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State of Art on Tribomechanical andTribo chemical Wear of Human Dental Enamel

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ABSTRACT

The application of tribology in dentistry is one of the rapidly growing and expanding fields. Intensive research has been conducted to understand dental tribology for selection of artificial dental materials. In the current paper, an overview on tribomechanical and tribochemical wear, combined with a description of the different wear simulating equipment and devices which allows us to better understand the multifactorial nature of wear has been presented. Wear and tear of the dental enamel due to tribomechanical factors such as two-body abrasion and three-body abrasion has been emphasized. Dental erosion due to chemical effect and the effect of oral environments has also been considered. In addition to these, overview of wear modes and wear locations has also been covered. According to results obtained by the authors and from the literature, the main progress in the area of dental tribology on natural dental enamel is reviewed.

Introduction

Basically human teeth are mainly composed of enamel, dentine and pulp. Dental enamel is the hardest and most mineralized tissue in the human body. Enamel, consists of 92–96% of inorganic substances, 1–2% of organic materials, and 3–4% of water by weight. Human teeth act as a mechanical device during masticatory processes such as cutting, tearing, and grinding of food particles and food bolus. The tooth is the only mineralized organ that is located partially internal and partially external to the human body. From advanced materials science point of view, a tooth is a functionally graded composite material with mineralized matrix and organic reinforcements (Fig.1). It is composed of three basic structural parts, namely enamel, dentin and the dentin-enamel junction (DEJ). The anatomical crowns of teeth are covered by dental enamel. Enamel comprises a mineral phase and an organic matrix. Dental enamel has a unique microstructure consisting of aligned prisms or rods, which run approximately perpendicular from the DEJ towards the tooth surface. The interfacial area between rods is termed interred enamel which is protein-rich material. The DEJ can be considered as a biological interface between the external enamel and underlying dentin. It is a unique junction between highly mineralized tissues of different embryogenic origins, matrix composition and physical properties.

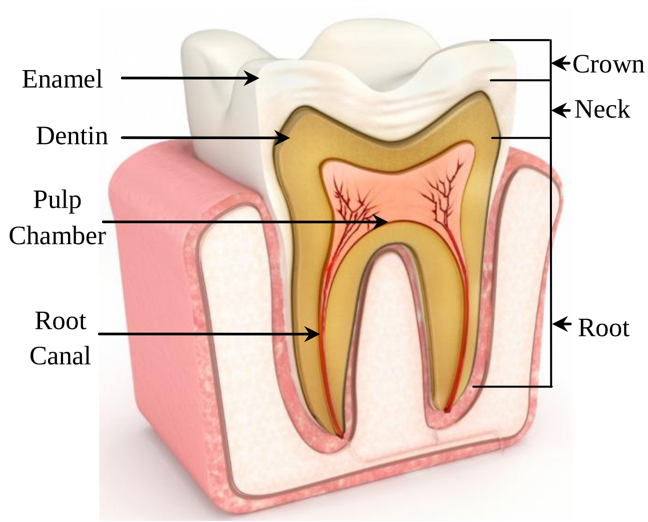

Figure 1.Schematic sectional view of various parts of the teeth

Tribology is the science of the mechanisms of wear, friction and lubrication of interacting surfaces which are in relative motion. Wear is defined as material removal whenever a surface is exposed to another surface or to chemically active substances, which can result in a progressive removal of material from surfaces through mechanical or chemical action. Wear of human

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teeth is a complex process that involves mechanical and thermal actions along with chemical reactions. The removal of surface material is accomplished broadly by tribomechanical and tribochemical wear. Normally, wear occurs due to a combination of these mechanisms. Generally, chemical factors are part of the process and have a strong interaction with other wear mechanisms. When chemical factors are dominant, the wear mechanism are called as ''tribochemical''. Chemical action, together with the mechanical loads involved, can modify the dental enamel and restoring materials, altering their properties. Friction is the rubbing of one object or surface against another. In general, oral biomechanical functions can result in some tribological movement of teeth, restorations and implants occurring in the mouth. During mastication, the teeth, together with any restorations, move in contact with one another, then friction and wear occur generally with the lubrication of saliva or food slurry. It has been accepted that tooth wear is a clinical problem that is becoming increasingly important. Therefore tribology of dental enamel has increasing attention by researchers.

