TOPICAL REVIEW

Tribology of dental materials: a review

Z R Zhou\(^1\) and J Zheng

Tribology Research Institute, Key Laboratory for Advanced Technology of Materials of Ministry of Education, Southwest Jiaotong University, Chengdu 610031, People’s Republic of China

E-mail: zrzhou@home.swjtu.edu.cn (Z R Zhou)

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Abstract

The application of tribology in dentistry is a growing and rapidly expanding field. Intensive research has been conducted to develop an understanding of dental tribology for successful design and selection of artificial dental materials. In this paper, the anatomy and function of human teeth is presented in brief, three types of current artificial dental materials are summarized, and their advantages and disadvantages, as well as typical clinical applications, are compared based on the literature. Possible tribological damage of tooth structure, which is induced by complex interfacial motion, and friction-wear test methods are reported. According to results obtained by the authors and from the literature, the main progress in the area of dental tribology on both natural teeth and artificial dental materials is reviewed. Problems and challenges are discussed and future research directions for dental tribology are recommended.

(Some figures in this article are in colour only in the electronic version)

1. Introduction

Human teeth are not only an important masticatory organ but are also closely associated with both pronunciation and the facial aesthetics of human beings. Beyond all doubt, teeth play an extremely significant role in our daily life. With ageing, various pathological factors and traumas, tooth lesions such as caries, partial or overall tooth tissue loss will occur unavoidably. As a result, artificial dental materials have gradually been developed and used to restore and treat the lesions of human teeth. Nowadays, metals and alloys, ceramics and composite materials are most widely used for dental restorations and implants.

Tribology is the science of the mechanisms of friction, lubrication and wear of interacting surfaces that are in relative motion. By definition, friction is the rubbing of one object or surface against another, whilst wear is a process that occurs whenever a surface is exposed to another surface or to chemically active substances [1], which can result in a progressive removal of material from surfaces through mechanical or chemical action. In general, oral biomechanical functions can result in some tribological movement of teeth, restorations and implants occurring in the mouth [2–5]. For example, during chewing food, the teeth, together with any restorations, have to move in contact with one another, and then friction and wear occur generally with the lubrication of saliva or food slurry [5]. It has been accepted that tooth wear is a clinical problem that is becoming increasingly important in ageing populations. Understanding of dental friction and wear behaviour would help the clinical management of tooth wear, which involves the replacement of missing tooth tissue with dental materials, together with an attempt to minimize the causal factors and develop new dental materials [5]. In addition, tooth wear proceeds in a regular progressive manner, particularly in the molar teeth, endowing it with potential as a method of estimating the evolution, age, diet and health changes of ancient humans in archaeology [6–9]. Therefore tribology of dental materials has developed and is paid increasing attention by various researchers.

Attention to the issue of dental friction and wear paid by clinicians can be traced back hundreds of years [10]. In 1778, Hunter wrote one of the first textbooks of dentistry [10], in which he explained that there are three modes of tooth wear in the mouth: attrition, abrasion and erosion. With the rapid development of material science, more and more dental practitioners and engineering researchers have focused on the tribological behaviour of human teeth and artificial dental materials.

Author to whom any correspondence should be addressed.

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materials since the 1960s. Howden (1971) first reported a special pattern of surface loss caused by the movement of acid gastric juice in patients with gastroesophageal reflux disease (GERD) [11]. Cvar and Ryge (1971) devised a scoring system to assess the wear of dental materials, which is known as the United States Public Health Services (USPHS) system [12]. Subsequently Smith and Knight (1984) described a categorization index which is most commonly used for the wear assessment of human teeth [13]. Based on replica laboratory models, Leinfelder (1986) developed a popular indirect method for measuring wear in dentistry [14]. More recently, Grippo coined a relatively new term ‘abfraction’ to define the loss of dental tissues caused by stress-induced noncarious lesions [15]. In addition, in order to simulate and investigate the tribological behaviour of dental materials systematically, several research centres developed wear testing devices and methods of different degrees of complexity, which improved dental tribology to a considerable degree. Notable are the relative dentine abrasion (RDA) method (Hefferren 1976) [16], the ‘artificial mouth’ conception (Delong and Douglas 1983) [17] and the Oregon Health Science University Oral Wear Simulator (Condon and Ferracane 1996) [18]. In 1999 the International Standard Organization (ISO) published a technical specification on ‘Wear by tooth brushing’, followed in 2001 by another technical specification called ‘Wear by two- and/or three-body contact’ [19].

