinusoidal cyclic loading was used in this study as opposed to constant stress-rate loading. In the current study, most of the crack growth was expected to occur at and near the maximum stress intensity factor. The subcritical crack growth (SCG) parameters determined using the statistical approach by Munz and Fett can be presumed to be similar for both frequencies, because the 95% confidence interval for n values determined by other methods is usually ± 4 and the 95% confidence interval for A values ranges over several orders of magnitude [24, 25]. This would prove that subcritical crack growth for this material or similar glass-matrix ceramics is not affected by the frequency of testing. It is also evident from the SCG curves (Figure 2) which almost overlap each other. The n value obtained in this study is in the range of 19–21. This value is similar to the n values of other glass-matrix ceramics reported in the literature [2, 3, 26–28]. Also, the n value is similar to the α_2 parameter in the general log-linear model. This suggests that this model can be used to fit the fatigue data with different stress-amplitudes and different frequencies when there is no effect of cyclic degradation, as evident from the parameters of the general log-linear model. However, the model should also be validated for additional dental ceramics.

The results of rapid monotonic loading showed that there was no significant difference in the Weibull parameters for the air-abraded and polished specimens. The characteristic strength

of polished specimens was 68 MPa. This strength is less than the mean biaxial strength reported by the manufacturer, which is 110 MPa. One possible reason may be that the furnace and air pressure recommended by the manufacturer were not used. However, uniaxial four-point bending strength values are lower on average than biaxial strength values because of a difference in effective volume based on specimen dimensions and loading geometry [29], which may be the reason or a contributing factor for the discrepancy.

In this study, the specimens were tested in deionized water instead of saliva. A previous study found that there is no difference in n measured in water and artificial saliva [1]. The specimens were tested in a four-point bending rectangular beam geometry. There is concentration of stresses at the edges in this geometry. Although the specimens were chamfered to avoid stress concentration, a few specimens still failed from the edges. However, they were excluded in the calculation of fracture toughness and SCG parameters. Also, only the single-layer veneering ceramic was tested in this study compared to the multilayered structure of all-ceramic crowns and FPDs. The distribution of stresses is different in a clinical situation because of several factors such as varying shape and volume of dental restorations, the presence of residual stress in a layered structure and varying mechanical and thermal stresses during mastication. Therefore, the results gained from this study cannot be directly applied to make clinical lifetime predictions. Instead, this study was aimed at determining the mechanisms of ceramic degradation.

The results did not show an accelerated crack growth due to cyclic loading. Hence, clinicians and researchers should not disregard the results of studies that use higher than the physiologic frequency for testing predominantly glassy ceramics. However, testing at higher frequency will not reduce the testing time for this class of materials.

Conclusions

Based on the results of this study, the following conclusions can be made:

1. There was no significant effect of cyclic degradation mechanism on subcritical crack growth in the fluorapatite glass-ceramic IPS e.max ZirPress, rejecting the first experimental hypothesis.
2. There was no interactive effect between cyclic degradation and stress corrosion for this material, rejecting the second experimental hypothesis.

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References

1. Morena R, Beaudreau GM, Lockwood PE, Evans AL, Fairhurst CW. Fatigue of dental ceramics in a simulated oral environment. *J Dent Res*. 1986; 65(7):993–997. [PubMed: 3458762]