Dental enamel is one of those unique natural substances which still yet to be substituted effectively by artificial materials. Many researchers have tried to discover the nature of good wear performance of tooth enamel. Many test devices and techniques have been designed and implemented for many 'tribological' purposes. Most of them are used for two-body tests employing relative movement between the sample and abrasive surface.

Generally three kinds of methods are used to study tribological behavior of dental enamel:

1. In vivo observations are mostly practised in clinics to observe and evaluate the loss of dental enamel and dental hard tissue caused by tribological wear of teeth in the mouth.

2. In vitro laboratory simulations are implemented by materials and tribology researchers to explore wear mechanisms of natural teeth and artificial materials by mimicking the wear conditions in the mouth.

3. In situ method, specimens are mounted in devices worn in the mouth and finally removed for ex vivo measurements. Specimens are exposed to the real oral environment. In situ testing creates a balance between the in vivo and in vitro conditions.

With the current trend in increasing life expectancy, wear of dental enamel is becoming an important issue as teeth are required to last longer. As a result, there is an increasing demand in dentistry for restoration materials more and more similar to the natural teeth, not only in their aesthetic characteristics, but also in their mechanical and chemical behavior. Excessive enamel wear results in poor masticatory function which in turn reduces one's quality of life and can deteriorate health. Human dental enamel, considered as the ideal material for its function, needs to be better understood from the material and engineering point of view, so as to provide a standard for the development of alternatives. Therefore, it has become necessary to study the tribological property of human teeth, aiming to reveal the wear mechanism of dental enamel and how significant the wear is so as to help the clinical treatment for teeth and develop new dental restorative materials to protect human teeth.

Dental terminologies

Anterior teeth:

The teeth in either arch which are towards the front of the mouth are termed anterior teeth. The anterior teeth include the incisors and canines in both the deciduous and permanent dentitions.

Posterior teeth

The teeth in either arch which are towards the back of the mouth are termed posterior teeth. Posterior teeth include the two molars in the deciduous dentition and both premolars and molars in the permanent dentition.

Midline

The imaginary vertical line which divides each arch, as well as the body, into approximately equal halves. The two approximately equal portions of each arch divided by the midline are termed quadrants, since there are four in the entire mouth. They are termed:

1) Upper
   a) Maxillary right.
   b) Maxillary left.

2) Lower
   a) Mandibular right.
   b) Mandibular left.

Teeth Surfaces:

Anterior Teeth Surfaces:

All anterior teeth display four surfaces and edge on their crowns namely

a) Mesial - The surface towards the midline.
b) Distal - The surface away from the midline.
c) Labial - The outside surface which is towards the lips.
d) Lingual – The inside surface which is towards the tongue. The lingual surface is sometimes called the palatal surface on the teeth of the maxillary arch only.
e) Incisal edge (or ridge) - The biting edge of the anterior teeth.

Posterior Teeth Surfaces:

All posterior teeth display five surfaces on their crowns. Mesial, distal and lingual can be defined according to surfaces of the anterior teeth.

a) **Buccal:** The outside surface which is toward the cheek, and corresponds to the labial surface of the anterior teeth. The term Facial surface can be used for either the labial surface of anterior teeth or the buccal surface of posterior teeth.

b) **Occlusal:** The chewing surface of the posterior teeth. Technically, occlusal represents the relationship between the maxillary and mandibular teeth when they approach each other, as occurs during mastication or at rest.