Based on published papers since 1960, a wide ranging literature search for key words (human teeth, dental materials, friction and wear, attrition, abrasion, erosion and abfraction) was examined and some useful information on dental tribology was estimated, as shown in tables 1 and 2. It can be seen that increasing attention is paid to tribological behaviour of dental materials. In addition, with increased life expectancy and the increased consumption of soft drinks, tribological problems of human teeth, especially chemical effects, have been frequently investigated since the 1990s.

In this paper, concepts of dental wear and relevant factors including microstructural, physical, chemical and clinical factors are presented based on research published in English. The main investigations and progress of dental tribology obtained by the authors and from the literature are reported. The main aim of the overview is to achieve better understanding of the associated mechanisms, to conduct successful design and suitable selection for dental materials and to recommend and identify major activities of dental tribology based on current trends in research activities and technological opportunities and needs.

Table 1. Statistics of papers concerning tribology of dental materials.

<table>
<thead>
<tr>
<th>Period</th>
<th>Papers on human teeth</th>
<th>Papers on dental materials</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Attrition</td>
<td>Abrasion</td>
</tr>
<tr>
<td>1960–1969</td>
<td>5</td>
<td>8</td>
</tr>
<tr>
<td>1970–1979</td>
<td>17</td>
<td>38</td>
</tr>
<tr>
<td>1980–1989</td>
<td>40</td>
<td>19</td>
</tr>
<tr>
<td>1990–1999</td>
<td>31</td>
<td>61</td>
</tr>
<tr>
<td>2000–present</td>
<td>54</td>
<td>38</td>
</tr>
</tbody>
</table>

Table 2. The number of research papers versus time and dental materials.

<table>
<thead>
<tr>
<th>Period</th>
<th>Paper sum</th>
<th>Papers on human teeth</th>
<th>Papers on artificial materials</th>
</tr>
</thead>
<tbody>
<tr>
<td>1960–1969</td>
<td>27</td>
<td>≥25 (92.6%)</td>
<td>≥2 (7.4%)</td>
</tr>
<tr>
<td>1970–1979</td>
<td>95</td>
<td>≥78 (82.1%)</td>
<td>≥17 (17.9%)</td>
</tr>
<tr>
<td>1980–1989</td>
<td>189</td>
<td>≥103 (54.5%)</td>
<td>≥86 (45.5%)</td>
</tr>
<tr>
<td>1990–1999</td>
<td>416</td>
<td>≥235 (56.5%)</td>
<td>≥181 (43.5%)</td>
</tr>
<tr>
<td>2000–present</td>
<td>318</td>
<td>≥201 (63.2%)</td>
<td>≥117 (36.8%)</td>
</tr>
</tbody>
</table>

![Figure 1. Human tooth structure. (Reprinted with permission from [6]. Copyright 2006, Professional Engineering Publishing.)](image)

2. Dental materials

Normally dental materials can be classified as natural materials, namely human teeth, and artificial materials which are mainly used for dental restorations and implants.

2.1. Anatomy and function of human teeth

Human teeth possess a unique structure [20] composed of enamel, dentine–enamel junction, dentine and pulp (shown in figure 1), and each zone is anisotropic. The two most important elements of a tooth from the tribological perspective are the outer enamel and the inner dentine, whose properties [21] are given in table 3.

Enamel is the hardest tissue in the human body, while dentine is usually considered to be elastic and soft. Initially the enamel of a thickness of 2–3 mm is exposed to the occlusal surface and chemical environment within the mouth. Enamel
is composed of 92–96% inorganic substances, 1–2% organic materials and 3–4% water by weight [22]. Most of the inorganic substances are hydroxyapatite that is contained in the basic structural unit of enamel, the rod or prism. These prisms align and run approximately perpendicular from the dentine–enamel junction towards the tooth surface [23–25]. The high hardness of enamel is attributed to its high mineral content, while its brittle property is due to its high elastic modulus and low tensile strength. Investigations have shown that mechanical properties of enamel vary with location on a tooth, local chemistry and prism orientation [25–27]. Finite element stress analysis results showed that the enamel absorbs most of the applied chewing load during mastication due to its greater stiffness as compared with dentine, and therefore masticatory forces tend to flow around the enamel cap to the root dentine [28].

