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DENTIN TOUGHENING

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ABSTRACT:
Tooth fracture is a concern in the field of restorative dentistry. Causes of tooth fracture can be attributed to formation of microcracks and macrocracks in the dentin microstructure. Dentin consists of the mineral hydroxyapatite (70%), organic material (20%), and water (10%).Dentin is harder than bone but softer than enamel, it is mostly made of phosphoric apatite crystallites. Dentin serves as the elastic foundation for enamel and as a protective enclosure for the dental pulp. Fracture behaviour of biological porous dentin is important to the success of dental restoration. The role of dentinal microstructure on the fracture properties of human dentine is investigated by analysis of its crack tip shielding effect on microcracks and macrocracks. Many studies report evolution of microcracks and macrocracks around dentinal tubules under Scanning Electron Microscope observations. The complex microstructures of dentin, structural anisotropy, their role in resisting tooth fracture, and the importance of hydration and aging on the fracture resistance of tooth are important for evaluation. Toughening mechanisms based on the presence of collagen fibrils have been proposed for mineralized biological tissues like dentin. The effect of orientation of collagen fibrils and dentinal tubules on the toughness of dentin are discussed primarily in terms of the salient toughening mechanisms active in dentin, specifically, the role of crack bridging, both from uncracked ligaments and by individual collagen fibrils, is considered, achieving damage tolerance. This review article will highlight different toughening mechanisms of dentin.

Keywords: crack deflection, crack bridging, microcracks .

INTRODUCTION

The human teeth is a multi-layered biological tissue of enamel, dentin pulp and cementum. Among these dentin occupy main bulk of the tooth, both by weight and volume and is hydrated. Though enamel is the most highly calcified tissue in the body serving as a stiff and wear-resistant outermost layer but ultimately the dentin serves as the elastic foundation for brittle enamel and as a protective enclosure for the dental pulp, the innermost tissue.

Human teeth withstand various forces like load on teeth during mastication throughout life, reaching values upto 700N and greater.[1] Macroscale contacts involving teeth and larger food particles and under higher load ranges (100–1000N) can cause damages in the form of cracks. Despite the development of cracks on the surface of teeth as a result of function, these cracks seldom result in bulk fracture of the tooth. [1] That raises questions such as: "What prevents tooth fracture from originating from the visible external cracks in enamel?" The capacity for teeth to withstand the loads of mastication without causing tooth fracture is of substantial interest in the field of dentistry and to biological evolution.

Tooth fracture resulting from mechanical forms of degradation that originate at defects, which could be extrinsic or intrinsic, e.g. as a result of treatment or induced during function(mastication), or potential synergism between participating chemical and mechanical modes, are major contributors of tooth failure. The nature of damage and propensity for bulk fracture of the tooth are different for unrestored and restored teeth. Unrestored teeth often exhibit cracks on the surface. These cracks propagate on the tooth's surface depending on various parameters such as the amount and condition of contact loading, tooth morphology, the microstructure of subunits(dentinal tubules, peritubular dentin, intertubular dentin, collagen fibrils and nanohydroxyapatite crystals) of the teeth[2].

The rate of fracture varies between unrestored, aged and endodontically treated tooth

For endodontically treated tooth:- 58% Understanding what causes the initiation of cracks and the mechanisms responsible for crack arrest is relevant to development of new dental materials that are inspired by the biological systems they replace.[1] Restored teeth generally undergo failure due to cracks that cannot be seen. These cracks develop within the dentin, at the interface between the restoration and surrounding hard tissue. Mechanical failures of restored teeth are likely to result from large stresses and/or fatigue. Fracture toughness of dentin is of particular importance which characterizes their resistance to incipient cracking and fracture, and the microstructural and nanostructural mechanisms that are the source of such resistance [3]. The dentine has some advantages in overcoming fracture behaviours since it has the ideal characteristics of increasing toughness with crack extension. The dentin structure and composition is the key to distributing functional stresses/strains from the tooth to the surrounding bone. In clinical dentistry, knowledge of properties of dentin is important for understanding the effects of variety of restorative material that mimic the dentin microstructure and functioning [4].