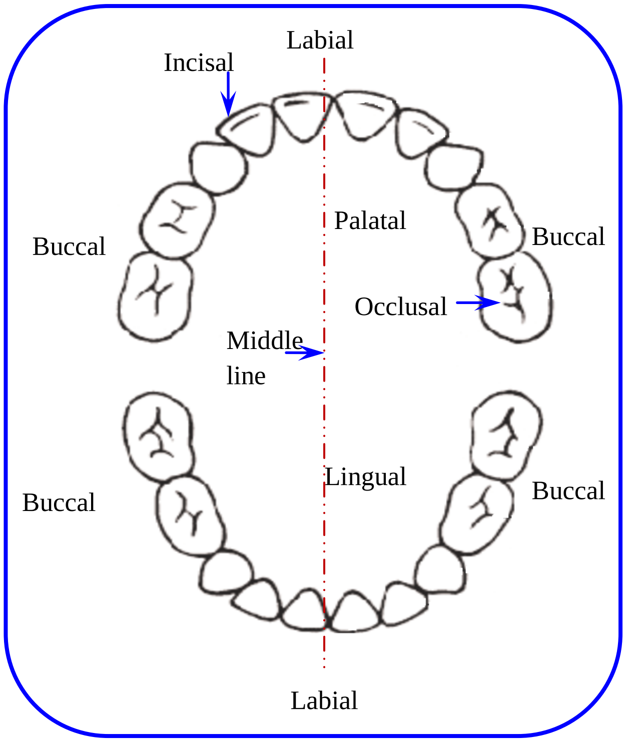

Figure 2.Schematic view of various teeth locations in the human mouth

Wear locations

Occlusal surfaces and incisal surfaces wear of teeth and restorations occur mainly during mastication, thegosis and bruxism. During mastication when coarse food is forced against the surfaces by the tongue, lips and cheeks, lingual and buccal surfaces wear occur. Tooth brushing, scaling, cleaning, etc causes prophylactic wear which generally affect the buccal, lingual, occlusal and approximal aspects of teeth. Occlusal surface shows the greatest wear followed by the cervical, lingual and buccal respectively [1]. Minimal wear at sites of proximal contacts are often neglected [2-3]. With respect to the tooth position, the first molar showed maximum wear followed by the canine and premolar, respectively. Regarding the tooth location, mandibular occlusal surfaces showed greater wear than maxillary occlusal surfaces in all age groups [4].

Tribomechanical and tribochemical wear of dental enamel

Tribochemical wear:
Wear due to inducing of mechanical forces and/or stresses are generally categorized as tribomechanical wear [5].

Two-body abrasion

Abrasion of surface due to another by direct contact is generally called two-body abrasion. At a microscopic level, no surfaces are perfectly smooth and therefore the teeth contact by the meeting of their surface asperities. Whenever there is severe surface contact during teeth movement, the tooth surface asperities fractures or deform. If both surfaces are 'brittle', there is fracture of the asperities. If one surface is 'soft', then the harder surface tries to plough into softer one, raising up 'chips' which eventually fracture away. In time all the asperities fracture and the cumulative effect of microscopic loss results in wear [6]. Two-body abrasion can easily be recognized as it always results in mating surfaces only.

Bruxism

The grinding of teeth and typically the clenching of the jaw is termed as bruxism. It is the common wear problem functional that occurs in most of the humans. In most people, bruxism is mild enough, so it won't considered as a health problem. Bruxism may be diurnal or nocturnal activity, but bruxism during sleep causes majority of health issues; it can even occur during short naps. Bruxism is one of the most common sleep disorders and the difference between the normal and bruxism teeth are shown in figure.3.

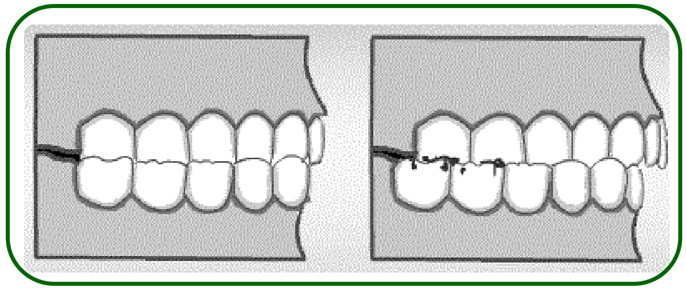

Figure 3.Difference between normal teeth (left) and bruxism (right)

Attrition

The wear caused by tooth-to-tooth or tooth-to-restoration or restoration-to-restoration friction is called attrition. It is the physiological wearing of dental hard tissues due to tooth-to-tooth contact without the intervention of foreign substances that causes localized wear at occlusal contacts. The loss of teeth structure by mechanical forces from opposing teeth generally accounts for attrition. Initially attrition affects the enamel and, if unchecked, may leed to the underlying dentin. Once past the enamel, attrition quickly destroys the softer dentin. Erosion is a very important contributing factor to the loss of tooth substance by attrition. The most common cause of attrition is bruxism. Para-functional habits, such as clenching and clicking the teeth together nervously, place greater amounts of forces on opposing teeth and begin to wear the teeth. Wear usually begins on the incisal or occlusal surfaces.

Three-body abrasion

Abrasion of surfaces due to an 'intervening slurry of abrasive particles' is called three-body abrasion. The pressure between the surfaces is transferred to the particles which then cut away the asperities. This type of wear occurs during mastication and is prevalent in patients who eat an abrasive diet such as graned bread. At initial stage, when the occlusal surfaces are separated by the food bolus, the abrasive particles act as slurry and abrade the whole enamel surface.