Dentine is a hydrated biological composite composed of 70% inorganic material, 18% organic matrix and 12% water by weight, and its properties and structural components vary with location [29]. The structural composition of dentine includes oriented tubules surrounded by a highly mineralized cuff of peritubular dentine and an intertubular matrix consisting of type I collagen fibrils reinforced with apatite [30]. Between enamel and dentine, the dentine–enamel junction, a biological interface, may dissipate stresses inhibiting further crack propagation [30, 31]. The dentine–enamel junction has high fracture toughness and, along with the more resilient underlying dentine, supports the integrity of enamel by preventing its fracture during function [25, 26]. Another possible mechanical function of the soft dentine beneath the dentine–enamel junction may be related to the ability of a whole tooth to resist impact forces which often occur when the tooth is working [32].

The major functions of teeth, together with any restorations and implants, are associated with speech, breathing, taste, chewing and supporting bone, soft tissues and the muscles of mastication. Initially a human has 20 primary (or baby) teeth [33]. These are eventually replaced, during childhood, with 32 permanent (or adult) teeth. To allow the more resilient underlying dentine, supports the integrity of enamel by preventing its fracture during function [25, 26]. Another possible mechanical function of the soft dentine beneath the dentine–enamel junction may be related to the ability of a whole tooth to resist impact forces which often occur when the tooth is working [32].

2.2. Artificial materials

Due to various pathological factors and trauma, some patients have always had to suffer tooth lesions. Therefore, various artificial materials have been developed and used in dentistry to replace missing teeth or tooth tissue and uneaesthetic, but otherwise healthy, tooth enamel. Recreating function and aesthetics are the two practical goals of such treatments. Although the field of dental materials is highly catholic in nature [34], for selecting a material for dental application, it is necessary to remember that the choice of material depends on a number of factors such as corrosion behaviour, mechanical properties including strength and wear resistance, cost, availability, biocompatibility and aesthetic values. Normally dental materials may be grouped into three categories: metals and their alloys, ceramics, polymers and composites [34–40]. Different forming/processing methods and main clinical applications are shown in table 4.

2.2.1. Metals and alloys. Metals have been used as dental materials for over a century [34]. Generally, most metals are strong enough to withstand the maximum possible oral forces and have been found to be competitive among dental materials. Therefore, metallic restorations and particularly those made from precious metal alloys retain a particular role in managing the dental needs of patients. A general classification of dental metallic materials, their class and broad application areas are listed in table 4.

Currently the clinical use of metals and their alloys in dentistry has been significantly confined by two major problems: (1) the colour being very different from that of tooth tissue and (2) the irritability or cytotoxicity of a metal to cells. For example, as one of the most popular direct restorative materials, amalgam has been successfully used by the dental profession for approximately 100 years [41]. The major attraction of this material is the proven longevity in clinical service and ease of clinical use. However, the potential toxicity of mercury in amalgam has increasingly aroused safety concerns for both patients and dental personnel. Furthermore,
Table 4. Current artificial dental materials.

