Published in final edited form as:

Dent Mater. 2013 November ; 29(11): . doi:10.1016/j.dental.2013.08.208.

Fatigue loading and R-curve behavior of a dental glass-ceramic with multiple flaw distributions

Gaurav V. Joshi¹, Yuanyuan Duan¹, Alvaro Della Bona², Thomas J. Hill³, Kenneth St. John¹, and Jason A. Griggs¹

¹Department of Biomedical Materials Science, School of Dentistry, University of Mississippi Medical Center, Jackson, Mississippi

²Post-graduate Program in Dentistry, University of Passo Fundo, Passo Fundo, Brazil

³Ivoclar-Vivadent, Inc., Amherst, New York

Abstract

Objectives—To determine the effects of surface finish and mechanical loading on the rising toughness curve (R-curve) behavior of a fluorapatite glass-ceramic (IPS e.max ZirPress) and to determine a statistical model for fitting fatigue lifetime data with multiple flaw distributions.

Materials and Methods—Rectangular beam specimens were fabricated by pressing. Two groups of specimens ($n=30$) with polished ($15\ \mu\text{m}$) or air abraded surface were tested under rapid monotonic loading in oil. Additional polished specimens were subjected to cyclic loading at 2 Hz ($n=44$) and 10 Hz ($n=36$). All fatigue tests were performed using a fully articulated four-point flexure fixture in 37°C water. Fractography was used to determine the critical flaw size and estimate fracture toughness. To prove the presence of R-curve behavior, non-linear regression was used. Forward stepwise regression was performed to determine the effects on fracture toughness of different variables, such as initial flaw type, critical flaw size, critical flaw eccentricity, cycling frequency, peak load, and number of cycles. Fatigue lifetime data were fit to an exclusive flaw model.

Results—There was an increase in fracture toughness values with increasing critical flaw size for both loading methods (rapid monotonic loading and fatigue). The values for the fracture toughness ranged from 0.75 to $1.1\ \text{MPa}\cdot\text{m}^{1/2}$ reaching a plateau at different critical flaw sizes based on loading method.

Significance—Cyclic loading had a significant effect on the R-curve behavior. The fatigue lifetime distribution was dependent on the flaw distribution, and it fit well to an exclusive flaw model.

Keywords

Dental ceramic; pressable ceramic; fractography; exclusive flaw model

© 2004 Academy of Dental Materials. Published by Elsevier Ltd. All rights reserved.

Corresponding Author: Jason A. Griggs, PhD, FADM; Department of Biomedical Materials Science, School of Dentistry, University of Mississippi Medical Center, 2500 N State St, Room D528, Jackson, MS 39216-4505, Tel 1-601-984-6170, Fax 601-984-6087, JGriggs@umc.edu.

Publisher's Disclaimer: This is a PDF file of an unedited manuscript that has been accepted for publication. As a service to our customers we are providing this early version of the manuscript. The manuscript will undergo copyediting, typesetting, and review of the resulting proof before it is published in its final citable form. Please note that during the production process errors may be discovered which could affect the content, and all legal disclaimers that apply to the journal pertain.

Introduction

Fractography is an important tool in identification of the size and location of the fracture initiating crack or defect, the stress state at failure, and the presence or absence of local or global residual stress [1]. Fractographic analysis of retrieved clinical restorations has been used to identify initial flaws and to determine the possible cause and mechanism of failure of restorations [2-4]. It can also be used to determine the fracture toughness of the material by measuring the critical flaw dimensions on the fracture surfaces of standard geometry specimens [5].

Dental ceramics suffer from intrinsic, processing, and service flaws [6, 7]. It is challenging to predict the lifetimes of all-ceramic prostheses when multiple flaw types are present. Ceramic components show the presence of two or more types of flaws, with each flaw type having an independent distribution of flaw sizes [8]. The presence of multiple flaw types can be detected by fractographic analysis showing more than one fracture initiating defect and a simultaneous deviation of strength data from the expected distribution function. The multiple flaw distributions can be divided into three types – concurrent, partially concurrent, and exclusive [8]. If the flaw types are mutually exclusive within each specimen, then they are referred to as “exclusive flaw distributions”. When two flaw types are observed as in the present study, the probability of failure for the “exclusive flaw model”, P_T , is given by the following equation,

$$P_T = (1 - \Pi_B) P_A + \Pi_B P_B \quad (1)$$

where Π_B is the proportion of specimens having the flaw type B, P_A is the probability of failure for specimens containing flaw type A, and P_B is the probability of failure for specimens containing flaw type B.

