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Ductility, brittleness, and fracture toughness

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Abstract: There are many important mechanical properties related to dental materials like ductility, brittleness, and fracture toughness. Those properties describe the resistance of materials to plastic deformation, crack propagation, and fracture under the applied force. It is important to predict how dental materials react to forces (masticatory and fabrication) to prevent their early fracture and prolong their proper clinical performance.

Keywords: *ductility, brittleness, fracture toughness, failure.*

Introduction:

There are many important mechanical properties related to dental materials like ductility, brittleness, and fracture toughness. Those properties describe the resistance of materials to plastic deformation, crack propagation, and fracture under the applied force. It is important to predict how dental materials react to forces (masticatory and fabrication) to prevent their early fracture and prolong their proper clinical performance.

Failure of prosthetic and restorative dental materials depends on both their mechanical properties and microstructure; the mechanical properties are defined by the law of mechanics as the physical science that deals with the energy and forces and their effects on the bodies.

According to the magnitude of the applied force, the amount of the induced stresses, and the nature of the materials (type and nature of the interatomic bonding), the material could deform elastically (temporarily) or plastically (permanently). (1, 2) Generally, most metals behave in a ductile manner while glass and ceramics materials tend to behave in a brittle manner. (1)

According to the type of bonding. In metals, their metallic bonds allow the atoms to slide past each other easily. The sliding of rows of atoms results in slip, which allows the metal to deform plastically instead of being fractured.

On the other hand, the presence of ionic bonds in ceramics results in such sliding motion resistance. Since in ionic bonding, every other atom is of opposite charge, when a row of atoms attempts to slide past another row, positive atoms encounter positive atoms and negative atoms encounter negative atoms. This results in a huge electrodynamic repulsion which inhibits rows of ceramic atoms from sliding past other rows Accordingly, ceramics cannot plastically deform. Instead, they fracture in a brittle manner.

Ductility

Ductility is defined as the relative ability of metals or alloys to withstand vast permanent deformation by a tensile load to the fracture point, the metal can be drawn into thin wires. While **Malleability** is a Latin word that comes from malleus or harmer, which means that the metal can be hammered into thin sheets without fracture. In other words, the material can withstand permanent deformation under compressive load without fracture. (1)(2)

Ductility indicates the workability of the material (the burnishability of casted metal margin). It is related to the force needed to make permanent deformation during burnishing which is called the burnishing index. (2) The burnishing index determines the simplicity of burnishing the alloy and is the division of the %elongation to the yield strength. The most malleable and ductile pure metal used in dentistry is gold and silver, while the most ductile alloy is stainless steel. (1) (2)

How to measure the ductility:

There are three approaches used for measuring ductility which are: (1) the percent elongation after fracture, (2) the reduction in the cross-sectional area after the tensile test, and (3) the maximum number of bends (a cold bend test). (2)(3)

1. **The percent of elongation (% EL)** is the simplest quantitative method used to measure the ductility of the material. It represents the maximum amount of permanent deformation. It is calculated by measuring the change in length of a wire or rod after fracturing under tension to its original length before fracture, which can be calculated as

Percent Elongation (% EL) = (change in length / original length) X100

$$\%EL = (L_F - L_O) / L_O X100$$

Where:

L_F is the final length, while L_O is the original length.

This is done by placing two marks on the wire or the rod and is related to the original gauge length, the common gauge length for dental materials equal to 51 mm, by pulling the wire or the rod by tensile load, the change in gauge length is remeasured as final length. (2)(3)

A material with % EL of 20% at the time of fracture that has increased in length by one-fifth of its original length is considered a material with a high value for plastic or permanent elongation. E.g., most dental gold alloys. On the other hand, a material with only 1% elongation has a limited amount of permanent elongation and is considered brittle like nickel-chromium alloys.

2. **The Percent reduction (%RA)** is calculated by measuring the change in a cross-sectional area divided by the original area. The (reduction) change in cross-sectional area is known by necking or cone-shaped constriction that occurs at the fractured end of a ductile metal wire that ruptures under a tensile load to its original area. It is calculated by the following equation:

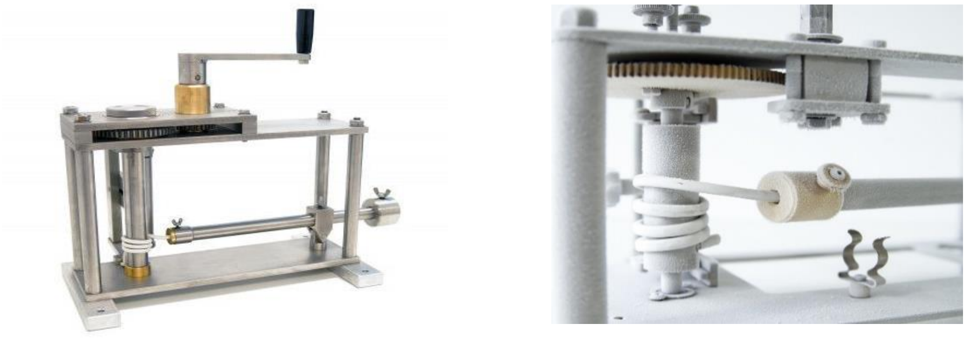
$$\%RA= (A_{F}-A_{O})/A_{O}X100$$

Where:

A_F is the final area, while A_O is the original area. (3)

3. **The cold bend test** is calculated by counting the number of bends of material by tightening the material in a vise and bending around a mandrel with a predetermined radius. The number of bends to fracture is recorded. The more the bends numbers, the larger the ductility. The first bend is formed at 90 degrees from vertical to horizontal, but all succeeding bends are formed at 180 degrees. (3) **(Fig. 1)**

Fig. 1: Cold Bend Machine



The cold bend test is considered the simplest qualitative test not only for the ductility but also used to measure the soundness of material, “used as quality control test” because the outside of the bend is extensively plastically deformed so that any defects in, or embrittlement of the material will be revealed by the premature failure.

Importance of ductility and malleability in dentistry:

- Fabrication of endodontic files and reamers.
- Adjustment of partial denture clasps.
- Adaptation of orthodontic wires.
- burnishing of crowns and inlays

Brittleness

Brittleness can be defined as a relative inability of a material to deform plastically before its fracture. Brittle material fractured at or near its proportional limit.

Examples of brittle dental materials: amalgam, resin composite, ceramics, cement, and some base metal alloys.

Brittle materials can withstand compressive strength more than tensile strength because of their inability to reduce tensile stress at flow tips. This fact should be taken into consideration during cavity preparation to reduce the tensile stresses subjected to brittle restorative material. (1)(2)

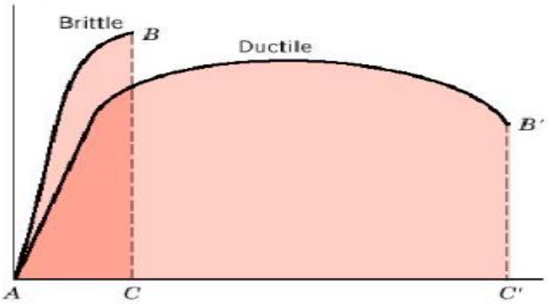
The temperature may affect the brittleness of dental material inside the oral cavity as amalgam, resin composite, and ceramics are brittle in temperatures ranging from 5 to 55 ℃. (2)

If the material is brittle this does not mean that it is weak, some examples show brittleness with high strength and low percent elongation, for example, cobalt-chromium partial denture alloy is a brittle material with 1.5% elongation and high ultimate strength of nearly 870 MPa. Additionally, glass infiltrated alumina core ceramic has 0% elongation and high strength equal to 450 MPa. (2)

Fig. 2: showing the difference between ductile and brittle materials on the stress-stain curve.

The ultimate strength of brittle material

The ultimate tensile strength of brittle material can be measured indirectly by the Diametral compression test or the Brazilian method or indirect tensile. This test depends on applying two compressive forces along the long axis of a cylindrical-shaped specimen. Tensile stresses are developed on the plane perpendicular to the applied compressive



forces that are directly proportional to them. (1) Accordingly, the tensile stresses are calculated from the following equation:

$$\text{Tensile stress} = {}^{2P}/_{\pi DT}$$

Where,

P: The compressive load.

D: Diameter of the specimen.

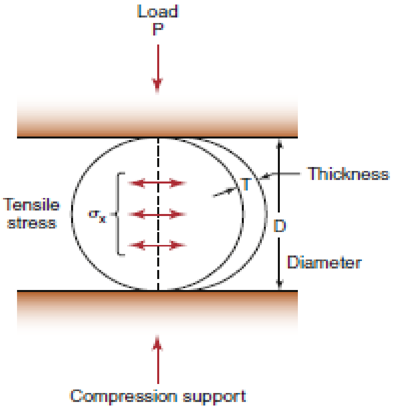
π : Constant value.