<table>
<thead>
<tr>
<th>Material type</th>
<th>Forming/processing method</th>
<th>Typical application</th>
</tr>
</thead>
<tbody>
<tr>
<td>Metals and their alloys</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Amalgam</td>
<td>Low copper</td>
<td>Posterior restoration</td>
</tr>
<tr>
<td></td>
<td>High copper</td>
<td>Posterior restoration</td>
</tr>
<tr>
<td>Noble alloys</td>
<td>Gold (non-heat-treatable)</td>
<td>Restoration of single teeth</td>
</tr>
<tr>
<td></td>
<td>Gold (heat-treatable)</td>
<td>Fixed bridges</td>
</tr>
<tr>
<td></td>
<td>Palladium–silver</td>
<td>Restoration of single teeth</td>
</tr>
<tr>
<td></td>
<td>Nickel</td>
<td>Restoration of single and missing teeth, partial denture frameworks</td>
</tr>
<tr>
<td></td>
<td>Cobalt</td>
<td>Denture framework and implants</td>
</tr>
<tr>
<td></td>
<td>Partial</td>
<td>Orthodontic appliances and endodontic instruments</td>
</tr>
<tr>
<td></td>
<td>Iron</td>
<td>Implants</td>
</tr>
<tr>
<td></td>
<td>Titanium</td>
<td></td>
</tr>
<tr>
<td>Base alloys</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Ceramics</td>
<td>Feldspathic porcelain</td>
<td>Condensed and sintered</td>
</tr>
<tr>
<td></td>
<td>Pressure moulded</td>
<td>Veneers, inlays, anterior crowns</td>
</tr>
<tr>
<td></td>
<td>Leucite-reinforced porcelain</td>
<td>Pressure moulded</td>
</tr>
<tr>
<td></td>
<td>Silicate-reinforced porcelain</td>
<td>Pressure moulded</td>
</tr>
<tr>
<td></td>
<td>Al₂O₃-reinforced porcelain</td>
<td>Condensed and sintered</td>
</tr>
<tr>
<td></td>
<td>Alumina core ceramic</td>
<td>Anterior and posterior crowns, anterior bridges</td>
</tr>
<tr>
<td></td>
<td>Glass-infiltrated core ceramic</td>
<td>Slip cast, sintered and infiltrated with glass</td>
</tr>
<tr>
<td></td>
<td>Machinable ceramic</td>
<td>Anterior and posterior crowns, anterior bridges</td>
</tr>
<tr>
<td></td>
<td>Zirconia core ceramic</td>
<td>Anterior and posterior crowns, anterior bridges</td>
</tr>
<tr>
<td>Unfilled polymers and composite</td>
<td>Lightly filled or unfilled composite</td>
<td>Homogeneous microfill</td>
</tr>
<tr>
<td></td>
<td>Macrolit composite</td>
<td>Restorations and crowns of anterior and posterior teeth, inlays, onlays, veneer</td>
</tr>
<tr>
<td></td>
<td>Microfill composite</td>
<td></td>
</tr>
<tr>
<td>Hybrid composite</td>
<td>Heterogeneous microfill</td>
<td>Obturation materials for dental caries</td>
</tr>
<tr>
<td></td>
<td>Composed 70–80% glass fillers and 20–30% nanofillers polyacid-modified</td>
<td>Dental post, orthodontic archwires and brackets</td>
</tr>
<tr>
<td>Compomers fibrous composite</td>
<td>Carbon fibres for the core and glass fibres for sheathing</td>
<td></td>
</tr>
<tr>
<td>Glass ionomer</td>
<td>Resin-modified</td>
<td>Adhesives, obturation materials for dental caries</td>
</tr>
<tr>
<td></td>
<td>Metal-reinforced</td>
<td>Adhesives, obturation materials for dental caries</td>
</tr>
</tbody>
</table>

its metal-like appearance does not meet current aesthetic demands and it requires a more complex cavity preparation to compensate for its lack of adhesion to tooth tissues [42]. Therefore, amalgam has been gradually replaced by resin-based composites which have excellent aesthetic appearance and can be bonded to the tooth structure easily.

Given these drawbacks, together with the material and labour costs associated with metal substrate fabrication, metals and their alloys have increasingly been limited to orthodontic appliances and dental implants. However, the dental literature indicates that among direct and indirect restorations, gold-based casting alloys are considered the most ideal dental material especially for posterior teeth because they are wear resistant and cause minimal wear of opposing enamel [34, 43, 44].

2.2.2. Ceramics. Ceramics are used as an alternative to gold-based casting alloys because of their greater aesthetic potential. Ceramics were first used successfully in dentistry in 1774 [45–47], and many efforts were made therefore to improve their aesthetics over the next 190 years. In the early 1960s [45], dental ceramics were first formulated for routine fusion onto metal substructures, significantly broadening the use of ceramics and then increasing the demand for dental ceramic materials. Subsequently, with the employment of dispersion strengthening, alumino-silicate porcelain, a ceramic material suitable for all-ceramic substructures, was created and used [44, 45]. A wide variety of dental ceramics is currently available [35].