As a result of the shearing action of food on contact stress, they abrade the surface in the food shedding pathways. This process is very common in restorations with buccal or palatal extensions, as these take the main force of the masticatory slurry in the escape root of the groove. The process tends to hollow out the softer regions on a surface. In composite filling materials, the slurry preferentially abrades the softer polymer matrix, exposing the filler particles. During the final stages of mastication, the remaining slurry particles get trapped between the asperities, in pits and in surface grooves. These particles then scratch away the opposing surface [6]. If both surfaces are of similar morphology, then the abrasive particles may transfer between scratches and cause more or less equal loss of both surfaces.

Mastication (or chewing)

The process by which food is crushed and ground by teeth is called mastication. The food is positioned between the teeth for grinding by the cheek and tongue during the mastication process. In mastication, wear occurs as a combined action of food particles and occlusal surfaces (Fig.4). During mastication, the coefficient of friction is lower than that for enamel-to-enamel due to lubrication. The combination of reduced friction and reduced force (the occlusal force is distributed over a larger area) implies that three-body wear is less than two-body wear [7].

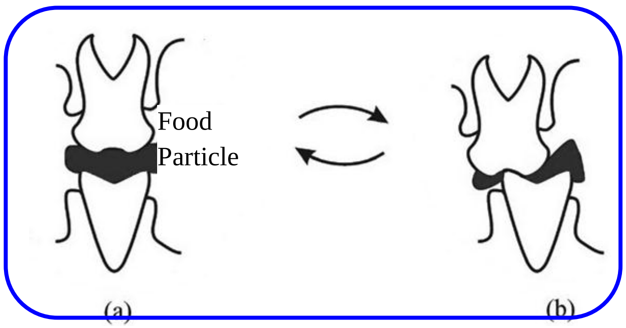

Figure 4.Schematic diagram of inter-oral movement of teeth during mastication (a) open phase mastication (b) closed phase mastication

Abrasion

Friction between a tooth or restoration and an exogenous agent (such as food bolus, toothpaste, toothpick and dental floss) causes the form of wear called abrasion. It is the loss of tooth structure by mechanical forces from a foreign element. If wear occurs due to friction from the food bolus, then the wear is termed masticatory abrasion.If the force begins at the cementoenamel junction, then progression of tooth loss can be rapid since enamel is very thin in this region of the tooth. Once past the enamel, abrasion quickly destroys the softer dentin and cementum structures. Toothbrushes, toothpicks, floss, and any dental appliances frequently set in and removed from the mouth are possible sources of this kind of tooth wear. Generally V-shaped appearances are observed when abrasion is caused by excessive pressure during tooth brushing. The teeth most commonly affected are premolars and canines.

Fatigue wear

When repeated contacts at the asperities eventually cause the material to fracture over a period a time, then the wear is termed fatigue wear. Friction occurs from surfaces riding up and over the asperities [7]. Some of the movement of the surface molecules is transferred to the subsurface causing rupture of intermolecular bonds and a zone of 'subsurface damage'. Eventually 'microcracks' form within the subsurface and, if these coalesce to the surface, then there can be loss of a fragment of material inducing fatigue wear [6].

Adhesive wear

Whenever there is a high attraction between surfaces such that 'cold welds' occur between the asperities, adhesive wear take place [6]. As the movement continues these micro-welds fracture, but not along their original line of fusion. In the end, the plates of one surface build up on the other surface. Generally this type of wear is normally associated with metals.

Abfraction

The loss of dental hard tissue due to inducing of stress is termed as abfraction. This kind of wear occurs most commonly in the cervical region of teeth.

Tribochemical wear

When the chemical aspects are more dominant dental enamel wear, the wear is called tribochemical wear. This process is caused when chemicals weaken the inter-molecular bonds of the surface and therefore potentiate the other wear processes. Erosion, attrition and three-body abrasion play significant role in tooth wear. Normally this effect is caused by acids, which may be extrinsic such as dietary acids or intrinsic resulting from gastric reflux. The dental enamel surface molecules are weakened by the acid and then rubbed away by the erosion, attrition and three-body abrasion [2].

Dental erosion due to chemical effects

Surface loss of either teeth or restorations caused by chemical or electrochemical action is called 'erosion'. Dental erosion, is the irreversible loss of tooth structure due to chemical dissolution by acids not of bacterial origin. Initially, erosion is found in the enamel and, if unchecked, that might proceed to the underlying dentin.