T: Thickness of specimen.

Fig .3: Diametral compression test for measuring the ultimate tensile strength of brittle materials.

<u>Fundamental of fracture</u>

Fracture is dividing or separating the body into two or more fragments after subjecting it to stress. Fracture is divided into two main categories which are brittle and ductile fractures or maybe a mix of both. This depends on several factors such as the type of materials, the nature of applied force, temperature, and strain rates. Some ductile metals may possess brittle fractures. (3)(4)



The main difference is that ductile metals exhibit a substantial amount of plastic deformation with high energy absorption before fracture while the brittle material has limited or no plastic deformation with low energy absorption before fracture.

Brittle fracture is a serious complication that can occur suddenly without warning and should be avoided while ductile fracture occurs with warning as more strain energy is needed to be induced. It is called a **shear fracture.** (3)

Brittle material fractures by cracks and crack propagation while **Ductile fracture** results in decreasing in the area at the site of fracture known by necking.

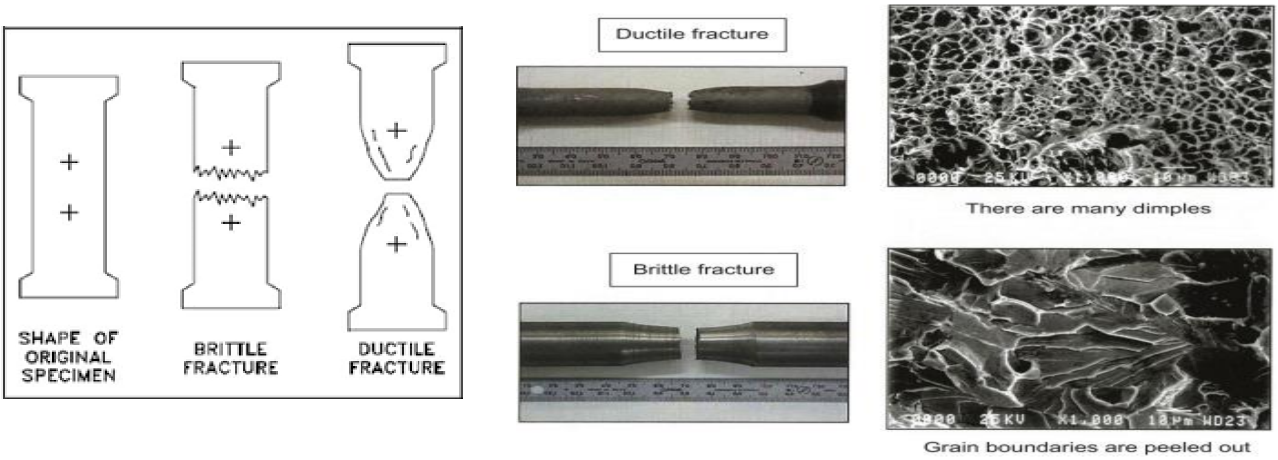


Fig. 4: Difference between brittle and ductile fracture

Ductile fracture

It is characterized by a certain feature on both microscopic and macroscopic levels, fracture takes place in several steps starting with necking when the induced stress is equal to the (ultimate) tensile strength. The ductile fracture appears fibrous and dull. (3)

Complex stress arises in the neck region resulting in the highest stress values at the center of the specimen.

Cavities nucleate forming microvoids at the center of the neck part (**Fig. 5-a**). Plastic flow occurs around these inclusions leading to an increase in the cavities' size that will coalesce to form a crack at the center of the specimen (**Fig. 5-b**). The crack grows in a parallel direction to its major axis and perpendicular to the applied stress. These cracks reach the surface of the specimen resulting in its fracture. This is known as cone and cup shape fracture. (4) **(Fig. 5-c)**

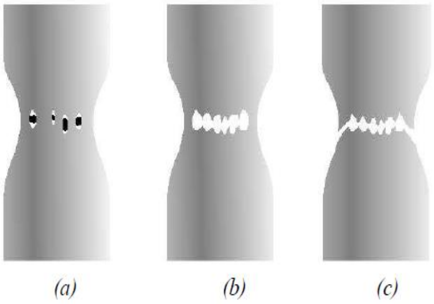


Fig. 5 shows the stages of the cup and cone shape in ductile fracture (a) small microvoids formation (b) coalesce of cavities to form crack (c) crack propagation

Fractographic Study (Microscopic examination)

A scanning electron microscope is used to study the microscopic features of fractured surfaces. It gives better resolution, higher magnification, and depth of field compared to an optical microscope. It gives more information that helps in analyzing the fracture mode, site of crack formation, and stress state.