Aesthetics is an obvious attribute of ceramics and, along with biocompatibility, durability and etchability (ability to be bonded), is the primary reason why dentists often choose ceramics over other materials. However, two major problems arise in their dental usage: (1) the potential for catastrophic brittle fracture and (2) the potential to abrade the opposing natural teeth or restorations [47]. Many studies have shown that enamel wear against dental ceramics is substantially greater than against gold [43, 44, 48, 49]. In addition, dental
ceramics with high strength and toughness are not generally aesthetic [35].

2.2.3. Composites. Resin-based composite materials are widely used in restorative dentistry nowadays (table 4). Being introduced in the mid-1960s [40], the first composite restoratives were mainly unfilled resins (called polymers) and their use was confined to dental adhesives and direct restorative materials in anterior teeth due to insufficient material properties [5, 34, 37]. In order to improve strength, hardness and wear resistance and to reduce polymerization shrinkage, tooth coloured resin matrix composites containing filler particles were developed and then used for restoring posterior stress-bearing cavities as a viable alternative to amalgam approximately 30 years ago [34, 50–52]. Composite resin denture teeth were developed in the 1980s [51]. Due to the major influence of the fillers on their physical properties [53, 54], the classification of dental filling composites is based on the type of filler used and the particle size thereof [36]. In general two types of composites are in the market, i.e. microfill and hybrid composite filler materials. Polycarboxyl-modified composite resins, known trivially as composers, were also introduced to the dental profession in the early 1990s and were used for restoring teeth damaged by dental caries [39]. With biocompatible fibres and matrix systems, fibrous composites found application as biomaterials, and a number of fibrous composite materials for dental applications have been developed [38].

The use of resin-based composites in restorative dentistry has increased significantly in recent years. These materials feature the advantage of good aesthetics for dental restorations and are able to bond to tooth structures easily by the acid-etch technique. However, excessive wear of composite restorations is still a major problem encountered in their use in stress-bearing applications although significant improvements have been made [42, 55, 56]. Higher wear rates than either metals or ceramics have limited clinical longevity of dental composites.

3. Tribology related to human teeth

3.1. Oral environment

The oral environment plays an extremely important role in the tribological behaviour of both human teeth and artificial teeth. Saliva is the most important component of the chemistry of the human mouth. All solid substrata as well as mucosa membranes exposed to the oral environment are covered by a layer of absorbed salivary proteins, the acquired pellicle [57], whose formation starts within seconds on any solid surface exposed to the oral environment. The physiological role of saliva in the oral cavity is manifold. An important function of saliva is to form a boundary lubrication system and serve as a lubricant between hard (enamel) and soft (mucosal) tissues [58] to help decrease the wear of teeth and reduce the friction of oral mucosa and tongue surfaces to prevent lesions and make swallowing easier, which is of crucial importance to maintain functions such as mastication, deglutition and the faculty of speech. Results of in vitro wear tests, carried out by the authors [59], have shown that artificial saliva, a simulation of real saliva, can have both cooling and lubricant effects during the toothwear process, and the risk of tooth texture burn may be significantly reduced under the artificial saliva condition compared with the dry condition. The lubricating mechanism of saliva is presumably based on a full separation of the sliding surfaces by salivary films [58], which can be maintained within the clinical occlusal forces in the mouth. In addition, the presence of the lubricant influences how much kinetic energy is absorbed by the shearing of the inter-molecular bonds in salivary films and how much is transferred to the teeth [60].

In general saliva is pH 7 (neutral); however, corrosive agents such as acids can be introduced into the mouth [33]. The mouth of a person with a particularly acidic diet could be at pH 3, and regurgitated gastric acid is pH 1.2. Acidic drinks contain a range of different acids, which can range from pH 1 to pH 6. Increased acidity in the mouth has been clearly shown to initially decrease both the hardness and the elastic modulus of enamel [61, 62] and then result in pathological wear of teeth [63, 64]. Therefore, the role of saliva in the mouth is also thought to involve both the protection of the enamel surface against acid attack because it is a buffer to acids produced in plaque and the provision of a matrix for remineralization [65, 66] because it supplies calcium and phosphate ions to remineralize enamel. There has been a worldwide monumental increase in the consumption of soft drinks, fruit juices and sport drinks, and signs suggest a similar increase in the future, rather than slowing down [67]. This implies that exposure of teeth to an acid environment is increasing. The presence of even a minute film of salivary pellicle (thickness of 100–500 nm) can protect the exposed materials’ surface from the acid, thereby preventing its removal during the next friction phase. So, the protective properties of saliva are extremely significant for minimizing the corrosive effects of acids on teeth and restorations.