A few studies have been made to analyse the fracture behaviour of dentine. The other reasons for crack formation can be dehydration resulting from endodontic treatment and aging.

Dentine is able to resist fracture by various toughening mechanisms. Dentin is an extrinsically toughened material and consequently its fracture properties are best characterized utilizing a crack-growth resistance approach [5].

Toughening refers to improving the fracture resistance of a given material.

Dentin Toughening refers to increasing the amount of energy required for fracture or methods that prevent the strain energy from reaching the crack tip. Fracture resistance studies of dentine have identified some toughening mechanisms, including microcrack constraining, crack bridging and crack blunting (ANIL KISHEN, 2015)[5].

Importance of dentin toughening:

Prevention of crack propagation thus maintaining the structural integrity of the tooth.

Development of new biomimentic dental materials that are inspired by the biological systems they replace, with fracture process zone possessing a dentin-like microstructure (hard peritubular dentin surrounding the dentin tubules is embedded in the soft intertubular dentin), the composite resin structure consisting of a soft matrix and hard reinforcements with cylindrical voids resembles this.

The ultrastructures of dentin contribute to the toughening mechanism in natural tooth:-

PERITUBULAR DENTIN (PTD) (Fig 1)

A significant degree of microcracking in PTDs occurs, which dissipates energy and contributes to the fracture toughness of dentin. The presence of PTD around DT slightly reduces the crack tip plastic zone and decreases the stress concentration near the crack tip[8]. The dentine can be regarded as a continuous fiber-reinforced composites with the intertubular dentin forming the matrix and the tubule lumens with their associated cuffs of peritubular dentin forming the cylindrical fiber reinforcement.[4] This microstructure topology can apparently improve the fracture toughness of dentine. Shielding effect becomes greater with the increase of the thickness of PTD. PTD can prevent the stress concentration and inhibit the energy release so as to prevent the crack from propagating into the ITD.

DENTINAL TUBULES (DT)- (Fig 1)

Fracture toughness in the direction perpendicular to dentin tubules is significantly lower than that in the

Volume 4, Issue 3; May-June 2021; Page No 13-21

direction parallel to dentin tubules, which is attributed to the existence of brittle PTD and the arrangement of collagen fibers which run perpendicular from the dentinal tubules, responsible for the dissipation of energy.