Ductile fractured surface: The Fracture surface has elongated 'dimples' as if they had formed from numerous holes separated by thin walls. As the cavities approach the edge of the specimen, the crack changes direction and spreads along localized shear planes at an angle of 45 degrees to the tensile axis. As this is the direction of maximum shear stress under necking conditions, each dimple is one-half of a micro-void and may be elongated or C-shaped as seen in **Fig. 6 a and b**. (3)

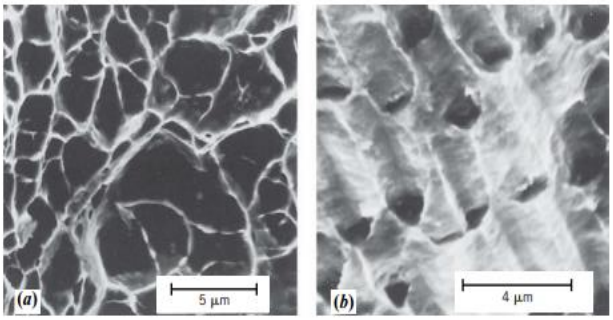


Fig. 6 Scanning electron micrograph of fractured surfaces. (a) spherical dimples characteristic of ductile fracture resulting from uniaxial tensile load 3300X, (b) parabolic shaped dimples characteristic of ductile fracture resulting from shear loading 5000X. (3)

Brittle fractured surface: an amorphous brittle material characterized by a shiny and smooth appearance in the site of fracture as in ceramics. Fracture of brittle material has different patterns; as in some steel pieces, a series of V-shaped takes place on the surface. It looks like river lines and is known by the chevron mark (**Fig. 7&8).** These river lines indicate the initiation point of fracture accordingly, crack propagation occurs in the opposite direction which helps identify the crack propagation direction and trace it when material fractures in a brittle manner, other brittle fracture surfaces display lines or ridges from the source of crack, forming a fan-like pattern that can be detected by necked eye as it has a noticeable coarse appearance. (3)(4)(5)

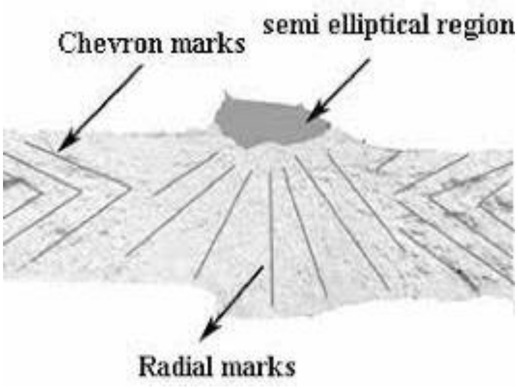


Fig. 7: The different patterns of brittle fracture

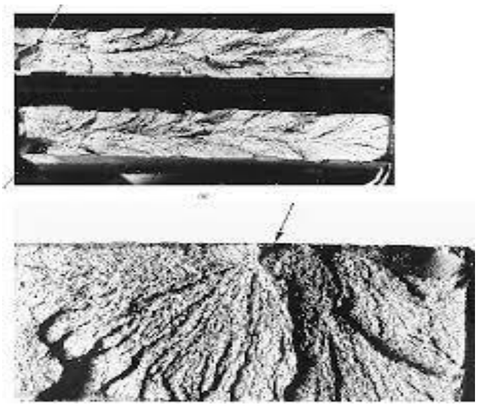


Fig. 8: The V-shaped 'chevron' marks and radial fan-shaped ridges are characteristic of brittle fracture. (3)

Most crystalline materials exhibit fracture separation along crystallographic planes which is known as cleavage fracture, in brittle fracture, the crack propagation is rapid and has a trans-granular shape usually although it can be inter-granular under embrittling conditions or weakening of the grain boundaries region.

The difference between trans-granular and inter-granular fractures is that trans-granular fracture passes through the grain forming a cleavage pattern, while inter-granular fracture takes place along the grain boundaries (3) **(Figs. 9&10**).