3.2. Biomechanics

Mastication is the most important function of teeth. It has been widely accepted that wear of dental materials in the mouth results mainly from chewing cycles. Therefore, it is important to understand the biomechanics of mastication. Mastication is the action of chewing food, which is a complex and compound process [68]. Mastication involves two stages: open phase and closed phase [3]. During the first stage the teeth are brought by the jaw from the open position to a position of contacting the food bolus. Normally, no occlusal forces are involved in this phase (sticky foods represent an exception), and the abrasive particles are suspended and free to move in the food slurry. The second stage starts when the teeth first contact the food bolus and continues until the jaw begins to open. During this phase occlusal loads are applied and distributed through the food bolus so that the food particles are trapped between the opposing surfaces of the teeth (especially upper and lower molars) and dragged across them. Therefore, the food bolus is compressed and crushed, and then grinding occurs either with tooth–food–tooth (or indirect) or...
at the end of the chewing cycle [73, 74]. The magnitude of the posteriorly to reach around 500 N at the molars. at the incisors is 100 N, gradually increasing as one moves age and muscle build. Typically, the maximum biting load In addition, the maximum biting forces vary according to sex, there is a great variety of foods, various forces can be expected. As a result, tooth motion of this type is usually undetected and neglected.

3.3. Wear mode

As mentioned above, friction and wear can result from direct contact between teeth and from any abrasive particles or devices sandwiched between them during mastication, thegosis, bruxism, toothbrushing and other functions. Tooth surface loss caused by wear is a common clinical problem, with various epidemiologic studies suggesting prevalence estimates of up to 97%, with around 7% of the population showing pathological wear requiring treatment [78].

The main categories of wear that contribute to the destruction of natural teeth and artificial materials are classified as follows [2]: physiological wear (vital life functions), pathological wear (disease and abnormal conditions), prophylactic wear (preventive conditions) and finishing procedure wear. An overview is provided in table 6.

Physiological wear, inevitable due to the mastication function [3–5, 79], is surface degradation that results in progressive but very slow loss of the convexity of tooth cusps, which manifests as a flattening of both cusp tips on the posterior teeth and incisal edges on the anterior teeth for mammalian.

Compared with physiological wear, some pathological factors can cause excessive wear of teeth and restorations [2, 3]. Clinical reports show that wear usually becomes significantly severe due to erosion, bruxism, xerostomia, and so on. Pathological wear also can be caused by detrimental oral habits [3, 80], which generally include chewing tobacco, biting on hard objects such as pens, pencils or pipe stems, opening hair pins with teeth and biting fingernails. In addition, occupational
Dental terminology

Three terms ‘attrition’, ‘abrasion’ and ‘erosion’ have been widely used in dentistry to describe the wear of natural teeth and artificial materials since 1778 [3–6, 10, 33, 69, 80]. Recently, abfraction has also been used by some researchers. Most of the terms are peculiar to dentistry and have either little or no meaning in engineering tribology.

Attrition. The wear caused by tooth-to-tooth or tooth-to-restoration or restoration-to-restoration friction is called ‘attrition’, which is often regarded as a result of two-body interactions.

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’, which is usually regarded as a result of three-body interactions. If teeth are worn by friction from the food bolus, this wear is termed ‘masticatory abrasion’ [80].

Erosion. Surface loss of either teeth or restorations caused by chemical or electrochemical action is widely called ‘erosion’ in the dental literature.

