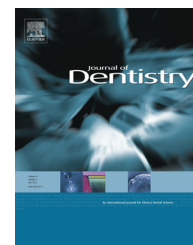


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Review

Fatigue of dental ceramics

Yu Zhang^{a,*}, Irena Sailer^b, Brian R. Lawn^a^a Department of Biomaterials and Biomimetics, New York University College of Dentistry, New York, NY 10010, USA^b Division of Fixed Prosthodontics and Occlusion, School of Dental Medicine, University of Geneva, 19 rue Barthélemy-Menn, CH-1205 Geneva, Switzerland

ARTICLE INFO

Article history:

Received 29 July 2013

Received in revised form

30 September 2013

Accepted 1 October 2013

Keywords:

Dental ceramics

Fatigue

Fracture modes

Lifetime

Crowns

Fixed-partial dentures

ABSTRACT

Objectives: Clinical data on survival rates reveal that all-ceramic dental prostheses are susceptible to fracture from repetitive occlusal loading. The objective of this review is to examine the underlying mechanisms of fatigue in current and future dental ceramics.

Data/sources: The nature of various fatigue modes is elucidated using fracture test data on ceramic layer specimens from the dental and biomechanics literature.

Conclusions: Failure modes can change over a lifetime, depending on restoration geometry, loading conditions and material properties. Modes that operate in single-cycle loading may be dominated by alternative modes in multi-cycle loading. While *post-mortem* examination of failed prostheses can determine the sources of certain fractures, the evolution of these fractures *en route* to failure remains poorly understood. Whereas it is commonly held that loss of load-bearing capacity of dental ceramics in repetitive loading is attributable to chemically assisted 'slow crack growth' in the presence of water, we demonstrate the existence of more deleterious fatigue mechanisms, mechanical rather than chemical in nature. Neglecting to account for mechanical fatigue can lead to gross overestimates in predicted survival rates.

Clinical significance: Strategies for prolonging the clinical lifetimes of ceramic restorations are proposed based on a crack-containment philosophy.

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1. Introduction

Major dental restorations such as crowns and fixed-partial dentures (FDPs), as well as other biomechanical prostheses, are experiencing a rapid shift towards ceramic materials, partially for their strength and biointerfacing but more so for their aesthetics.^{1–3} However, ceramics are brittle and susceptible to fatigue fracture in repetitive function. Although occlusal loading is nominally compressive, with bite forces supported in individual 'dome-like' structures (crowns) or in

frameworks with connectors (FDPs), some tensile stresses are inevitable. Cracks tend to follow paths where these tensile stresses are greatest. While a ceramic restoration may fracture abruptly from a single intense overload, it is more likely that failure will occur cumulatively after an extended period of seemingly innocuous but lower-load biting events. Such fractures are manifest in the clinical literature as 'lifetime' or 'survival rate' data. Beyond such data lies a burning question: what are the underlying physical bases for designing next-generation ceramic materials for greater long-term performance?

* Corresponding author at: Department of Biomaterials and Biomimetics, New York University College of Dentistry, 345 East 24th Street, Room 813C, New York, NY 10010, USA. Tel.: +1 212 998 9637; fax: +1 212 995 4244.

E-mail address: yz21@nyu.edu (Y. Zhang).

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<http://dx.doi.org/10.1016/j.jdent.2013.10.007>

The drive towards ceramic restorations is fraught with compromise.^{2,4} There is a perception that ceramic crowns and FDPs are not yet as reliable as those with traditional metal-frameworks.¹ The ceramics with the most desirable aesthetics, notably porcelains, tend also to have the lowest resistance to crack propagation ('toughness').^{5–7} Conversely, tougher ceramics such as aluminas and zirconias^{5,8} are not generally aesthetic. Glass-ceramics^{9,10} occupy a middle ground. Two well-grounded routes exist to overcome these countervailing tendencies. The first is to bond an aesthetic porcelain veneer onto a stiff alumina or zirconia core to provide support in flexural loading.^{1,2,11} However, the veneer remains a weak link, susceptible to chipping and delamination from the core (although as will be demonstrated later the core itself is not immune). Coefficient of thermal expansion (CTE) mismatch between veneer and core and low thermal diffusivities in most ceramics can lead to deleterious tensile stresses within the bilayer during heat treatment.^{12–16} The second route is to develop crack-resistant but partially translucent monolith ceramics to circumvent the need for veneering altogether – e.g. lithium disilicate glass-ceramics (IPS e.max Press or CAD by Ivoclar-Vivadent),¹⁷ or zirconias with fine grains (e.g. Lava Plus by 3M ESPE, Bruxzir by Glidewell, Allzir by New Image) or surface-infiltrated with glass.^{18–22} Monolith ceramics also avoid weak veneer/core interfaces, minimising the risk of delamination. In both routes, zirconia-based ceramics are emerging as materials of choice.