Effect of environment

The most common cause of erosion is by acidic foods and drinks. In general, foods and drinks with a pH below 5.0–5.7 trigger dental erosion effects. Numerous clinical and laboratory reports link erosion to excessive consumption of drinks. Those thought to pose a risk are soft drinks and fruit drinks, fruit juices such as orange juice (which contain citric acid) and carbonated drinks such as colas (where in citric and phosphoric acids cause erosion but not carbonic acid). The effect of attrition with citric acid is shown in Fig. 5. Additionally, wine has been shown to erode teeth,(pH of wine as low as 3.0–3.8). Other possible sources of erosive acids are from exposure to chlorinated swimming pool water, and regurgitation of gastric acids [6]. In general, pH of saliva is 7 (neutral) and pH of regurgitated gastric acid is 1.2. Acidic drinks contain a range of different acids, which can range from pH 1 to 6. An acidic diet could push the pH to even 3. Increased acidity in the mouth decreases both the hardness and the elastic modulus of enamel and eventually results in pathological wear of teeth.

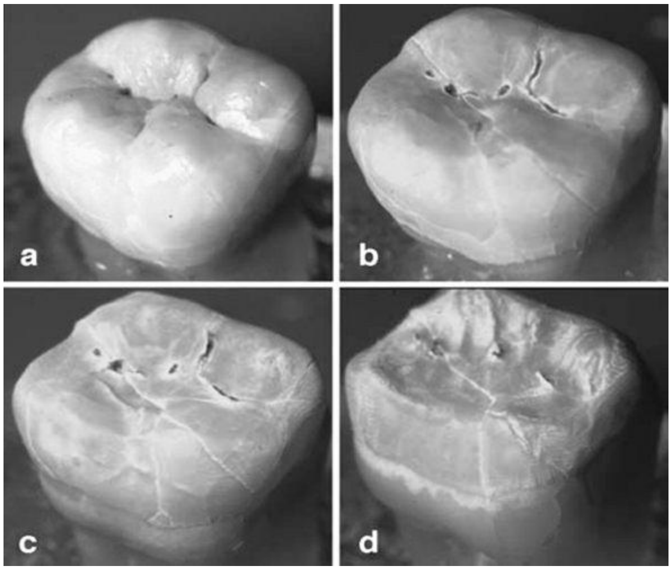

Figure 5.Stages of attrition due to continuous exposure of a human third molar to 10% citric acid, (a) unaffected tooth,(b) tissue loss after 4 hrs immersion time,(c) tissue loss after 8 hrs immersion time, and (d) tissue loss after 12 hrs immersion time.

Effect of enzyme

Just like acids, enzymes seem to have the potential to degrade the teeth during in vitro testing. de Gee et al. [8] used and esterase solution in the ACTA wear machine. Chemical cycling can induced a generalized swelling of the composite samples and a modified wear curve. These enzymes can be generated in saliva and by bacterial metabolism.

Oral Environment (Effect of saliva)

The oral environment plays an extremely important role in the tribologicalbehaviour of dental enamel. Saliva is the most important component of the human mouth chemistry. Saliva forms a boundary lubrication system and serves as a lubricant between enamel and mucosal tissues to help decrease the teeth wear. This also reduces the friction of oral mucosa and tongue surfaces in order to prevent lesions and make mastication easier. Saliva helps in cooling and lubricantion during the tooth wear processes.

Saliva is involved in the protection of the dental enamel surface against acid attack produced in plaque. Saliva also helps in remineralization of dental enamel by suppling calcium and phosphate ions. The protective properties of saliva are extremely significant for minimizing the corrosive effects of acids on teeth and restorations [9].
To analyze the various tribological properties of dental enamel various instruments are utilized and the same are listed in table.1. This table explains various tribological techniques and the probable measurable parameters of dental tribology.

Other Factors

Xerostomia

The medical term used for the subjective complaint of dry mouth which may or may not be associated with a lack of saliva is Xerostomia. It is also colloquially called pasties, cottonmouth, drooth, or doughmouth. It could be caused due to several diseases, treatments, and medication and exacerbated by smoking or drinking alcohol. The adverse effects of xerostomia are difficulty in talking and eating. As the saliva's remineralizing of enamel is no longer present, which could lead to halitosis and a dramatic rise in the number of cavities. This also can make the mucosa and periodontal tissue more vulnerable to infection.