It is worth noting that the term ‘erosion’ has a remarkably different meaning between dentistry and engineering tribology. Normally, in dentistry, erosion is used to describe surface loss of dental materials resulting from the solution by acids

<table>
<thead>
<tr>
<th>Inter-oral wear event</th>
<th>Type of wear</th>
<th>Lubricant</th>
<th>Substrate</th>
<th>Opponent</th>
<th>Abrasive</th>
</tr>
</thead>
<tbody>
<tr>
<td>Physiological causes of wear</td>
<td>Three-body</td>
<td>Saliva/food</td>
<td>Tooth/restoration</td>
<td>Tooth/restoration</td>
<td>—</td>
</tr>
<tr>
<td>Direct contact wear</td>
<td>Two-body</td>
<td>Saliva</td>
<td>Tooth/restoration</td>
<td>Tooth/restoration</td>
<td>—</td>
</tr>
<tr>
<td>Sliding contact</td>
<td>Two-body</td>
<td>Saliva</td>
<td>Tooth/restoration</td>
<td>Tooth/restoration</td>
<td>—</td>
</tr>
<tr>
<td>Pathological causes of wear</td>
<td>Three-body</td>
<td>Saliva</td>
<td>Tooth/restoration</td>
<td>Tooth/restoration</td>
<td>—</td>
</tr>
<tr>
<td>Bruxism</td>
<td>Two-body</td>
<td>Saliva</td>
<td>Tooth/restoration</td>
<td>Tooth/restoration</td>
<td>—</td>
</tr>
<tr>
<td>Xerostomia</td>
<td>Two-body</td>
<td>—</td>
<td>Tooth/restoration</td>
<td>Tooth/restoration</td>
<td>—</td>
</tr>
<tr>
<td>Erosion</td>
<td>—</td>
<td>Saliva</td>
<td>Tooth/restoration</td>
<td>Tooth/restoration</td>
<td>—</td>
</tr>
<tr>
<td>Unusual habits</td>
<td>Two-body</td>
<td>Saliva</td>
<td>Tooth/restoration</td>
<td>Foreign body</td>
<td>—</td>
</tr>
<tr>
<td>Prophylactic causes of wear</td>
<td>Three-body</td>
<td>Water</td>
<td>Tooth/restoration</td>
<td>Toothbrush</td>
<td>Dentifrice</td>
</tr>
<tr>
<td>Toothbrush and dentifrice</td>
<td>Three-body</td>
<td>Water</td>
<td>Tooth/restoration</td>
<td>Polishing cup</td>
<td>Pumice</td>
</tr>
<tr>
<td>Prophylactic pastes</td>
<td>Three-body</td>
<td>Water</td>
<td>Tooth/restoration</td>
<td>Instrument</td>
<td>—</td>
</tr>
<tr>
<td>Scaling and cleaning</td>
<td>Two-body</td>
<td>Water</td>
<td>Tooth/restoration</td>
<td>Bur</td>
<td>—</td>
</tr>
<tr>
<td>Cutting, finishing, polishing</td>
<td>Two-body</td>
<td>Water</td>
<td>Tooth/restoration</td>
<td>Bur</td>
<td>—</td>
</tr>
<tr>
<td>Cutting burs/diamonds</td>
<td>Three-body</td>
<td>Water</td>
<td>Tooth/restoration</td>
<td>Polishing cup</td>
<td>Abrasive slurry</td>
</tr>
<tr>
<td>Finishing burs</td>
<td>Two-body</td>
<td>Water</td>
<td>Tooth/restoration</td>
<td>—</td>
<td>—</td>
</tr>
<tr>
<td>Polishing pastes</td>
<td>Three-body</td>
<td>Water</td>
<td>Tooth/restoration</td>
<td>—</td>
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</tr>
</tbody>
</table>

Figure 6. Contact and contact-free areas. (Reprinted with permission from [69]. Copyright 2006, Elsevier.)

which are not of bacterial origin [5]. However, in engineering, ‘erosion’, as defined by the American Society for Testing and Materials Committee on Standards [88], is ‘the progressive loss of a material from a solid surface due to mechanical interaction between that surface and a fluid, a multicomponent fluid, impinging liquid or solid particles’, whilst the wear caused by the interaction of chemical degradation and movement of the surfaces is termed ‘corrosion’ [5]. By definition, erosion can be observed as a shoreline being eroded by the pounding surf or bridge supports being eroded by the rush of river waters around them, while no such powerful flow of fluids occurs in the human mouth to affect teeth. Therefore, more recently Grippo et al [80] pointed out that the term ‘erosion’ should be deleted from the dental lexicon and supplanted by the term ‘corrosion’ to denote chemical dissolution of teeth. It should be noted that the term ‘erosion’ in this paper only has its meaning in dentistry, that is, it refers to the surface loss of teeth or restorations caused by chemical dissolution rather than mechanical attack.