2. Myers ML, Ergle JW, Fairhurst CW, Ringle RD. Fatigue failure parameters of IPS-Empress porcelain. *Int J Prosthodont*. 1994; 7(6):549–553. [PubMed: 7748450]
3. Lohbauer U, Kramer N, Petschelt A, Frankenberger R. Correlation of in vitro fatigue data and in vivo clinical performance of a glassceramic material. *Dent Mater*. 2008; 24(1):39–44. [PubMed: 17467049]
4. Studart AR, Filser F, Kocher P, Gauckler LJ. In vitro lifetime of dental ceramics under cyclic loading in water. *Biomaterials*. 2007; 28(17):2695–2705. [PubMed: 17337047]
5. Wiederhorn, SM. Subcritical crack growth in ceramics. In: Bradt, RC, Hasselmann, DPH, Lange, FF, editors. *Symposium on Fracture Mechanics of Ceramics*. Vol. 2. University Park, PA: Plenum; 1974.
6. Michalske TA, Freiman SW. A molecular interpretation of stress corrosion in silica. *Nature*. 1982; 295(5849):511–512.
7. Anusavice KJ, Lee RB. Effect of firing temperature and water exposure on crack propagation in unglazed porcelain. *J Dent Res*. 1989; 68(6):1075–1081. [PubMed: 2808866]
8. ASTM C1368. Standard test method for determination of slow crack growth parameters of advanced ceramics by constant stress rate flexural testing at ambient temperature. West Conshohoken, PA: ASTM International; 2001.
9. Ritchie RO, Dauskardt RH. Cyclic fatigue of ceramics - a fracture-mechanics approach to subcritical crack-growth and life prediction. *Nippon Seram Kyo Gak*. 1991; 99(10):1047–1062.
10. Evans AG, Fuller ER. Crack propagation in ceramic materials under cyclic loading conditions. *Metall Trans A*. 1974; 5(1):27–33.
11. Twiggs SW, Fairhurst CW, Lockwood PE, Ringle RD. Cyclic fatigue of a model feldspathic porcelain. *Dent Mater*. 1995; 11(4):273–276. [PubMed: 8621051]
12. White SN, Li ZC, Yu ZK, Kipnis V. Relationship between static chemical and cyclic mechanical fatigue in a feldspathic porcelain. *Dent Mater*. 1997; 13(2):103–110. [PubMed: 9467312]
13. Studart AR, Filser F, Kocher P, Gauckler LJ. Fatigue of zirconia under cyclic loading in water and its implications for the design of dental bridges. *Dent Mater*. 2007; 23(1):106–114. [PubMed: 16473402]
14. Marocho SMS, Studart AR, Bottino MA, Della Bona A. Mechanical strength and subcritical crack growth under wet cyclic loading of glass-infiltrated dental ceramics. *Dent Mater*. 2010; 26(5):483–490. [PubMed: 20303160]
15. Mettas, A. Annual Reliability and Maintainability Symposium - 2000 Proceedings. New York: I E E E; 2000. Modeling & analysis for multiple stress-type accelerated life data.
16. ISO 6872. Dental Ceramic. Geneva, Switzerland: International Organization for Standardization; 2008.
17. ASTM C1161. Standard test method for flexural strength of advanced ceramics at ambient temperature. West Conshohoken, PA: ASTM International; 2002.
18. Weibull WA. A statistical distribution function of wide applicability. *J Appl Mech*. 1951; 18:293–297.
19. ASTM C1239. Standard practice for reporting uniaxial strength data and estimating Weibull parameters for advanced ceramics. West Conshohoken, PA: ASTM International; 2007.
20. Munz, D, Fett, T. *Ceramics: mechanical properties, failure behaviour, materials selection*. Berlin: Springer-Verlag; 1999.
21. Joshi GV, Duan Y, Della Bona A, Hill TJ, St. John K, Griggs JA. Fatigue loading and R-curve behavior of a dental glass-ceramic with multiple flaw distributions. *Dent Mater*. 2013; 29(11):1123–1131. [PubMed: 24034441]
22. Newman JC, Raju IS. An empirical stress-intensity factor equation for the surface crack. *Eng Fract Mech*. 1981; 15:185–192.
23. Joshi GV, Duan Y, Neidigh J, Koike M, Chahine G, Kovacevic R, Okabe T, Griggs JA. Fatigue testing of electron beam-melted Ti-6Al-4V ELI alloy for dental implants. *J Biomed Mater Res B Appl Biomater*. 2013; 101(1):124–130. [PubMed: 23077086]
24. Ritter JE Jr, Bandyopadhyay N, Jakus K. Statistical reproducibility of the dynamic and static fatigue experiments. *Am Ceram Soc Bull*. 1981; 60(8):798–806.