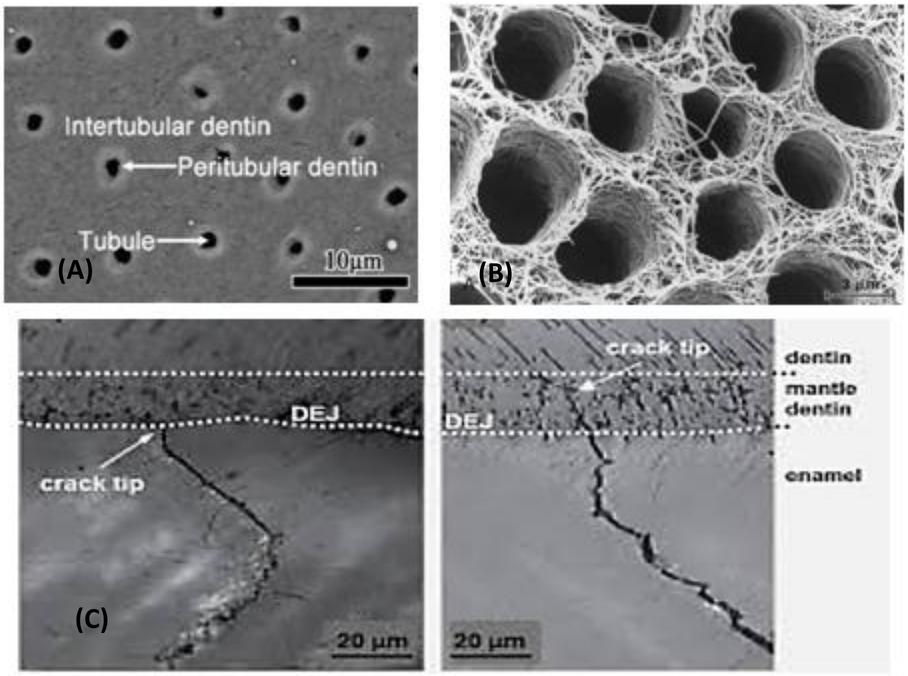


Fig 1(A) Ultrastructure of Dentin 1(B) Collagen And Dentinal Tubules

1(C) Extension of crack when fracture toughness of dentin is exceeded

Fracture instability is reached when the stress intensity ahead of a pre-existing crack exceeds the fracture toughness dentin[2].

For the cracking along the dentin tubules, crack bridging caused by uncracked ligaments and collagen fibers appears in the crack wake, which alleviates the stress intensity at the crack tip and increases the propensity of crack closure, thereby enhancing fracture toughness[9].

The consequent contact between the crack surfaces during crack opening can result in some degree of toughening due to elastic bridging. Microcracking surrounding the main crack can also be seen in intertubular dentin which results in some degree of dilation in the highly stressed region close to the crack, another potential toughening mechanism in dentin.

EFFECT OF ORIENTATION OF DENTINAL TUBULES:

The dentinal tubules arrangement has an influence on the work of fracture which is defined as the work per unit area required for crack extension. The fracture toughness of dentin has been found to be largest when the crack is oriented parallel to the dentinal tubules. In the latter orientation the collagen fibrils are perpendicular to the direction of crack extension as they form a 90 degree angle with the dentinal tubules and this element is responsible for dissipating the fracture energy at the crack tip thus contributing to toughening.

In perpendicular orientation the consequent contact between the crack surfaces during crack opening can result in some degree of toughening due to elastic bridging[2].

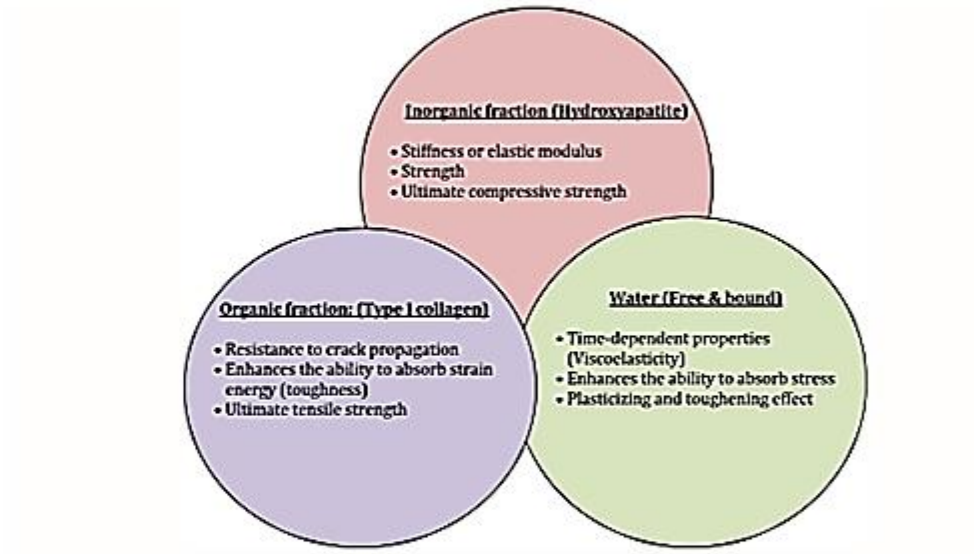
In parallel orientation a significant difference from the perpendicular orientations, however, is the occurrence of uncracked ligament bridging in the wake of the crack tip.

