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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) and (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 ($N = 30/\text{group}$) with polished ($15\ \mu\text{m}$) 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 $37\ ^\circ\text{C}$. 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.

Significance. (1) Cyclic fatigue does not have a significant effect on SCG in the fluorapatite glass-ceramic evaluated and (2) there was no interactive effect between cyclic degradation and stress corrosion for this material.

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1. 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 [10] 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. Twiggs et al. [11] showed that there is no significant difference between crack growth parameters obtained from dynamic fatigue and cyclic fatigue for a model porcelain. On the other hand, White et al. [12] 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. 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 and (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 and (2) there is an interactive effect of stress corrosion and cyclic fatigue to accelerate subcritical crack growth.

2. Materials and methods

2.1. 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 min, followed by a press time of 6 min 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, IL, 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 Invex liquid (Ivoclar-Vivadent) and cleaning in a sonicator (Aquasonic 150T, VWR Scientific Products, Radnor, PA) for 5 min, 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.

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