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Fatigue behavior of zirconia under different loading conditions

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ABSTRACT

Purpose. To investigate the influence of surface damage on the fatigue behavior of zirconia under two different loading conditions.

Materials and methods. One hundred twenty zirconia bar-shaped received either airborne particle abrasion using 50 μm or 120 μm alumina particles while polished specimens served as control. The specimens were subjected to two fatigue regimes: dynamic fatigue (1,000,000 cycles, 1 hz and 0.5 s contact time) or static fatigue (a constant load applied for 5000 s) under water using the staircase application of the load. The flexure strength after fatigue (dynamic fatigue strength) was compared to the initial flexure strength of the tested specimens ($\alpha = 0.05$). The critical crack shape and size of fractured specimens was examined using scanning electron microscopy.

Results. Compared to the initial flexure strength of the tested specimens, dynamic fatigue strength was 86.3% for the polished specimens, 73.4% for 50 μm particle abrasion, and 42.3% for 120 μm particle abrasion while the static fatigue strength was 85.9%, 78.5%, and 51.5% respectively. Significant statistical differences ($F = 223.679$, $P < 0.001$) were found between different surface treatments but not between dynamic and static fatigue strengths for the same type of surface treatment.

Conclusions. The dynamic and static fatigue strengths of zirconia are significantly influenced by type of surface damage.

Clinical Implications. Within the limitations of this study, surface damage have great influence on fatigue behavior of zirconia.

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1. Introduction

During function, dental restorations are subjected to different types of stresses that change in magnitude and direction during each masticatory cycle [1–3]. Nowadays, the tendency to use metal free restorations became the driving force to shift to the more esthetic and more biocompatible all-ceramic restorations. Nevertheless the brittleness of these materials stood as a barrier against their wide-spread use at least in the posterior region of the mouth [4,5]. The introduction of zirconia to the dental field opened the design and application limits of all-ceramic restorations as today long span and complex zirconia restorations are manufactured using CAD/CAM systems with high accuracy and success rate.

Pure zirconia undergoes a crystal phase transformation during cooling from tetragonal to monoclinic phase starting at about 1170 °C, which is accompanied by a volume increase of approximately 4.5% [4]. However, addition of dopants such as CaO, MgO, Y_2O_3, and CeO_2 stabilizes the tetragonal phase at room temperature. The stabilized tetragonal phase could revert to the more stable monoclinic phase when subjected to stress which generates compressive stresses at the tip of propagating crack contributing to superior mechanical properties and higher fracture toughness. Nevertheless, zirconia ceramics are still brittle materials and are very sensitive to surface defects and structural flaws [4,5].

According to literature, the fracture strength of brittle ceramics is strongly related to the propagating crack size [6]. For the same material, a large structural defect would result in lower failure stress and vice versa. This relationship is clearly illustrated using the following formula:

$$\sigma = \frac{K}{Y\sqrt{a}} \tag{1}$$

where σ is the failure stress, K the fracture toughness of the material, Y the geometric constant, and (a) is the depth the critical crack. There is also a strong correlation between the initial crack size a_i, subcritical crack growth (SCG), and the lifetime (cyclic fatigue number N_f) of brittle ceramics [7]. The closer the initial crack size (a_i) is to the critical size (a_c) the more rapidly the crack grows to a fatal stage. This relationship is illustrated using the following formula:

$$N_f = \frac{2(\Delta\sigma)^{-n}}{AY^n\,(n-2)}\left(C_i^{\frac{2-n}{2}} - C_c^{\frac{2-n}{2}}\right) \tag{2}$$

where A and n are subcritical crack growth parameters and $\Delta\sigma$ is the difference between applied cyclic maximum and minimum stresses.

In fact, surface treatments such as milling, grinding, and particle abrasion which are routinely used during fabrication of zirconia frameworks can significantly compromise its strength [8–10]. The resulting surface or near-surface damage [11] could be large enough to initiate an initial crack and reduce the time required for propagation of subcritical crack growth [7] which would ultimately end in catastrophic fracture of the material.

Simulating fatigue under laboratory conditions represents a real challenge. While using anatomically shaped specimens bonded to natural teeth closely resembles the real situation, using standardized bar-shaped specimens allows accurate standardization of preparation and testing procedures and better control of the variable under investigation [4]. Another problem remains to be related to selection of the proper loading conditions in term of applied load and number of loading cycles. The aim of this study was to evaluate the influence of surface damage on the fatigue behavior of bar-shaped zirconia specimens using two different loading conditions.

2. Material and methods

2.1. *Preparation of the specimens*

Fully sintered bar shaped zirconia specimens (25 mm × 2 mm × 1 mm) were prepared by cutting and sintering green state CAD/CAM zirconia blocks (Cercon, Degudent GmbH, Hanau-Wolfgang, Germany) [9]. The sintered bars were polished with silicon carbide paper in a sequence from 300 to 1200 grit (Ecomet Grinder/Polisher; Buehler Ltd, Evanston, IL) and their edges were rounded to prevent stress concentration at the corner angles. For some specimens, the central region of one surface was airborne particle abraded using either 50 μm or 120 μm alumina powder (S-U-Alustral; Schuler-Dental, Ulm, Germany) at 2 bar pressure for 5 s at a distance of 1 cm (P-G 400/3, Harnisch + Rieth, Winterbach, Germany). The surface roughness of the prepared specimens was measured using a travelling contact diamond point which covered at least 4 mm of the surface treated region of every specimen (SJ-400, Mitutoyo Corporation, Japan). Three surface roughness parameters were recorded: (Ra: average roughness; Rv: valley depth; Rp: peak height).

2.2. *Evaluation of the initial flexure strength*

To determine the flexural strength (F_S) of zirconia before fatigue, 3-point-bending test was used (n = 20). The bars were fixed between the two supports (20 mm) and the specimens were subsequently loaded (0.5 mm/min crosshead speed) until fracture, using a universal testing machine (ACTA intense, ACTA, Amsterdam, NL). The flexural strength was calculated using the following equation:

$$F_S = \frac{3FL}{2wh^2} \tag{3}$$

where F is the load at fracture, L is loading span, w and h are the specimen width and thickness, respectively.

2.3. *Dynamic fatigue test*

The same 3-point flexure strength test setup was used to apply cyclic load resulting in alternating flexure stress at the tensile surface of the zirconia bars. Twenty specimens for every surface treatment (polished, particle abraded with 50 μm or 120 μm alumina) were cyclically loaded in a pneumatic driven fatigue machine (ACTA Cyclic Fatigue Tester, ACTA, Amsterdam, The Netherlands). A minimum load (5 N) was applied at all time to prevent generation of surface damage under the loading indenter. The cycle time was set at 1 s and the load