Anisotropy which is defined by Webster as exhibiting properties with different values when measured in

Volume 4, Issue 3; May-June 2021; Page No 13-21

different directions was evaluated by Nalla et al. in the fracture behaviour of dentin from elephant tusks, which enabled the use of larger specimen sizes. Results were in agreement with those obtained for human dentin, with estimated fracture toughness being lowest for cracks growing perpendicular to the tubules (K_{IC} 1.6 MPa m0.5) and with regards to the condition where cracks extension occurs parallel to the tubules (K_{IC} 2.5 MPa m0.5).

Wang reported that the fracture toughness of root dentin (4.8 *MPa m0.5*) was substantially greater than that for tissue of the crown (2.1 *MPa m0.5*).[1] They postulated that the differences in fracture resistance are related to properties of the collagen fibrils in coronal and radicular dentin and the anisotropy in the tissue cause by the fibril orientation in the root.



MECHANISM OF DENTIN TOUGHENING:-

Essentially, microstructure can influence toughness in two primary ways :

(i)Intrinsic toughening mechanisms that operate ahead of the crack tip and act to enhance the material's inherent resistance to microstructural damage and cracking, and (ii) extrinsic toughening mechanisms that operate primarily behind the crack tip by promoting crack-tip shielding, which act to reduce the stress intensity actually experienced at the crack tip. Microcracking, crack blunting, and crack bridging are examples of extrinsic toughening mechanisms in dentin

Intrinsic mechanisms, such as crack blunting, tend to affect the crack initiation toughness, whereas extrinsic mechanisms, promote crack-growth toughness. Since the latter mechanisms operate in the crack wake, their effect is dependent on the size of the crack.

Although crack propagation can be considered as a mutual competition between these two classes of mechanisms, intrinsic toughening tends to dominate in ductile materials, whereas extrinsic mechanisms are generally the main source of toughening in brittle materials and many composites.

Microcracking causes dilation and increases the compliance of the region surrounding the crack. The sharpness of the crack tip focuses strain energy onto the next susceptible bond and is an important factor governing fracture propagation. (Fig 2a)

Crack blunting causes the stresses at the crack tip to be defocused. This process tend to affect the crack-initiation toughness. with inelastic deformation, some degree of blunting occurs at a crack tip such that the location of the maximum stresses Hydration also increases the fracture toughness of dentin by extensive crack blunting

In **crack bridging**, as the crack opens, fibers or filaments extend across it, dissipating energy by their own deformation or by friction as they pull out from the bulk of the material. Crack bridging is the commonest form of crack-tip shielding, particularly in fiber composites where intact fibers tend to bridge the crack and oppose crack opening. (Fig 2b)

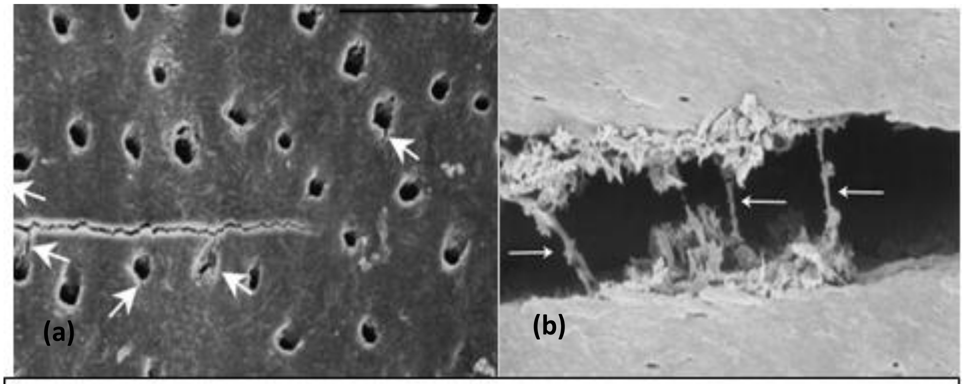


Fig 2(a)TOUGHENING BY MICROCRACKING (white arrow denotes microcracks formed around peritubular cuffs) Fig 2(b) TOUGHENING BY CRACK BRIDGING(white arrow indicates uncracked ligaments)

