

CERAMICS: Properties 2 (Brittle Fracture Analysis)

S.C. BAYNE,¹
J.Y. Thompson²

¹University of Michigan
School of Dentistry,
Ann Arbor, MI 48109-1078
sbayne@umich.edu

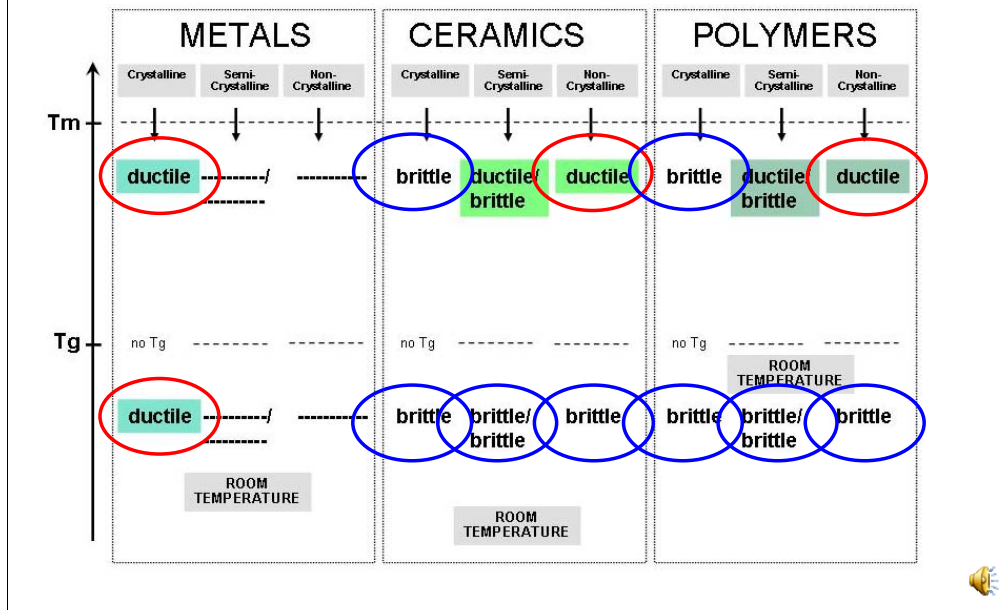
²Nova Southeastern
College of Dental Medicine,
Ft. Lauderdale, FL 33328-2018
jeffthom@nova.edu



Mechanical properties of ceramic materials are linked to understanding brittle fracture.

FAILURE TYPES

Ductile and brittle fracture



As just presented in the last module, FRACTURE can be simplistically categorized as DUCTILE or BRITTLE. There is no simple cut off where one stops and the other begins. From a macroscopic point of view, materials that undergo less than 10% plastic deformation at failure are generally called BRITTLE. However, it is really more important to look at the fracture mechanisms that are involved.

[CLICK] PLASTIC DEFORMATION occurs because (a) LONG-RANGE crystallographic deformation is possible (e.g., METALS) or (b) materials are non-crystalline and capable of local structural sliding (e.g., non-crystalline ceramics or polymers, both above Tg).

[CLICK] BRITTLE fracture is common with (a) “crystalline ceramics or polymers” above or below their Tg or (b) “non-crystalline ceramics or polymers” below their Tg. Since ceramics are so susceptible to brittle fracture, it is important to examine the details of the process.

BRITTLE FRACTURE

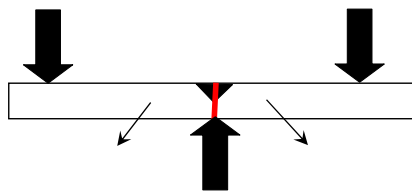
Short-range deformation mechanisms.

Brittle ceramic strength is lower than expected:

- Theoretical Strength: (e.g., TS = 6000 MPa)
- Observed Strength: (e.g., TS = 0.10 to 0.001 of theoretical)

GRIFFITH-OROWAN Theory:

- FLAWS are stress concentrators (e.g., PORES) and form cracks
- Fracture occurs in sequential steps
- Crack tips move at low stresses
- Crack tip radius of curvature is atomic size



Ceramic deformation typically does not involve LONG-RANGE deformation (i.e., deformation of all of the parts of the structure) -- but rather it entails very localized or SHORT-RANGE deformation. Before the mechanism of this process was understood, there was a great conundrum over the difference between theoretical strength and observed strength. Observed values were from 0.1% to 10% of theoretical values.

[CLICK] Griffith and Orowan explained the process in terms of CRACKS. Flaws in ceramics produced crack. Crack tips propagating across a material only affect the local region of the crack tip. This is called the GRIFFITH-OROWAN theory although all the parts of the process are now pretty well understood.

Cracks are INITIATED at weak spots in ceramic materials (e.g., internal pores or external surface irregularities). Cracks are PROPAGATED by small stresses. Even water within the crack can propagate it. Ultimately cracks are TERMINATED by being stopped or by crossing through the material to cause failure.