Advanced ceramics such as partially stabilized zirconia, coarse-grained alumina, and silicon nitride show an increase in fracture toughness with increase in flaw size until a certain limit [9-11]. This is called R-curve behavior. Previous studies have shown that the materials that exhibit R-curve behavior are susceptible to crack growth due to cyclic degradation [12-14]. The mechanisms of cyclic degradation can be classified into two categories; intrinsic mechanisms where the cycle results in enhanced microstructural damage ahead of the crack tip (as in metals), and extrinsic mechanisms which act in the wake of the crack. In one extrinsic mechanism, premature contact upon unloading acts to diminish the effect of a crack-tip shielding process [12]. Also, ceramics exhibiting grain-bridging show extrinsic cyclic degradation because of damage to the bridging zone [15, 16]. Kishimoto *et al* studied the crack propagation behavior under static and cyclic loading in compact tension specimens of polycrystalline alumina with two types of average grain size. Cyclic loading decreased crack extension resistance to be below that for monotonic loading. This effect was greater in coarse-grained alumina compared to fine-grained alumina [15]. Kruzic *et al* investigated the crack growth under cyclic fatigue for both long and short cracks in 99.5% pure alumina. The crack growth rates were far higher at the same stress intensity factor range for short cracks than for long cracks, and fatigue thresholds were markedly lower for short cracks than for long cracks [16]. Lathabai *et al* tested disk specimens of alumina with indentation flaws under biaxial flexure. They showed that there was no significant cyclic degradation from possible damage to bridges for indentation cracks. However, the microstructure of the alumina used in the study might have been too fine for grain-bridging to happen [17].

Although currently available dental ceramic materials show R-curve behavior, they are not known to exhibit toughening due to grain-bridging. More knowledge about this area would advance the science of predicting the lifetimes of all-ceramic restorations. Thus, the first

objective of this study was to determine the effects of surface finish and type of mechanical loading (monotonic vs. cyclic) on the rising toughness curve (R-curve) behavior of a fluorapatite glass-ceramic. The second objective of the study was to determine a statistical model for fitting fatigue lifetime data with multiple flaw populations. The hypotheses of the study were that cyclic loading has a significant effect on R-curve behavior of this glass-ceramic, and fatigue lifetime data with multiple flaw populations fit well to an exclusive flaw model.

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 technique. The composition of IPS e.max ZirPress as provided by the manufacturer is (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 [18].

Rectangular bars of the abovementioned dimensions were cut from casting wax sheets (Kinco dental waxes, Kindt-Collins Company, Cleveland, OH, USA). Sprueing, investing in the invest 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). This furnace uses lower air pressure than the air pressure of 5 bar recommended by the manufacturer. 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. After cooling the investment ring to room temperature, divesting was carried out by airborne particle abrasion with glass beads (100 µm) at 4 bar pressure (for rough divestment) followed by at 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). Specimens were polished to a 15-µm surface finish using circular rotating motion of diamond lapping films (30-µm film followed by 15-µm film). Thirty specimens were not polished but were treated by immersing in Invex 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 at a 45-degree angle using a motion 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

Polished specimens for cyclic fatigue were tested at two different frequencies, 2 Hz and 10 Hz, and at various peak stress levels ranging from 40 to 60 MPa, which were determined using fast fracture data in conjunction with ALTA PRO software (Reliasoft, Tucson, AZ, USA) to predict appropriate peak stress levels that corresponded to a small probability of fast fracture and achieved fatigue fracture of all specimens within the study timeline [19].

The specimens for cyclic loading included two groups of 30 specimens each tested at 2 Hz and 10 Hz frequencies and a peak stress level of 45 MPa. The cyclic loading was applied using a custom-made fully articulated four-point flexure fixture 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 air abraded surface finish and a group of 30 polished specimens were tested in oil by rapid monotonic loading at a stressing rate of 1 MPa/s.