Crack deflection: Where cracks deviate from the plane of maximum driving force, the stress intensity experienced at the crack tip is reduced, thereby providing a source of toughening.. For the "perpendicular" orientation some amount of crack deflection is noted in the microscopic level. However, as noted previously, the crack does make occasional small (up to 20 μm) deflections locally along the tubule axis. The local stress intensities at the tip of such a crack can be evaluated using crack deflection mechanics.

Comparing the fracture resistance across the regions is that the toughening mechanisms were actually dependent on location.

SPATIAL VARIATION IN TOUGHENING MECHANISM:-

Toughness decreases as pulp is approached . Within the inner dentin, which exhibits the largest tubule density, toughening is achieved by meandering of the crack to nearby lumens.(Fig 3a)[1]This process results in a reduction of the stress intensity at the crack tip via within the specimens of middle dentin microcracking of peritubular cuffs were also dominant

Volume 4, Issue 3; May-June 2021; Page No 13-21

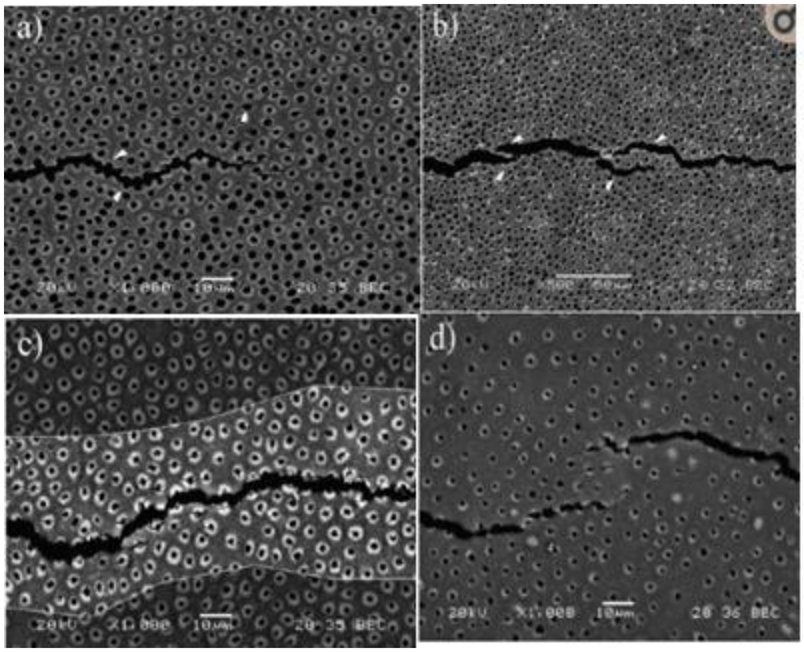


Fig 3(a) Crack extension in inner dentin: crack extension from lumen to lumen. Some amount of peritubular microcracking is also prevalent **(b)**Ligament Bridging The Crack **(c)**Microcracking Of Peritubular Cuffs In Middle Dentin **(d)** Ligament Bridging The Cracks And Microcracks In Outer Dentin

In the outer dentin the toughening behaviour appeared to be largely attributed to the development of unbroken ligaments behind the crack tip(Fig 3d)

Thus, in addition to exhibiting anisotropy in the fracture resistance, human dentin also exhibits spatial variations.

The microstructure of dentin appears to have been graded in such a manner that, in case of failure of the enamel and the DEJ to achieve crack arrest, can serve as the “third” defense.