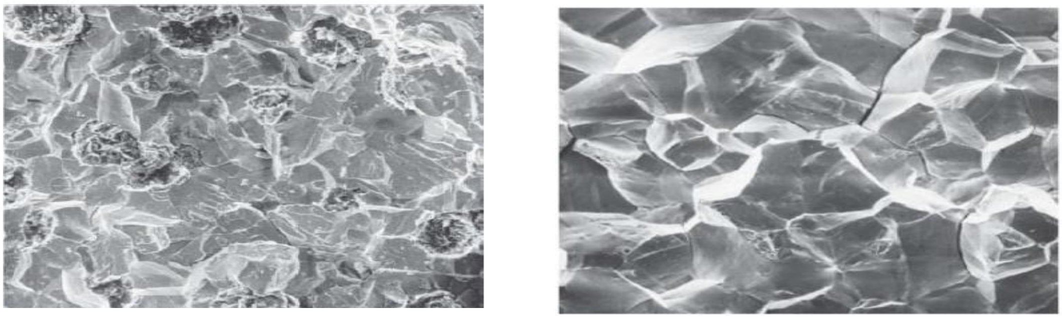


Fig. 9: Trans-granular and inter-granular fracture of crystalline brittle materials. (3)

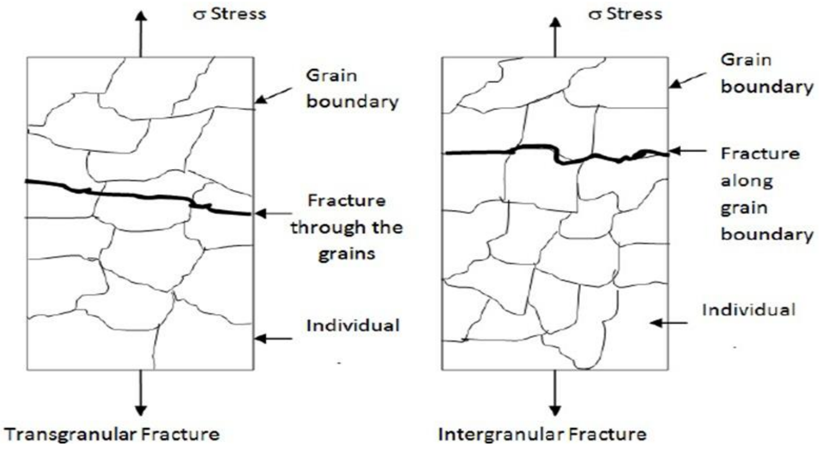


Fig. 10: Schematic cross-section profile showing crack propagation in the trans-granular and inter-granular fracture types

How to guard against brittle fracture

Several approaches can be considered to avoid brittle fracture occurrence. They can be summarized as follows: cavity design to withstand compressive stress more than tensile stress, elimination of sharp edges and notches in the cavity design and proper finishing to the restoration, avoid impact loading on brittle material.

Ductile To Brittle Transition

It has been reported that steel changes from ductile to brittle fracture when the temperature is around or below 4°C, once a crack originated at stress concentration it propagates. (3)

Pure metals have a definite transition temperature below which the material behaves ductile while above it behaves brittle. Most HCP metals and FCC as copper and aluminum tend to have no ductile to brittle transition. **Fig.11**

The transition temperature of low-strength steel (BCC) depends on the alloy composition and microstructure, the grain size refinement will lead to a decrease in the transition temperature and increase the strength as well as toughness. Both ceramics and polymers show ductile to brittle transition, ceramics develop transition at a high temperature above 1000°C. While polymer show transition at a narrow range of temperature below room temperature.(3) The Charpy impact test is used to determine the ductile to brittle transition by testing the impact strength. (3) **Fig 12**

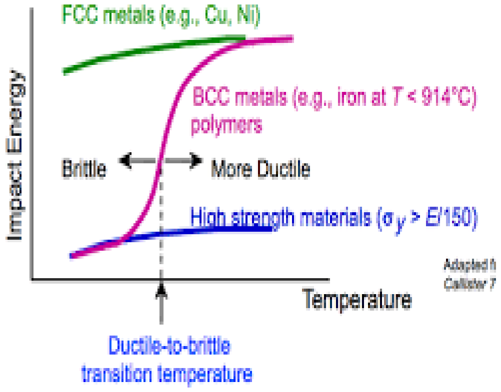


Fig.11 Schematic curves for the three general types of impact energy–versus–temperature behavior. (3)