Fractography

All of the failed specimens were examined using fractographic techniques. The fracture toughness of each specimen was determined from the critical flaw dimensions and failure stress. The critical flaw depth, a , and half-width, b , were measured using an optical microscope (MZ12.5, Leica Microsystems, Bannockburn, USA) and a scanning electron microscope (SEM) (SUPRA 40, Carl Zeiss Microimaging, Thornwood, NY, USA). 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 [20]. The critical flaw dimensions and failure stress were used for calculation of the fracture toughness using the following equation.

$$K_{Ic} = Y \sigma_f \sqrt{a} \quad (2)$$

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 specimens failing from edges and deep internal defects were excluded in determination of fracture toughness. For the purpose of comparing critical flaw sizes, the size of the equivalent semi-circular flaw radius, c , was calculated using the depth, a , and half-width, b , of the semi-elliptical flaw on the surface, so that the stress intensity factor is same for both flaws [21].

$$c = (ab)^{1/2} \quad (3)$$

The fracture toughness values estimated from the specimens were compared to the corresponding critical flaw sizes to determine the presence of R-curve behavior. The following non-linear regression equation was used:

$$K_{Ic} = \beta_0 + \beta_1 [1 - \exp(-\beta_2 c)] \quad (4)$$

where β_0 , β_1 , and β_2 are regression coefficients.

Five-parameter Weibull model

The failure analysis showed more than one flaw type with simultaneous deviation of the data from the expected two-parameter Weibull distribution that would be expected for a single flaw population. Therefore, Weibull++ software (Reliasoft, Tucson, AZ, USA) was used to estimate the parameters of the mixed Weibull model for multiple flaw types. Confidence intervals for the statistical model parameters were determined by Monte Carlo simulation using the Simumatic tool of ALTA PRO software. A modified Kolmogorov-Smirnov (K-S) test was performed to determine the goodness-of-fit of the distribution. The value of the K-S statistic, D , was determined using ALTA PRO software.

Results

Fractography

Table 1 presents the proportion of flaw types in each group of specimens. Surface flaws were dominant in all groups. The majority of flaws for the air abraded specimens resulted from air abrasion. The primary flaw type for the polished specimens tested under rapid monotonic loading was surface porosity, while the polished specimens tested under cyclic loading exhibited approximately an equal proportion of specimens failing from surface porosity and grinding flaws.

Figures 1 represents SEM micrographs of the fractured specimens. Figure 1(a) represents a picture of a specimen that failed from an air abrasion flaw. It shows the fracture surface at the top and the tensile stressed air-abraded surface at the bottom. Figure 1(b) shows the fracture surface of another specimen failing from an air abrasion flaw. The white arrows indicate the boundaries of the critical flaw. Figure 1(c) presents a specimen failing from surface porosity. The wake hackles indicate the direction of crack propagation (white arrows). Figure 1(d) represents a typical grinding flaw, which is elongated and shallow with a series of short, semi elliptical cracks. Figure 1(e) shows a failure originating from the edge of the specimen. For many of the fatigue specimens, the crack initiated on the tensile surface, progressed slowly to the edge, and then propagated rapidly due to stress concentration at the edge. This was evident in the fractography when the critical flaw intersected the edge. Figure 1(f) represents such a failure.

R-Curve behavior

The values for all the coefficients of the R-curve model (Equation 4), the coefficients of determination for the regression models (r^2), and the p values are summarized in Table 2. The regression model for R-curve behavior of rapid monotonic loading specimens is plotted with the observed data in Figure 2(a). The 95% confidence band and 95% prediction bands are represented by blue and red lines, respectively. The term confidence band refers to the region of uncertainty in the location of the regression model that best fits the data. The term prediction band refers to the region of uncertainty in predicting the response for a single additional observation at each point within a range of independent variable values. The p values for the coefficients of the regression model were not significant ($p>0.05$) for rapidly loaded specimens. The model showed large scatter in data points and hence a low r^2 value. The regression model for R-curve behavior of fatigue specimens is plotted with the observed data in Figure 2(b). The p values for the β_1 and β_2 coefficients of the regression model were significant ($p \leq 0.05$). As seen in the graphs, fatigue specimens showed tighter confidence intervals compared to rapid monotonic loading specimens. Forward stepwise regression analysis was performed to determine the effect of different variables on fracture toughness such as, flaw type, a:b ratio, peak load, frequency, number of cycles to failure, $\sqrt{c}$, $\sqrt{a}$ and $\sqrt{b}$. For both rapid monotonic loading and fatigue specimens, $\sqrt{b}$, $\sqrt{a}$, and $\sqrt{c}$ had significant association ($p \leq 0.05$) with the fracture toughness, while flaw type, a:b ratio, peak stress, frequency, and number of cycles to failure did not have significant associations ($p>0.05$). This is illustrated by Figure 2(a) and Figure 2(b), where different surface finish, frequency, and flaw type are indicated by different symbols. $\sqrt{b}$ had the strongest association ($p=0.0022$) with the fracture toughness for rapid monotonic loading specimens, $\sqrt{a}$ had the strongest association ($p<0.001$) with the fracture toughness for fatigue specimens.