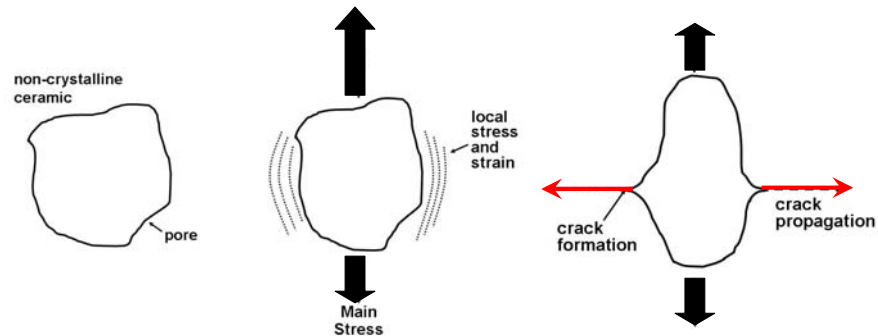
[CLICK] Window glass is strong. **[CLICK]** To cut it, you use a diamond to scratch it. **[CLICK]** This creates an external surface defect. Then flexing the pane away from the scratch creates tension and breaks the pane into pieces easily. **[CLICK]** The scratch is the crack initiator. The tensile stress is the crack propagator.

CRACK INITIATION

Crack initiation, (propagation, and termination).

Crack Generation (in tension):

- Cracks are always perpendicular to the applied stress
- Pores are most detrimental under tensile stress (not compression)
- Water tends to propagate existing cracks in most materials



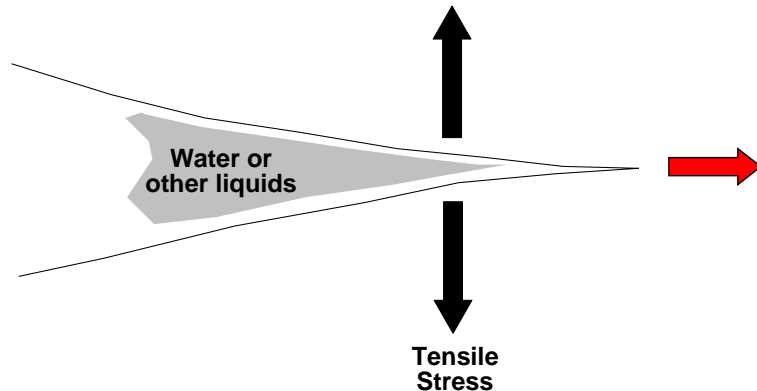
Ceramics are weak in tension and strong in compression. Tensile forces encourage crack formation and propagation. Let's look at a simple pore. **[CLICK]** A pore can exist in anything -- but let's consider a non-crystalline phase for the time being. **[CLICK]** Now assume that tensile stresses are being placed on the structure. **[CLICK]** The forces elongate the pore and cause a crack to form which is perpendicular to the tensile stress direction.

CRACK PROPAGATION

(Crack initiation), propagation, (and termination).

Crack Propagation:

- Tensile stresses tend to propagate crack tip
- Water or other observed liquids tend to open crack tip



Crack propagation can occur because of stress around the crack (e.g., tension) **[CLICK]** or internal forces (e.g., water or other liquids within the crack) **[CLICK]** that create capillary pressures and push on the crack tip. Both plague dental restorations. Because of these problems, dental ceramics are "defect-limited."

CRACK MANAGEMENT

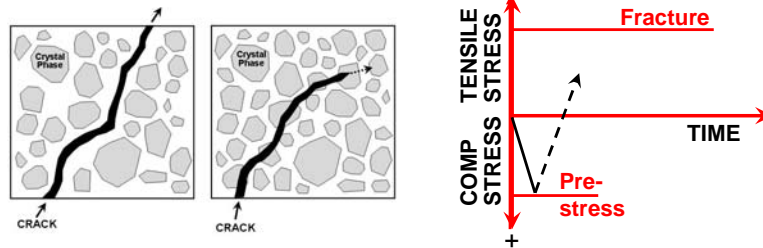
How to make brittle ceramics survive.

Crack Prevention:

- Eliminate internal defects (e.g., eliminate pores).
- Eliminate surface defects.
- Eliminate design feature that concentrate stress (e.g., sharp corner).
- Prevent tensile stresses.

Crack Slowing or Stopping Mechanisms:

- Design material to be only under compressive stress.
- Pre-stress material in compression to cancel early tensile stresses.
- Add crystalline phases that are stronger and slow or stop cracks.
- Add crystalline phases that make path more tortuous.
- Add phases that interact with cracks and compress the tip.



The rules for helping ceramics to survive are simple: (1) prevent cracks, and (2) make materials more crack-tolerant. We will deal with these in more detail when we talk about specific dental types and their applications. For now, here is a quick summary.