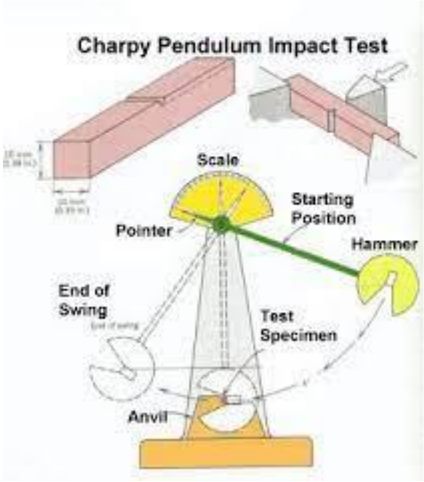


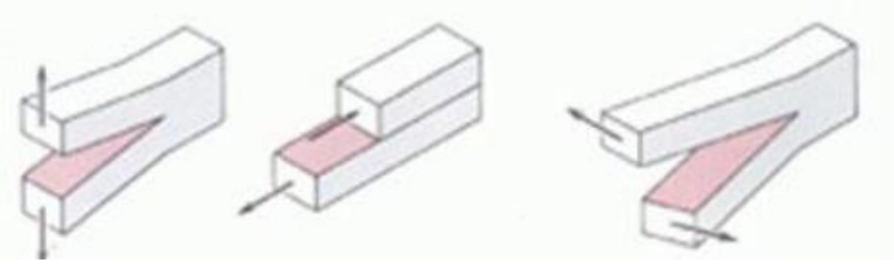
Fig.12 Charpy impact test

Fracture mechanism

The steps of fracture start with the crack formation and then its propagation in response to the induced stress. Cracks and flaws are present naturally in any material. It is a type of volume defect that occurs and nucleates after a time in service. This leads to the fact that the actual fracture strength is lower than the theoretical one predicted from the atomic bond energies. There are two types of flaws one present on the surface and the other located in the interior body of material. Cracks act as stress concentration factors accordingly, less force is needed to fracture the material. (3)

Modes of crack surface displacement

There are three modes of crack displacement that result from force leading to either opening, sliding, or tearing (3)(6) **(Fig 13)**. The crack may be concentrated at the tip. This depends on crack orientation and geometry. In this case, the magnitude of the localized stress decreases as we go far away from the tip of the crack.



a b c

Fig.13: Modes of crack displacement (a) Mode I (opening or tensile), (b) mode II (sliding), and (c) Mode III (tearing)

<u>Stress Raisers</u> are flaws that can expand the area of stress. These stress raisers arise from surface cracks, defects, and surface roughness or from the internal as inclusion, pores that cannot be controlled or eliminated. Surface cracks are not preferred and should be avoided in dental procedures by proper finishing and polishing and glazing of dental porcelain. (3)(7)

The maximum stress at the crack tip under tensile loading can be calculated from the following equation result from the crack propagation of the <u>Griffith crack model</u>:

$$6_m=26_o\left(\frac{a}{\rho t}\right)^{1/2}$$

Where

6_o is the magnitude of the nominal induced tensile stress

ρt is the radius of curvature of the crack tip (**Fig.14**)

a represents the length of a surface crack or half of the length of an internal crack

for a long microcrack that has a small tip radius of curvature; we use this equation. (3)

$$k_t = \text{—} = 2\left(\frac{a}{\rho t}\right)^{1/2}$$

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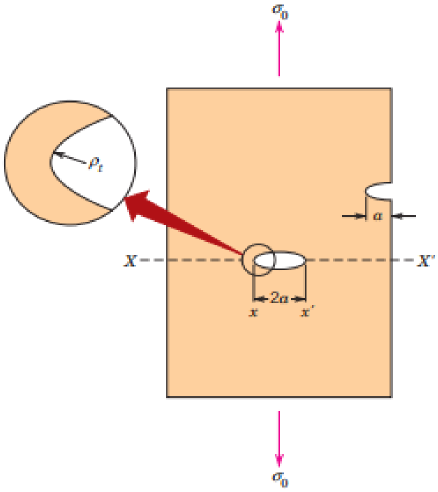

Fig. 14: The geometry of the surface and internal cracks. (3)

Fracture Toughness

Fracture toughness is a material property that can be defined as the ability of the material to be plastically deformed without fracture. It is the amount of energy needed to fracture the sample which contains a crack. It is more obvious in brittle material as the ductile material can be plastically deformed and redistribute the stresses. Therefore, brittle material has a lower fracture toughness value than ductile materials. (1, 3)