Five-parameter Weibull model

The parameters of the mixed Weibull model for fatigue specimens with their 95% confidence intervals are presented in Table 3. The Weibull moduli for surface porosity and

grinding flaw populations are denoted by m_p and m_g , respectively, while the characteristic lifetimes of surface porosity and grinding flaw populations are denoted by t_p and t_g , respectively. There was no significant difference between the Weibull moduli, characteristic lifetimes, and proportion parameters for the two frequencies. However, the statistical power for testing the difference between the model parameters for the two frequencies was not adequate. A sample size of 500 specimens per group was estimated by Monte Carlo simulation to be necessary for tight confidence intervals (CV 4.4-19%) for a five-parameter exclusive flaw model. For both frequencies, the surface porosity population showed significantly higher characteristic lifetime than the grinding flaw population. The Weibull plots of the exclusive flaw model for polished specimens tested at 2 Hz and 10 Hz frequency are presented in Figure 3(a) and Figure 3(b), respectively. A modified K-S test gave a D value of 0.58%, indicating the data fit the model well.

Discussion

The results indicated that σ_1 and σ_2 were not significantly different from zero for rapidly loaded specimens, but the graph was suggestive of R-curve behavior. There was an increase in the fracture toughness with increasing flaw size for fatigue loaded specimens. These results support the findings of Fischer *et al*, who demonstrated R-curve behavior in several different dental ceramic materials [22]. In the present study, the values for the fracture toughness ranged from 0.75 to 1.1 MPa-m^{1/2}. However, the steepness of R-curve was different for rapid monotonic loading specimens and fatigue specimens. For rapid monotonic loading specimens, the regression model showed that the fracture toughness reached a plateau at a fracture toughness of approximately 0.95 MPa-m^{1/2}, when the crack size reached approximately 175 μ m. On the other hand, for fatigue specimens, the fracture toughness did not reach a plateau, even when the crack size reached 600 μ m. Based on the observation that the specimens under cyclic loading required larger flaw size to reach the same fracture toughness as the specimens under monotonic loading, one might speculate that cyclic loading disrupts microscopic structures in the wake process zone. This study did not elucidate the mechanism of R-curve behavior and was not designed to do so.

The low r^2 value given by the regression model may be attributed to the presence of factors other than flaw size such as an error in the measurement of the critical flaw dimensions, random sampling error, and the presence of residual stress due to polishing or air abrasion. The results of forward stepwise regression analysis showed that fracture toughness was independent of the initial flaw type and a:b ratio. This proves that the crack shape did not affect the estimation of fracture toughness in this case.

Fractographic analysis showed that the primary flaw type was different for air abraded and polished specimens tested under rapid monotonic loading. Most of the air abraded specimens failed from air abrasion flaws. An air abrasion surface treatment was used to remove the reaction layer formed during the press procedure as recommended by the manufacturer. Air abrasion introduced severe surface flaws responsible for failure. On the other hand, polished specimens failed mainly from surface porosity. However, the polishing procedure used in this study differs from the polishing procedure used for dental restorations in a clinical situation, so there may not be such a large difference between air abraded and polished specimens clinically as observed in this study. Also, the presence of wake hackles inside the critical flaw as seen in Figure 1(b) may not be intuitive. One would not expect wake hackles when the crack is traveling at lower velocity. However, this has been observed in several publications before [23-26].

There was an increase in the proportion of the critical grinding flaws under fatigue loading. A previous study has shown that there is a different proportion of flaw types observed at

different stressing rates [27]. The different flaw distributions follow their own strength and lifetime distributions [8]. The independence of the flaw distributions was evident from the significantly higher characteristic lifetime for surface porosity population than for grinding flaw population (Table 3). The observed difference can be attributed to lower stress intensity shape factors for surface porosity than for grinding flaws. These data supports the findings of a previous study, which showed that there is an increase in the strength of porcelain specimens upon crack tip blunting due to accelerated aging [28]. The relative proportions of critical flaw types observed can change depending on the duration of the study. Hence, clinicians and researchers should be cautious in extrapolating the results of studies performed for short duration to the long-term clinical case.

