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Practical and theoretical considerations on the fracture toughness testing of dental restorative materials

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ABSTRACT

Background. An important tool in materials research, development and characterization regarding mechanical performance is the testing of fracture toughness. A high level of accuracy in executing this sort of test is necessary, with strict requirements given in extensive testing standard documents. Proficiency in quality specimen fabrication and test requires practice and a solid theoretical background, oftentimes overlooked in the dental community. Aims: In this review we go through some fundamentals of the fracture mechanics concepts that are relevant to the understanding of fracture toughness testing, and draw attention to critical aspects of practical nature that must be fulfilled for validity and accuracy in results. We describe our experience with some testing methodologies for CAD/CAM materials and discuss advantages and shortcomings of different tests in terms of errors in testing the applicability of the concept of fracture toughness as a single-value material-specific property.

Contents

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Nomenclature

a	Crack length
a_0	Notch length
a_{true}	Notch length + length of the defect in front of the notch
α	Ratio a/W
B	Beam width
B3B	Balls-on-3-balls
c	Half-length of a polished Knoop indentation
EPFM	Elastic-plastic fracture mechanics
F	Applied load
h	Height of a Knoop impression
K	Stress intensity factor
K_{Ic}	Critical stress intensity factor at instability, or fracture toughness according to the linear elastic fracture mechanics
K_R	Resistance against crack growth
$K_{R,max}$	Maximum applied stress intensity factor on a R-curve before instability
K_{I0}	Stress intensity factor at subcritical crack initiation
l	Length of a defect in front of the notch
L	Beam length
LEFM	Linear-elastic fracture mechanics
r	Notch/flaw root/tip radius
r_c	Critical notch root radius
R	Specimen radius in the ball-on-3-balls test
R-curve	Resistance curve
R_a	Support radius in the ball-on-3-balls test
S	Bending span in 3-point bending
S_i	Inner span in 4-point bending
S_o	Outer span in 4-point bending
SCCG	Subcritical crack growth
t	Thickness of disc- or plate-shaped specimen
W	Beam thickness
Y	Geometric factor
σ_{appl}	Applied stress
σ_f	Stress at fracture, or strength
ν	Poisson's ratio
3-PB	3-point bending
4-PB	4-point bending

Fracture toughness tests

B3B-K_{Ic}	Ball-on-3-balls fracture toughness test
C(T)	Compact tension
CNB	Chevron notch beam
CNSB	Chevron notch short bar
CNSR	Chevron notch short rod
DCB	Double cantilever beam
DCDC	Double cleavage drilled compression
DC(T)	Disc-shaped compact tension
DT	Double torsion
IF	Indentation fracture
IS	Indentation strength
M(T)	Middle-cracked tension
NTP	Notchless triangular prism
SCF	Surface crack in flexure
SCF-NB	Surface crack in flexure in notched balls
SE(B)	Single-edge bend
SEPB	Single-edge pre-cracked beam
SEVNB	Single-edge-V-notch-beam

1. Introduction

Currently the most accepted concepts pertaining to the mechanics of failure of solid matter are established by the field of *fracture mechanics*. The fundamentals of such concepts revolve around the idea that discontinuities (flaws, voids, defects, cracks) in a material, be that on the surface or in the bulk, act as stress concentration entities from which failure will begin and evolve (grow) to catastrophic fracture. After much theoretical development and experimental support in the 1950s and 1960s, a tangible parameter was derived relating the applied stress and the dimensions of an existing crack in a body, the *stress intensity factor*, K, for linear elastic materials (analogous quantities exists for nonlinear-elastic materials, which will not be covered in this article). This parameter quantifies the local stress concentration at the crack tip, increasing with applied load (stress) until it reaches a critical value, K_c, the *fracture toughness*. It has been long believed that the fracture toughness was a material-specific property that could fully characterize the resistance to fracture of a material in the presence of a defect (this has been later shown to be only partially true). The theory also implied that K_c could be probed by physical means through mechanical testing using cracked specimens, opening a door into new territories of materials science.

After mathematically resolving the existing geometrical issues for a variety of loading conditions, much effort was put in defining a practical and theoretically sound testing framework [1]. This crystallized over the years in national and international testing standards with strict guidelines having clear recommendations regarding specimen geometry, validity requirements, loading parameters, equipment, testing accuracy, data treatment, etc. The objectives with this were not only to obtain a value close to the materials' true K_c (precision), but also to render measurements across laboratories valid and comparable (accuracy and reproducibility). Ultimately, test standards evolved into official

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