R CURVE-

Most recent studies concerning the fracture behaviour of dentin have reported that it exhibits a rising crack growth resistance with crack extension. This is an important quality, and is exhibited by most materials with hierarchical microstructure.

Human dentin exhibits rising R-curve behaviour regardless of the tubule orientation.

EFFECT OF HYDRATION (Fig 4a & b)

Both hydrated and dehydrated dentin show this effect, with both the crack-initiation toughness and crack growth toughness being higher in the hydrated dentin.[10] Indeed, hydration is observed to elevate the initiation toughness by 60%, in terms of K_0. Additional evidence for the intrinsic toughening effect of blunting is seen in the hydrated dentin. Hydrated dentin undergoes more extensive inelastic deformation around the crack tip as a result of the intrafibrillar spaces being occupied by water molecules, which results in “plasticization” of this highly organic system. The viscoelastic nature of the near-tip deformation promotes crack blunting, and results in higher crack growth resistance in the hydrated condition. Crack bridging by unbroken ligaments of tissue is identified to be the major toughening mechanism contributing to the rising R-curve responses in conditions of hydration. [1] Dehydration results in a loss of interfibrillar spaces and overall fibril diameter. Groups capable of forming interpeptide hydrogen bonds but previously unable to do so due to the preferential H-bonding with water could form Hydrogen bonding in the absence of water. These interpeptide forces stabilize

Volume 4, Issue 3; May-June 2021; Page No 13-21

the structure of dried collagen, increasing its stiffness.

In contrast to the influence of dehydrating dentin by vacuum, chemical dehydration of dentin using polar solvents (e.g., ethanol) causes a marked rise in crack growth resistance

EFFECT OF AGING ON TOUGHENING(Fig 4c, 4d, 4e, 4f):- The sclerotic dentin appears to be a natural consequence of aging. The dentinal tubules in transparent dentin are gradually filled up with a mineral phase over time, beginning at the apical end of the root and often extending into the coronal dentin. There is a significant decrease in the crack growth resistance of dentin with age. Extent of reduction is dependent on the tubule density which is important to the mineral to collagen ratio. Average fracture toughness of old dentin is 30% lower than that of young dentin. Crack in the old dentin propagates mainly by development of a critical stress intensity at the crack tip. An important difference between the normal and aged groups is the prevalence of crack deflection. Crack propagation tended to be straighter in young dentin as compared to aged/transparent dentin. [11] Crack bridging is found in both groups, but the mechanism is different. The difference in bridge formation in young vs. aged dentin, is that in young dentin, the bridges form between the tubules and tend to be larger than that in the aged dentin where the occluded tubule itself forms the bridge.

The unfilled tubules in young dentin are linked with crack branching(Fig 4c). Because the filled tubules do not microcrack, they do not result in crack branching. The filled tubules in aged dentin result in local deflections as the crack propagates around their interface with the matrix and does not penetrate the tubules.(Fig 4d)

Crack propagation tends to be straighter in young dentin as compared to aged dentin(Fig 4e &f). Crack bridging is found in both groups, but the mechanism is different, the distinction between the two being that in young dentin, the bridges form between the tubules and tend to be larger than that in the aged dentin where the occluded tubule itself forms the bridge.