Although the mixed Weibull model in ALTA PRO software assumes that flaw types are mutually exclusive within each specimen, this was not the case in the current study. All of the fatigue specimens showed the presence of grinding flaws, while some of them showed both grinding flaws and surface porosity. Thus, a “partially concurrent model” would have been theoretically the most appropriate model to fit the lifetime data. The use of the exclusive flaw model underestimates the Weibull modulus for surface porosity, while it overestimates the characteristic lifetime for surface porosity. However, the shape of the total reliability distribution is same for both of the models [8]. Also, the proportion of flaw type parameters estimated by the exclusive flaw model supported the results of fractographic analysis. The model estimated a higher proportion of surface porosity for specimens tested at 10 Hz than for specimens tested at 2 Hz (Table 3). The proportion of critical flaw types observed by fractographic analysis exhibited the same trend (Table 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 reduce stress concentration, as recommended by the ISO standard [18], a few specimens still failed from the edges. Previous studies have shown that the core material at the margin is the most common site for failure origin of all-ceramic crowns, whereas fracture initiates most commonly from veneer surface at the gingival margin of the connector for all-ceramic FPDs [4, 6, 29]. Only the single-layer veneering ceramic was tested in this study compared to the multilayered structure of all-ceramic crowns and FPDs. In addition, 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. This difference in effective volume may have affected the proportion of critical flaw types. Also, previous studies have shown that adhesive resin cementation strengthens feldspathic porcelain and dental glass-ceramic restorations [30, 31]. The influence of resin cement layer on the critical flaws on ceramic surface was not investigated in the present study.

Conclusion

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

1. Cyclic loading had a significant effect on the R-curve behavior of this fluorapatite glass-ceramic. However, the frequency of cycling did not have a significant effect. There was no significant effect of surface finish and initial flaw type on the R-curve of this material.
2. The fatigue lifetime distribution was dependent on the flaw distribution, and it fit well to an exclusive flaw model. The effect of frequency of cycling on the model parameters could not be determined due to unfeasible sample size.

Acknowledgments

This study is based on a thesis submitted to the graduate school, University of Mississippi Medical Center, in partial fulfillment of the requirements for the MS degree. The study was supported by NIH-NIDCR grants DE013358 and DE017991. The ceramic material used in this study was donated by Ivoclar-Vivadent. The authors are thankful to Reliasoft (Tuscon, Arizona) for the educational discount on ALTA PRO software. Also, the authors would like to thank Mr. John Neidigh for the design of the fully articulated fixture and Dr. Paulo F. Cesar for his constructive comments on Figures 2(a) and 2(b).