[CLICK] Cracks can be prevented by **[CLICK]** (A1) eliminating internal defects, **[CLICK]** (A2) eliminating surface defects, **[CLICK]** (A3) eliminating stress concentrating design features, and **[CLICK]** (A4) preventing tensile stresses.

This is rarely easy to accomplish and so we must look at how to mitigate or stop existing cracks.

[CLICK] We need to make ceramics more crack tolerant by **[CLICK]** (B1) designing the material to be under only compressive stress, **[CLICK]** (B2) pre-stressing the material to be in compression and able to cancel out early tensile stresses, **[CLICK]** (B3) adding strong crystalline phases as obstacles to crack propagation, **[CLICK]** (B4) adding crystalline phases that force cracks into them, and **[CLICK]** (B5) adding phases that interact with cracks (e.g., tetragonal phases in zirconia).

[CLICK] Adding crystalline phases as obstacles is one of the main approaches. **[CLICK]** A commercial example of pre-stressing is with poured concrete. Reinforcing rods that are pre-stressed in tension are embedded in poured concrete. **[CLICK]** After setting, the tensile stresses are released, and the rods create compressive stresses on the concrete. **[CLICK]** Early or stray tensile stresses are cancelled out by local compressive stresses.

CRACK ENERGY

Toughness = energy to drive cracks through a material to failure.

- Observed strength = theoretical material strength + effect of defects (e.g., pores)
- Toughness (or fracture toughness) = energy to drive cracks through material to failure (and approximated by area under stress-strain curve or energy to fracture).

$$K_{IC} = (Y)(\sigma_c)(\sqrt{c})$$

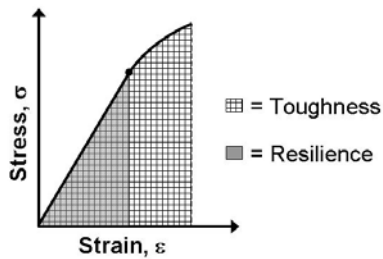
K_{IC} = critical stress intensity or fracture toughness.

Y = dimensionless parameter (based on crack, specimen, loading geometry).

σ_c = critical stress given the flaw size

c = critical flaw size

and so $\sigma_c \propto 1 / (\sqrt{c})$



Material K_{IC}	($MPa\sqrt{m}^{1/2}$)
Glasses	<1
Glass ceramics	1-3
Alumina	3-6
Zirconia	5-15
ZTA	10-18
Titanium Alloys	30-70
Stainless Steels	50-100



Ceramics are defect-limited. Their strength depends on the number and type of defects that are present. Generally, a ceramic with more defects is weaker. Another way at looking at resistance to failure for ceramic materials is to examine the ENERGY required to drive cracks through the system. We discussed this earlier. **[CLICK]** The resistance to fracture, or area under the stress-strain curve, is the called the TOUGHNESS.

You are not responsible for the formula which follows but should understand the concepts. **[CLICK]** One definition of toughness (K_{IC} , pronounced "K" "one" "c") is mathematical and is equal to -- a constant -- multiplied by a stress intensity factor -- multiplied by the critical flaw size. The crucial message here is to **"decrease the flaw size to increase the toughness."**

[CLICK] Toughness values range goes from zero to just above 100. The units are unusual. Materials typically used in dentistry have very low values (0.5-8). Because these materials are not tough, you must do everything possible to prevent cracks and impede their propagation. To measure the toughness, rather than integrating the area under the stress-strain curve, it is more typical to create a surface crack in a standard shape and measure the load required to propagate the crack. It is very similar to the example of scratching a window glass plane and then breaking it.

QUICK REVIEW

Crack initiation, propagation, and termination in brittle materials.

- What are the 2 major types of FAILURE (or FRACTURE)?
BRITTLE and DUCTILE
- What THEORY explains low observed values of ceramic strength?
GRIFFITH-OROWAN
- What direction of stress PROMOTES crack initiation?
TENSION
- What are the 2 major considerations for avoiding BRITTLE fracture?
(1) PREVENT CRACK FORMATION.
(2) CREATE OBSTACLES TO PROPAGATION.
- What parameter measures the ENERGY of crack propagation?
TOUGHNESS



Here is a quick review of the concepts from this module.

[CLICK] (1) What are the 2 major types of FAILURE (or FRACTURE)?

[CLICK]

[CLICK] (2) What THEORY explains low observed values of ceramic strength?

[CLICK]

[CLICK] (3) What direction of stress PROMOTES crack initiation?

[CLICK]

[CLICK] (4) What are the 2 major considerations for avoiding BRITTLE fracture?

[CLICK]

[CLICK]

[CLICK] (5) What parameter measure the ENERGY of crack propagation?

[CLICK]



THANK YOU



THANK YOU.