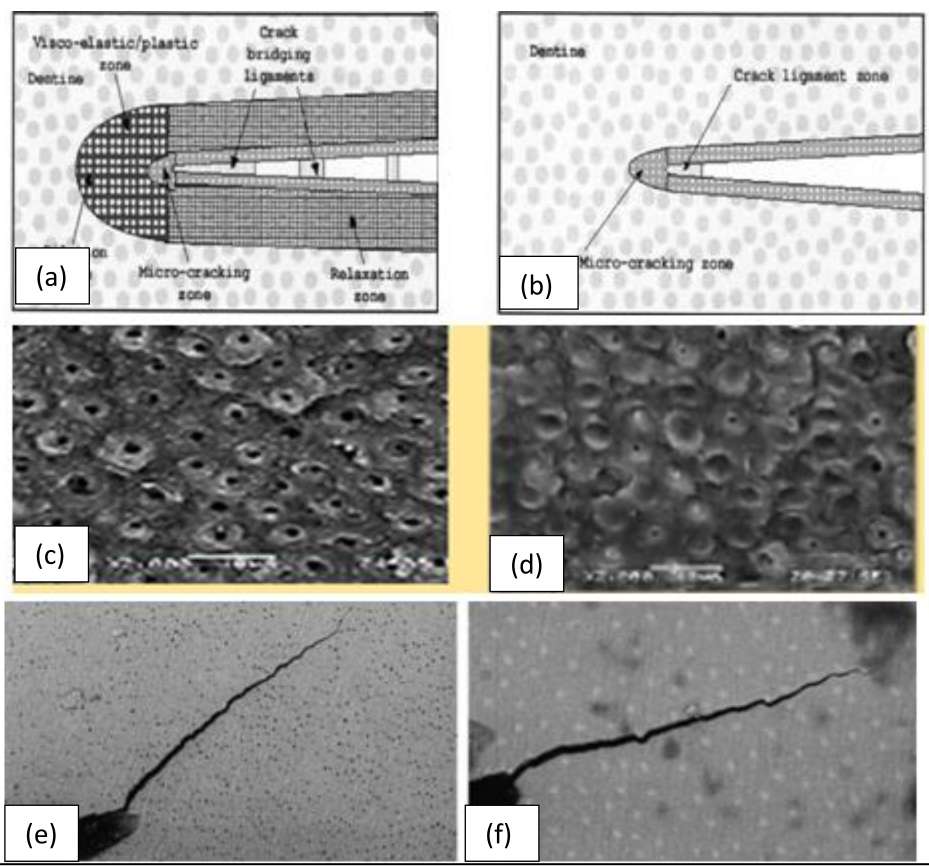


Fig 4: Toughening mechanism of **(a)** Hydrated and **(b)** Dehydrated dentin. Dentinal tubules in **(c)** young patient. Dentinal tubules in **(d)** aged dentin. Crack propagation in **(e)** young dentin and **(f)** aged dentin.

Volume 4, Issue 3; May-June 2021; Page No 13-21

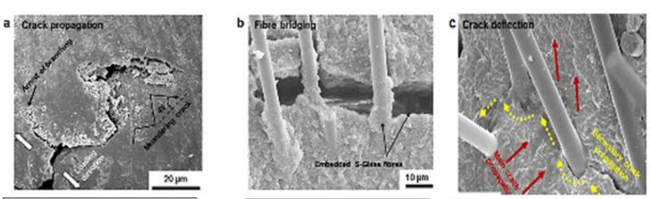
Fig 4: (a) TOUGHENING MECHANISM OF (a) HYDRATED AND (b) DEHYDRATED DENTIN. Dentinal tubules in (c) young patient. Dentinal tubules in (d) aged dentin. Crack propagation in (e)young dentin and (f) aged dentin.

APPLICATIONS;-

1)ADVENT OF FIBRE REINFORCED COMPOSITE :- It has been suggested that the microstructure of dentin can be considered as a cylindrical fiber reinforced composite , with the matrix as intertubular dentin and the reinforcements as the tubule lumens and the concomitant peritubular dentin cuffs. The optimum toughness would be expected for crack extension perpendicular to the fibers. Clinical success or failure of FRC is the ability of the material to minimize the microcracks and irregularities in the structure. They mimick the toughenism mechanism exhibited by human dentin. The fibres in FRC enhance the load bearing capacity of the structure by two separate and distinct mechanisms.

First the fibres act as stress bearing component. They support the forces of occlusion similar to dentin.