References

1. Mecholsky JJ. Fractography - determining the sites of fracture initiation. *Dent Mater.* 1995; 11(2): 113–116. [PubMed: 8621031]
2. Thompson JY, Anusavice KJ, Naman A, Morris HF. Fracture surface characterization of clinically failed all-ceramic crowns. *J Dent Res.* 1994; 73(12):1824–1832. [PubMed: 7814754]
3. Kelly JR, Tesk JA, Sorensen JA. Failure of all-ceramic fixed partial dentures in vitro and in vivo: Analysis and modeling. *J Dent Res.* 1995; 74(6):1253–1258. [PubMed: 7629333]
4. Scherrer SS, Quinn GD, Quinn JB. Fractographic failure analysis of a Procera AllCeram crown using stereo and scanning electron microscopy. *Dent Mater.* 2008; 24(8):1107–1113. [PubMed: 18314187]
5. Della Bona A, Mecholsky JJJ, Anusavice KJ. Fracture behavior of lithia disilicate- and leucite-based ceramics. *Dent Mater.* 2004; 20(10):956–962. [PubMed: 15501324]
6. Quinn JB, Quinn GD, Kelly J, Scherrer SS. Fractographic analyses of three ceramic whole crown restoration failures. *Dent Mater.* 2005; 21(10):920–929. [PubMed: 15882898]
7. Scherrer SS, Cattani-Lorente M, Vittecoq E, de Mestral F, Griggs JA, Wiskott HW. Fatigue behavior in water of Y-TZP zirconia ceramics after abrasion with 30 micron silica-coated alumina particles. *Dent Mater.* 2011; 27(2):28–42.
8. Johnson, CA. Fracture statistics in design and application. Corporate research and development, General Electric; Schenectady, NY: 1979. Physical chemistry laboratory
9. Knehans R, Steinbrech R. Memory effect of crack resistance during slow crack growth in notched Al_2O_3 bend specimens. *Journal of Materials Science Letters.* 1982; 1(8):327–329.
10. Marshall DB, Swain MV. Crack resistance curves in magnesia-partially-stabilized zirconia. *J Am Ceram Soc.* 1988; 71(6):399–407.
11. Choi SR, Salem JA. Crack-growth resistance of in situ-toughened silicon nitride. *J Am Ceram Soc.* 1994; 77(4):1042–1046.
12. Dauskarat RH, Marshall DB, Ritchie RO. Cyclic fatigue-crack propagation in magnesia-partially-stabilized zirconia ceramics. *J Am Ceram Soc.* 1990; 73(4):893–903.
13. Jacobs DS, Chen IW. Mechanical and environmental factors in the cyclic and static fatigue of silicon nitride. *J Am Ceram Soc.* 1994; 77(5):1153–1161.
14. Zhu P, Lin Z, Chen G, Kiyohiko I. The predictions and applications of fatigue lifetime in alumina and zirconia ceramics. *Int J Fatigue.* 2004; 26(10):1109–1114.
15. Kishimoto H, Ueno A, Okawara S, Kawamoto H. Crack propagation behavior of polycrystalline alumina under static and cyclic load. *J Am Ceram Soc.* 1994; 77(5):1324–1328.
16. Kruzic JJ, Cannon RM, Ritchie RO. Crack-size effects on cyclic and monotonic crack growth in polycrystalline alumina: Quantification of the role of grain bridging. *J Am Ceram Soc.* 2004; 87(1):93–103.
17. Lathabai S, Mai Y-W, Lawn BR. Cyclic fatigue behavior of an alumina ceramic with crack-resistance characteristics. *J Am Ceram Soc.* 1989; 72(9):1760–1763.
18. ISO 6872. Dental ceramic. International Organization for Standardization; Geneva, Switzerland: 2008.
19. Mettas, A. Annual reliability and maintainability symposium - 2000 proceedings. I E E E; New York: 2000. Modeling & analysis for multiple stress-type accelerated life data; p. 138-143.
20. Newman JC, Raju IS. An empirical stress-intensity factor equation for the surface crack. *Eng Fract Mech.* 1981; 15:185–192.

21. Mecholsky JJ, Freiman SW, Rice RW. Effect of grinding on flaw geometry and fracture of glass. *J Am Ceram Soc.* 1977; 60(3-4):114–117.
22. Fischer H, Rentzsch W, Marx R. R-curve behavior of dental ceramic materials. *J Dent Res.* 2002; 81(8):547–551. [PubMed: 12147745]
23. Scherrer SS, Denry IL, Wiskott HW. Comparison of three fracture toughness testing techniques using a dental glass. *Dent Mater.* 1998; 14(4):246–255. [PubMed: 10379252]
24. Scherrer SS, Kelly JR, Quinn GD, Xu K. Fracture toughness (K_{IC}) of a dental porcelain determined by fractographic analysis. *Dent Mater.* 1999; 15(5):342–348. [PubMed: 10863431]
25. Pallis K, Griggs JA, Woody RD, Guillen GE, Miller AW. Fracture resistance of three all-ceramic restorative systems for posterior applications. *J Prosthet Dent.* 2004; 91(6):561–569. [PubMed: 15211299]
26. Borba M, de Araujo MD, Fukushima KA, Yoshimura HN, Cesar PF, Griggs JA, Della Bona A. Effect of the microstructure on the lifetime of dental ceramics. *Dent Mater.* 2011; 27(7):710–721. [PubMed: 21536324]
27. Griggs JA, Alaqeel SM, Zhang Y, Miller AW, Cai Z. Effects of stress rate and calculation method on subcritical crack growth. *Dent Mater.* 2011; 27(4):364–370. [PubMed: 21167586]
28. Griggs JA, Kishen A, Le KN. Mechanism of strength increase for a hydrothermal porcelain. *Dent Mater.* 2003; 19(7):625–631. [PubMed: 12901987]
29. Taskonak B, Yan JH, Mecholsky JJ, Sertgoz A, Kocak A. Fractographic analyses of zirconia-based fixed partial dentures. *Dent Mater.* 2008; 24(8):1077–1082. [PubMed: 18282595]
30. Fleming GJ, Maguire FR, Bhamra G, Burke FM, Marquis PM. The strengthening mechanism of resin cements on porcelain surfaces. *J Dent Res.* 2006; 85(3):272–276. [PubMed: 16498077]
31. Addison O, Marquis PM, Fleming GJ. Resin elasticity and the strengthening of all-ceramic restorations. *J Dent Res.* 2007; 86(6):519–523. [PubMed: 17525350]