Fracture toughness (K_{C}) can be calculated from the following equation

$$K_{IC} = Y6\sqrt{\pi a}$$

Where

k_{IC} represents fracture toughness in mode I (shown in **Fig 13**)
Y dimensionless geometry factor
6 is the stress
a is the crack length (3)
Unit = stress times the square root of crack length
MPa•$m^{1/2}$ or MN•$m^{-3/2}$. (2)

Importance in dentistry

Fracture toughness describes the material resistance to crack propagation especially brittle materials when subjected to tensile loads that could lead to fracture. This can be prevented by several methods as designing a basis against these types of failure, modifying the material by adding fillers as in the case of resin composite to deflect cracks, presence of crystalline phase in ceramics can deflect/ obliterates cracks, and the presence of tough zirconia particle that acts as a crack healer. (1)

Method of testing fracture toughness

There are several testing methods for measuring fracture toughness. Among these methods:

1. Single edge notched beam:
    a. Single edge pre-cracked beam
    b. Single-edge V-notched beam
2. Chevron notch method
3. Compact tension method.
4. Short rod method (tension test).
5. Double torsion method
6. Indentation method:
    a. Vickers's hardness or Koop's indentation.
    b. Nano-indenter

The most commonly used method for measuring the fracture toughness of metal, ceramics, and resin composite materials is the one presented in the standardized ASTM method. It is the single-edge-v-notched beam (SEVNB) test:

Single-edge-V-notched beam (SEVNB) test:

Rectangular pre-notched specimens prepared in a mold using the single-edge notched design according to ASTM Standards E399-90(1992) as shown in **Fig.15**.

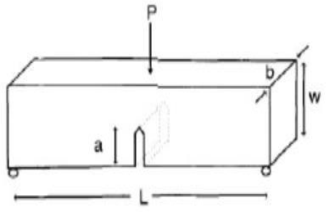

Fig.15 Specimen geometry for the determination of fracture toughness by single-edge V-notched method.

Testing Methods:

The specimens can be tested under 3-point or 4-point bending using the universal testing machine. In the case of the 3-point bending test, each specimen is supported on two parallel stainless-steel rods (10 mm in diameter) located at a certain distance from each other. The load was applied through a cylindrical stainless-steel rod at the middle as seen in **Fig. 16**. The load is applied with a certain crosshead speed (mm/min) until fracture. Both the load and the deflection are obtained from the load-deflection curve produced by the software program of the computer connected to the testing machine. Care should be taken on carrying the specimen that may be subjected to unexpected fracture before testing. (8) (9)

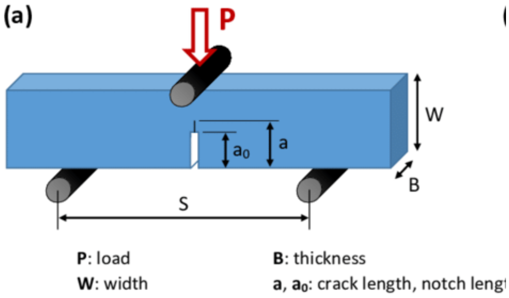

Fig.16 V-shaped pre-notched specimen subjected to 3-point bending.

Calculation of the fracture toughness (FT):

The fracture toughness of each specimen was calculated from the following equation.

$$K_{Ic} = [3\ P\ L\ a^{1/2} / 2\ b\ w^2] \times f\ (a/w)$$

Where:

P= Load at fracture in Newton (N)

L = Distance between the support in mm

a = Crack length in mm = W/2

b = Thickness of specimen in mm

w = Width of specimen in mm

f(a/w) = The value f (a/w) was obtained from ASTM slandered.

Ball-on three-balls method (B3B):

There is another method of testing the fracture toughness of ceramic materials known as “ball-on three-balls”. It depends on placing a circular disk or a rectangular plate, which is supported by three balls in contact and loaded on the opposite side by a fourth ball of the same size. The loading ball is positioned centrally to the three supporting balls. **(Fig.17)** Then by Using a Knoop indentation almost semicircular surface crack is introduced as a starter crack in the center of the specimen, opposite to the loading ball. (**Fig.18**)(9)