Second they also strengthen the composite by acting as crack stopping and crack deflecting component. As microcracks propagate through the resin matrix, if they encounter a fibre they are stopped and deflected along the interface between the fiber and resin. The fiber becomes circumferentially detached from the resin matrix. When the crack intercepts another fiber, it forks and divided, multiplying the number of cracks in the structure. The creation of each new crack consumes energy and increases the work of fracture for the material. This mechanism dissipates the energy applied to the structure. The process of branching of crack continues until energy demands become too high or the material fractures.



MICROCRACKING: FORMATION OF SMALL CRACKS WHICH CAUSES DISSIPATION OF STRESS FROM THE MAIN CRACK.

CRACK BRIDGING BY FIBRES: FORMATION OF FIBRE BRIDGES BEHIND THE CRACK TIP TO APPROXIMATE THE GAP.

CRACK DEFLECTION: THE FIBRES CAUSE DEFLECTION OF CRACKS FROM IT'S MAXIMUM POINT OF STRESS.

2)SELF HEALING COMPOSITE: Capsule based self-healing materials is a new field sought as an alternative to the conventional repairing techniques, requiring no manual intrusion.

Microencapsulation can be described as the enclosing or enveloping of materials inside another material, producing small capsules, in micron sizes. Organic polymer based micro-containers are one of the most significant encapsulants for applications in self healing composite coating systems. In **Epoxy based system** epoxy resin and hardener are separately encapsulated and embedded inside the polymeric composite matrix. When a crack occurs, both kinds of capsules rupture and the outflowing epoxy resin and hardener are mixed to heal the crack. When the encapsulated solvent is released, it locally swells and entangles the matrix across the plane and heals the crack. In **Ring-opening metathesis polymerisation (ROMP)** cell-like capsules containing dicyclopentadiene (DCPD) and Grubbs' catalyst were dispersed in a polymer matrix during material formulation. When the material is damaged and a crack occurs, the healing agent contained in the capsules will be released due to fracture of the poly urea-formaldehyde (PUF) capsule shell. The healing agent floods the crack and clots under the ROMP of DCPD catalysed by Grubbs' catalyst.

3)COMPOSITE WITH NANOTUBES:-

Nano fillers are very different from traditional fillers due to their large specific surface area, high aspect-ratio and unique microstructure. Additionally, many researchers have proved that the application of nanotechnology could greatly improve the mechanical performances of dental com-

Pos Nanofillers are very different from traditional fillers due to their large specific surface area, high aspect-ratio and unique microstructure. Nanotechnology could greatly improve the mechanical performances of dental composites.

Glass nanofibers- Substitution of traditional dental glass filler with glass nanofibers partially, the strength and toughness of the corresponding resin composites will enhance greatly. When dental resin composites are under external pressure or three-body friction, microcracks are easily tended to be produced in the body of dental matrix. Although the cracks are formed, the gap between crack planes is not a vacuum and thin and long glass fibers exist in the middle section bearing load constantly, until glass fibers are broken completely. So, we can make an easy understanding that crack expansion is inhibited by the fibers, and meanwhile the matrix will become more powerful.

Fibrillar Silicate- When dental composites are under tremendous pressure suddenly, they tend to create cracks in the body of composites; meanwhile, fibrillar silicate single crystals could continue to function across the cracks and restrain the expansion of cracks. So the inhibition of crack-extending and increased interaction between single crystals and matrix result in the reinforcement on the final mechanical property of the resin.

CONCLUSION:-

There are different iatrogenic and non-iatrogenic risk factors that could initiate or propagate cracks leading to fractures. The biomechanical response of a tooth structure to chewing forces has a significant association with its resistance to fracture. Growing knowledge on the fracture properties of natural materials has fueled engineers and scientists to develop new bioinspired microstructures with impressive performance. Also understanding the biomechanical principles will enable clinicians to realize the potential risk factors for fractures and scientists to develop novel treatment strategies to reinforce teeth.

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