Figure 1.

(a) Typical air abrasion flow (indicated by white arrows) that was the origin of uniaxial flexure failure of a pressed glass-ceramic beam loaded rapidly. (b) Critical flaw (white arrows) produced from an air abrasion flow in an air-abraded specimen loaded rapidly. (c) Wake hackles indicating the direction of propagation (white arrows) from a surface pore (black arrow) in an air-abraded specimen loaded rapidly. (d) Typical grinding flaw in a polished specimen subjected to cyclic loading (e) Critical flaw (white arrows) originating from an edge in an air-abraded specimen loaded rapidly. (f) Critical flaw (white arrows) intersecting the chamfered edge in a polished specimen subjected to cyclic loading.

Figure 2.

(a) Regression model for R-curve behavior of rapid monotonic loading specimens with different surface finish and initial flaw type. (b) Regression model for R-curve behavior of fatigue specimens with different loading frequency and initial flaw type.

Figure 3.

- (a) The mixed Weibull model for fatigue lifetime of polished specimens loaded at a frequency of 2 Hz. The red line indicates the Weibull distribution for grinding flaws, while the black line indicates the Weibull distribution for surface porosity.
- (b) The mixed Weibull model for fatigue lifetime of polished specimens loaded at a frequency of 10 Hz. The red line indicates the Weibull distribution for grinding flaws, while the black line indicates the Weibull distribution for surface porosity.

Table 1

Proportion (and number) of critical flaw types for all experimental groups

Flaws Group	Air abrasion	Surface porosity	Grinding flaw	Edge flaw	Volume pore
Air abraded – R (30)	0.77 (23)	0.10 (3)	0	0.065 (2)	0.065 (2)
Polished – R (30)	0	0.73 (22)	0.23 (7)	0	0.040 (1)
Polished – F All (73)	0	0.49 (36)	0.44 (32)	0.070 (5)	0
Polished – F 2 Hz (42)	0	0.43 (18)	0.52 (22)	0.050 (2)	0
Polished – F 10 Hz (31)	0	0.58 (18)	0.32 (10)	0.10 (3)	0

R: Rapid monotonic loading specimens

F: Fatigue specimens

Numbers in parentheses indicate the number of specimens.

Table 2

Coefficients of the regression model for R-curve behavior of rapid monotonic loading specimens and fatigue specimens

Coefficient	Rapid monotonic loading			Fatigue		
	Value	r^2	p value	Value	r^2	p value
θ	-0.035		0.98	0.28		0.25
1	1.01		0.47	0.88		<0.0001
2	0.023		0.19	0.0038		0.040
Total		0.20	0.0053	Total	0.70	<0.0001

Table 3

Parameters for the exclusive flaw model that best fits the lifetime data of polished specimens tested under cyclic loading at 45 MPa peak stress.

	Fatigue 2 Hz		Fatigue 10 Hz	
Weibull moduli	$m_p=0.87$ (0.37, 3.93)	$m_g=0.72$ (0.48, 4.97)	$m_p=0.47$ (0.56, 2.56)	$m_g=1.28$ (0.32, 1.35)
Characteristic lifetime (s)	$p=114000$ (6390, 289000)*	$g=1090$ (64.5, 2870)*	$p=166000$ (35900, 740000)*	$g=274$ (168, 822)*
Proportion	0.32 (0.14, 0.91)*	0.68 (0.09, 0.86)*	0.45 (0.23, 0.65)*	0.55 (0.35, 0.77)*

*
(indicates 95% confidence intervals)