dental materials xxx (2018) xxx–xxx

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Strength and fracture toughness of zirconia dental ceramics

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ARTICLE INFO

Article history:
Received 14 August 2017
Received in revised form
22 November 2017
Accepted 20 December 2017
Available online xxx

Keywords:
Fracture toughness
Flexural strength
3Y-TZP
12Ce-TZP
Small cracks
Low temperature degradation
R-curves
Ultra-short pulsed laser ablation

ABSTRACT

Objective. The aim of the paper is to determine and discuss the correlation between the fracture toughness and the fracture stress in zirconia transforming ceramics with a small artificial crack. As an R-curve behaviour is usually present in transforming ceramics for both small and long cracks, predictions of the fracture stress can only be done with an accurate knowledge of the R-curve and crack dimensions.

Methods. First, basic concepts of fracture mechanics, strength and testing of ceramic materials are introduced. This is followed by a very brief introduction to zirconia dental ceramics and to strength degradation by hydrothermal ageing of 3Y-TZP. Fracture toughness of 3Y-TZP and 12Ce-TZP are then determined for a short (~50 μm) sharp edge crack produced by ultra short pulsed laser ablation on prismatic bending bars in four point bending. The crack size is small but large enough for controlling fracture and for applying elastic fracture mechanics.

Results. In both materials the determined fracture toughness is similar, in spite of their difference R-curves. The results of fracture toughness and fracture stress are analysed by using a simple function to represent the R-curve, but which contains the main ingredients of experimental R-curves extracted from the literature either for short or long cracks in 12Ce-TZP.

Significance. It is concluded that the high R-curves reported in the literature for long and short cracks in 12Ce-TZP and 3Y-TZP might have only a marginal influence on the fracture resistance with cracks of the size studied. This effect is of more significance in 12Ce-TZP. The use of an ideal and simple model of R-curve is presented as a useful guide to predict whether the fracture stress will be enhanced by an existent R-curve.

Contents

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https://doi.org/10.1016/j.dental.2017.12.007

1. Essential concepts of fracture mechanics and strength of ceramics

Before examining the strength and fracture toughness of dental ceramics, some basic concepts of fracture mechanics, strength and testing of ceramic materials are introduced in this section.

Dental zirconia, as all ceramic materials, fail by brittle fracture that originates at flaws, which are generated during processing or in service. They are of very different size and shape, generally very small, and they are distributed all through the material. Elastic fracture mechanics can be used to predict the strength if flaws are considered as very sharp cracks embedded in an elastic continuous.

In an approach based on the stress around a crack, the criterion for fracture is formulated with the concept of stress intensity factor. If we machine a crack of length a on the edge of a plate over which acts an uniaxial applied stress, σ, perpendicular to the crack faces, the distribution of the stress in the plate is altered and becomes multiaxial very close to the crack tip reaching very high values. The components of the stress field are given by [1]:

$$\sigma_{ij} = (K_I/\sqrt{2\pi r}) f_{ij}(\theta) \quad (1)$$

where r and θ are the polar coordinates with origin in the crack tip, and f_{ij} are functions of only θ with values equal or smaller than one. The magnitude of the stress field depends on the parameter K_I, which is referred to as the stress intensity factor. This is the only parameter needed to characterize the elastic stress field very near the crack tip and it depends on the tensile stress perpendicular to the crack, the crack length a, and the geometry of the specimen. Very often it can be written in a simple form,

$$K_I = \sigma Y \sqrt{\pi a} \quad (2)$$

In this expression Y is a geometrical factor which accounts for the loading mode, the geometry of the crack and of the specimen. Since processing flaws in ceramic dental zirconia are generally very small in comparison to specimen dimensions, Y may be independent of the crack length. This is the case for a bulk small penny crack loaded in the direction perpendicular to the crack surface, where Y is equal to $2/\pi$ all along the crack front [2].

K_{Ic} is defined as the critical value of K_I for which fracture occurs and, in principle, is a material property. By imposing $K_I = K_{IC}$ in Eq. (2) we can find the fracture strength under a tensile stress acting perpendicular to the crack surface. The fracture strength depends linearly on K_{Ic} and is inversely proportional to the square root of the crack length. It shows two possible strategies to increase the strength of dental ceramic materials, namely, increase the fracture toughness or decrease the defect size. Although specimens often contain many defects of different size, the strength will be determined by the larger crack size.

If the strength is measured on a large number of specimens, the result is a distribution of the strength accordingly to the distribution of the largest flaw present in each specimen. The Weibull distribution is usually considered the best choice for fracture strength analysis. His fundamental assumption is the weakest link hypothesis, i.e. the specimen fails if its weakest volume element fails. In its simplest form, for a uniaxial homogenous tensile stress σ and volume V, the Weibull two parameters cumulative probability function can be written for the strength as [3],

$$P_f = 1 - exp\left[-(V/V_0)(\sigma/\sigma_\theta)^m\right] \quad (3)$$

The scale parameter or characteristic strength σ_θ is dependent on the stress configuration and test specimen size. The distribution shape parameter, m, is the Weibull modulus and V_0 is the chosen normalising volume. The coefficient of variation (ratio of standard deviation and the average strength) measures the dispersion of the data and it can be shown that it depends only on m.

For measuring the strength, tension tests are rarely used in ceramics and glasses because of several important disadvantages in comparison with flexural tests. Among them, the high cost of specimen fabrication and the difficulty in gripping without introducing bending stresses and damaging contact stresses. Flexural tests on rectangular specimens involving three and four point bending are often used. Today the most common testing configuration in advanced ceramic materials is a 3 mm by 4 mm cross section rectangular specimen on 20 mm by 40 mm span four-point flexure fixtures. The strength is defined by the maximum stress on the tensile surface at failure, which is given by,

$$\sigma_f = 3(L_1 - L_2)F/2W^2B \quad (4)$$

where L_1 and L_2 are the outer and inner spans respectively, F is the applied load, B is the thickness of the sample, W its width [4].

When testing specimen configurations in which the stress is not uniform, the substitution of the actual stressed volume of the specimen by the Weibull effective volume in Eq. (3) allows us still using this equation. The equivalent volume represents the volume that subjected to a uniform stress equal to the maximum stress in the actual specimen will give the same probability of failure. This allows to scale the strength from one loading configuration and specimen size to another [5].

Please cite this article in press as: Turon-Vinas M, Anglada M. Strength and fracture toughness of zirconia dental ceramics. Dent Mater (2018), https://doi.org/10.1016/j.dental.2017.12.007