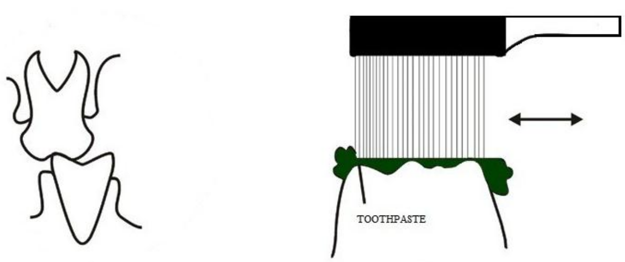

Figure 6.Schematic diagram of inter-oral movement of teeth during mastication (a) Thegosis/Bruxism (b) Tooth-brushing

Table 1.Measurable parameters with different tribologicaltechniques.

Techniques	Measured Parameter
Indentation	Elastic modulus, Surface hardness, Indentation creep
Nanoscratch	Adhesion failure of thin film and coating, Residual depth
Profilometry (Surfometry)	3D Profile
Microradiography	Mineral density
Pin-on-disc Tribometry	Coefficient of Friction, Friction Force, Wear Volume
Chemical analysis Atomic Absorption Spectroscopy (AAS) Spectrophotometry	 Calcium analysis Phosphate concentration
Microscopy Scanning Electron Microscopy (SEM) Field Emission Scanning Electron Microscopy (FESEM) Transmission Electron Microscopy (TEM) Atomic Force Microscopy (AFM)	High-resolution images of eroded enamel surfaces
Secondary Ion Mass Spectroscopy (SIMS)	Concentrations of positive or negative ions, Surface mapping, Depth profile of ions
Energy Dispersive Spectroscopy (EDS)	Element content in spectra
Quantitative Light-induced Fluorescence (QLF)	Loss in auto-fluorescence of enamel in the presence of demineralisation
White-light Interferometry	Surface roughness
Electron Back-Scatter Diffraction (EBSD)	Quantification of the microstructure with respect to grain size, grain morphology and texture
Focused Ion Beam (FIB) system	Microstructure
Surface analyser	Depth of wear tracks
Micro-Scale Abrasion Tester	Abrasion resistance
Ultimate Testing Machine (UTM)	Shear bond strengths

Effect of age

The permanent teeth at the young and middle age have better wear-resistance than the primary teeth as well as the permanent teeth at the old age, because of more hardness and perpendicular alignment of the enamel rods on their occlusal surfaces [10].

Effect of load and force

At initial contact, the force is distributed through the food bolus. The magnitude of the force experienced by the teeth depends on the food bolus stiffness. When the bolus is compressed, the mastication force gets distributed over the bolus surface which is in contact with the maxillary and mandibular teeth. The force per unit area decreases as the contact surface increases. The gliding phase, which does not always occur during mastication, starts with tooth-to-tooth contact (complete penetration of the food bolus) and continues until the jaw begins to open (start of the preparatory phase). At contact, the mastication force is concentrated in the occlusal contact area. Both two- and three-body wear mechanisms are occurring as a result of the tooth-to-tooth contact and the presence of the food bolus [7].

Effect of depth

Erosion had a significant influence on subsequent friction and wear behaviors of the dental enamel, and the influence depended strongly on the location of the dental enamel. Both the friction coefficient and wear loss of the eroded surface in the interior dental enamel increased more significantly than those in the outer dental enamel [11].

Effect of toothbrush

Wear occurs on the teeth cervical regions are due to tooth brushing. Cervical wear normally referred to as toothbrush abrasion [7].

Conclusion

The combination of tribomechanical and tribochemical reactions on the teeth is one of the important dental enamel wear mechanisms. The tribologicalbehaviour of dental enamel is basically a clinical problem in dentistry. Few research works are focused on the effect of bioactivity and biomechanics of human teeth on their tribologicalbehaviour. The lack of knowledge of wear mechanisms is one of the main obstacles hindering the understanding of tribologicalbehaviour of dental enamel and thereby impeding the development of dental materials. It is evident that collaboration among clinical dentists, materials researchers, palaeontologists and tribologists is helping in advancement of this research area of strong current interest.Future experimentations should aim at an understanding of the fundamentals which underly wear mechanisms. The development of new dental materials can be a great aid in elimination of various problems related to the wear of dental enamel such as poor mastication and various treatment problems.

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