25. Salem, JA, Jenkins, MG. The effect of stress rate on slow crack growth parameter estimates. In: Salem, JA, Quinn, GD, Jenkins, MG, editors. ASTM STP 1409: Fracture resistance testing of monolithic and composite brittle materials. West Conshohocken, PA: ASTM International; 2002. 213–227.
26. Fairhurst CW, Lockwood PE, Ringle RD, Twiggs SW. Dynamic fatigue of feldspathic porcelain. *Dent Mater.* 1993; 9(4):269–273. [PubMed: 7988760]
27. Teixeira EC, Piascik JR, Stoner BR, Thompson JY. Dynamic fatigue and strength characterization of three ceramic materials. *J Mater Sci Mater Med.* 2007; 18(6):1219–1224. [PubMed: 17277977]
28. Gonzaga CC, Yoshimura HN, Cesar PF, Miranda WGJ. Subcritical crack growth in porcelains, glass-ceramics, and glass-infiltrated alumina composite for dental restorations. *J Mater Sci Mater Med.* 2009; 20(5):1017–1024. [PubMed: 19112607]
29. Jin J, Takahashi H, Iwasaki N. Effect of test method on flexural strength of recent dental ceramics. *Dent Mater J.* 2004; 23(4):490–496. [PubMed: 15688709]

Figure 1.

Weibull probability plot for rapid monotonic loading of air-abraded specimens (blue) and polished specimens (black). Regression lines represent a two-parameter model fit using MLE. The dotted lines represent the 95% confidence intervals for probability of failure.

Figure 2.
 Subcritical crack growth curves for the crack growth parameters estimated from the specimens tested at 2 Hz (solid line) and 10 Hz (dotted line).

Table 1

Weibull parameters for rapid monotonic loading of air-abraded and polished specimens.

Group	MLE method		Rank regression method	
	m	σ_0 (MPa)	m	σ_0 (MPa)
Air-abraded	7.4 (5.0, 10) *	65.8 (61.1, 70.5) *	8.8 (4.6, 11) *	65.3 (60.2, 71.5) *
Polished	9.2 (6.2, 13) *	67.5 (63.9, 71.2) *	9.0 (6.3, 13) *	67.4 (63.9, 71.2)

* 95% confidence interval

Table 2

Weibull parameters determined using MLE for fatigue lifetime data of polished specimens.

Group	m^*	η (s)	η (h:min:s)
2 Hz	0.38 (0.25, 0.53) *	10800 (2800, 40300) *	03:00:00 (00:46:40, 11:11:40) *
10 Hz	0.30 (0.19, 0.43) *	11600 (1800, 87900) *	03:13:20 (00:30:00, 24:25:00) *

* 95% confidence interval

Table 3

SCG parameters determined according to the Munz and Fett statistical approach for polished specimens loaded in cyclic fatigue.

Group	Y	$K_{Ic} (MPa \cdot m^{1/2})$	n	$A \left(\frac{\text{m/cycle}}{(MPa \cdot m^{1/2})^n} \right)$
2 Hz	1.20	0.90	21.7	4.99×10^{-5}
10 Hz	1.19	0.93	19.1	7.39×10^{-6}

Table 4

The parameters of a general log-linear model after fitting data for fatigue lifetimes of polished specimens as a function of loading frequency (α_1 term), peak stress (α_2 term), and their interaction (α_3 term).

Coefficient	Value
α_0	90.0 (48.0, 146) [*]
α_1	-3.16 (-15.1, 6.30) [*]
α_2	-21.2 (-34.9, -9.73) [*]
α_3	0.820 (-1.59, 4.02) [*]

^{*} 95% confidence interval