Given the brittleness of ceramics, it is hardly surprising that prosthetic failures do occur. Some of the more commonly observed clinical fracture modes are sketched in Fig. 1. They include cracks initiating from the contact zone at the occlusal surface,²³ from the cementation surface beneath the contact,²⁴ and from the margins of crowns and connectors in FDPs.^{25–31} Some examples of clinically fractured prostheses are shown in Fig. 2a–c, revealing fracture from a wear facet on a porcelain-veneered zirconia crown occlusal surface, a longitudinal crack initiated from the margin of a Dicor glass-ceramic crown, and a flexure crack at the connectors of a porcelain-veneered zirconia FDP. All of these cracks can result in severe damage or irrecoverable failure. Chipping fractures initiate from contact damage sites and detach at least part of the veneer from the core. Through-thickness fractures initiate from the occlusal or cementation surface beneath the contact or from the margins or connectors and can split a prosthesis in two. Clinical trials reporting survival rates for several all-ceramic systems indicate vulnerabilities to all these fractures.^{25–27,32–48} Broadly speaking, porcelain-veneered systems show higher fracture rates than full-contour monoliths, FDPs more than single crowns, and glass-ceramic more than zirconia monoliths, although the variability in data from study to study can be high.

The physical mechanisms of fatigue in ceramic restorative materials have not been well documented in the dental literature. The prevailing view, borrowed originally from fundamental studies in the materials science community,^{49,50} is that fatigue can be accounted for by chemically enhanced, rate-dependent crack growth in the presence of moisture.^{51–60} According to this viewpoint, water enters incipient fissures and breaks down cohesive bonds holding the crack walls

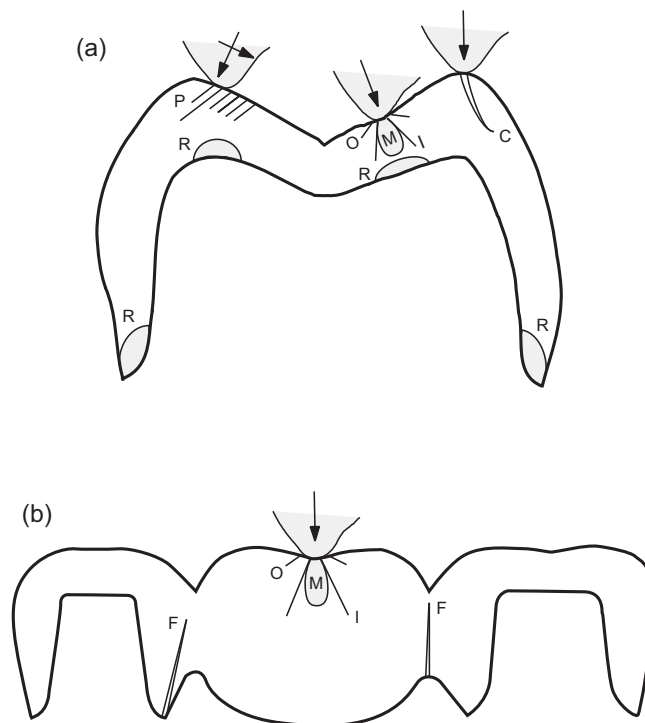


Fig. 1 – Schematic diagram depicting various fracture modes in (a) crown and (b) FDP all-ceramic structures: axisymmetric outer (O) and inner (I) cone cracks, and median (M) cracks; partial cone (P) cracks; edge chipping cracks (C); radial (R) cracks at cementation surfaces; flexure (F) cracks at connectors. Linear-trace cracks (O, I, P, C, F) extend out of the plane of diagram, shaded (R, M) cracks extend within the plane of diagram.

together.^{49,61} The result is so-called 'subcritical' or 'slow' crack growth (SCG) which progresses steadily over time, accelerating at higher stress levels and ultimately leading to failure. The notion is attractive because it lends itself to rigorous 'fracture mechanics' analysis in terms of explicit crack velocity equations, enabling one to predict lifetimes in terms of specified stress states.⁶² But recent studies in the materials science arena reveal that fatigue is more complex than just SCG. In addition to chemical degradation, there are mechanisms of mechanical degradation that can augment the fatigue process.^{12,63–69} Mechanical fatigue operates exclusively in cyclic loading and cannot be inferred from static or monotonic loading tests. It can be relatively destructive, meaning that predictions based exclusively on SCG assumptions may grossly overestimate potential lifetimes. 'Fractography'⁷⁰ – the microscopic analysis of post-failure restorations – can point to likely starting sources of fracture but is limited in its capacity to shed light on the fatigue mechanisms themselves, or to determine the sometimes complex evolutionary progression of competing fractures to completion.

It is important to understand the interplay between competing fracture modes in order that the best fatigue-resistant restorative ceramics may be developed. Accordingly, this article surveys the fatigue behaviour of commonly used dental ceramics from a biomechanics point of view. The principal mechanisms by which chemical and mechanical

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