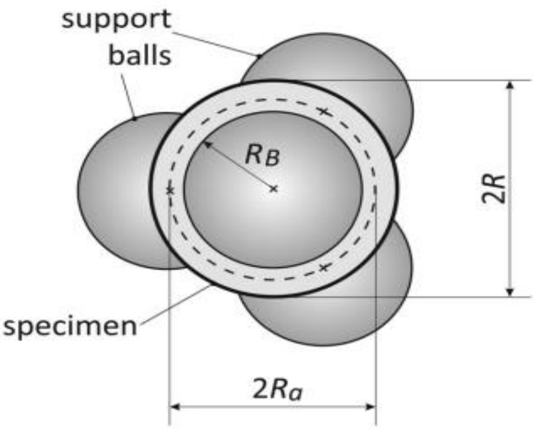

Fig.17 diagram showing Ball-on-three-balls test geometry with four equally sized balls of radius R_B. Specimen and loading ball is positioned centrally to the three supporting balls in contact. (9)

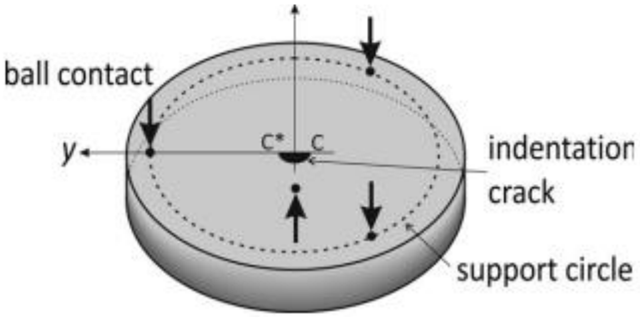

Fig.18 Diagram of crack position in B3B-KIc test (9)

Calculation of fracture toughness from the B3B method

$$K_{IC} = 6_{B3B}\ Y\sqrt{\pi a}$$

6_{B3B} the maximum tensile stress occurs in the center of the specimen opposite to the loading ball

a is the crack depth

Y is the load-independent geometric function that depends on the specimen and crack geometry as well as on Poisson’s ratio of the tested material.

Several errors may occur during this test related to the crack size and shape, the position of the crack, and the inaccurate knowledge of Poisson’s ratio of the material. (9)

Conclusions

- Cracks have a critical effect on materials' failure. They should be avoided especially those present on the surface of the dental material. There are two types of dental material; ductile (metal and alloys) and brittle materials like composite, ceramic, and amalgam.
- Ductile material shows a higher percent of elongation, and fracture toughness, than brittle material. Ductile material fractures away from the proportional limit while brittle material fractures at or near the proportional limit.
- Ductility can be measured with three methods which are: percent of elongation, percent of reduction, and cold bend test.
- Ductile fracture is characterized by necking while brittle fracture is characterized by crack propagation.
- Ductile fracture is more preferred than brittle ones because ductile fracture takes time and can be avoided while brittle fracture occurs without any warning and is characterized by rapid crack propagation.
- Fracture toughness is the material's ability to resist deformation in the presence of cracks.

References

1. Anusavice K., Shen C., and Rawls R.H.: Phillips Science of dental materials: 12th ed. Saunders, 2013. From pages 62,63,65,66.
2. Callister WD, Rethwisch DG. Materials science and engineering, 9 ed. Times Ten LT Std by Aptara, Inc., Quad Graphics/Versailles. Wiley Binder Version ISBN: 978-1-118-47770-0, USA, 2014. Chapter 6 from page 184, chapter 8 from pages 253 to 261 and 288, chapter 12 page 491
3. Metals Handbook, 9th Edition, Vol 11, Failure Analysis and Prevention, ASM International, Metals Park, Ohio, (1986)
4. Luiz Otávio Amaral Affonso, in Machinery Failure Analysis Handbook, 2006
5. Ring TA, Feeney P, Boldridge D, Kasthurirangan J, Li S, Dirksen JA. Brittle and Ductile Fracture Mechanics Analysis of Surface Damage Caused During CMP. J Electrochem Soc. 2007;154(3):H239.
6. Higgins, R A, "Materials for the Engineering Technician", Edward Arnold, London, 1997
7. Balakrishna B, Krishna SH. Fracture Toughness Prediction of Brittle & Ductile Materials. Int J Eng Res Technol. 2012;1(5):1–10.
8. Cicero S, Madrazo V, Carrascal IA. Estimation of Fracture Toughness by Testing Notched Fracture Specimens and

Applying the Theory of Critical Distances. ISRN Mater Sci. 2012;2012(September):1–8.

9. Lube, T., Rasche, S. and Nindhia, T.G.T. (2016), A Fracture Toughness Test Using the Ball-on-Three-Balls Test. J. Am. Ceram. Soc., 99: 249-256. https://doi.org/10.1111/jace.13842