Abfraction. Abfraction is used to term stress-induced dental hard tissue loss, which occurs most commonly in the cervical region of teeth.

3.6. Clinical significance

Friction between the surfaces of teeth has been implicated to be necessary for oral functions, especially mastication [69]. Moreover, tooth wear may be regarded as having significant clinical consequences both aesthetically and functionally [3, 69, 79], the presence of which can improve masticatory efficiency and reduce the susceptibility of dentition to disease and malocclusion. As teeth wear, they continue to erupt, which led to the concept of ‘wearing into occlusion’ [69]. In dentistry, occlusion is known as the alignment of the teeth of the upper and lower jaws when brought together.

However, if wear is not controlled, the enamel will eventually be breached, causing superficial dentine to be exposed in the mouth [69]. Once breached, both the enamel and the exposed dentine wear at accelerated rates. Excessive wear of teeth can result in disastrous consequences such as unacceptable damage to the occluding surfaces, alteration of the functional path of masticatory movement, dentine hypersensitivity and even pulpal pathology. It may also destroy the anterior tooth structure that is essential to the acceptable anterior guidance function or aesthetics, causing increased horizontal stresses on the masticatory system and associated temporomandibular joint remodelling [4, 89, 90]. Moreover, the wear of proximal surfaces may lead to loss of the proximal contact area and thereby result in food impaction and subsequent loss of bone and periodontal attachment.

In addition, excessive wear has been shown to be a major problem encountered in the use of artificial dental materials, especially composite restorations, in stress-bearing applications. It may lead to premature failure and replacement of the restoration and implant [19, 87].

4. Testing methods

The literature survey shows that nowadays three kinds of methods have been used by various workers to study tribological behaviour of dental materials: in vivo observation
and measurement, *in vitro* laboratory simulation and *in situ* testing. *In vivo* observation and measurement is generally used by clinicians to observe and evaluate clinical manifestations of the wear of teeth and restorations in the mouth, whilst *in vitro* laboratory simulation is usually used by materials and tribology researchers to explore wear mechanisms of natural teeth and artificial materials. More recently, the *in situ* method has been introduced and developed to investigate dental tribology [82].

### 4.1. *In vivo* observation and measurement

*In vivo* methods are widely used in clinics. Clinical observation of the loss of dental hard tissue caused by wear can be traced back hundreds of years [10].

As mentioned above, both oral environment and biomechanics are very complex; tooth wear is therefore multifactorial in the mouth and physical and chemical processes interact. So, it has been accepted that the main advantage of *in vivo* methods is to obtain and examine tribological behaviour of teeth and restorations resulting from a real oral environment and biomechanics [3, 33, 52, 68, 69, 84]. However, *in vivo* methods have some disadvantages which limit their contribution to the tribology of dental materials. Firstly, it is impossible for *in vivo* methods to isolate and study individual wear processes, including attrition, abrasion and erosion. Although some measures can be taken to unify the testing conditions among the subjects to some extent, it is still evident that subjectivity is indeed a variable, which leads to problems in interpreting results [3, 84]. Secondly, the lack of control over important variables that may influence tribological behaviour (such as chewing force, dietary intake or environment factors) significantly limits their contribution to tribology of dental materials, especially wear mechanisms [91]. In addition, wear processes clearly cannot be accelerated *in vivo* and research work is dependent on volunteer compliance [69]; as a result, *in vivo* studies are both time-consuming and expensive.

It is noted that sufficiently sensitive methods of wear measurement are also a problem for most *in vivo* studies. In general, the systems for wear measurement in dentistry use either clinical categorization systems or indirect methods which measure wear on replica laboratory models [3]. For toothwear the most commonly used categorization index is that described by Smith and Knight which separately scores the wear of the tooth surfaces according to the amount of exposed dentine [13]. For restorative materials probably the most universally used scoring system is the one devised by Cvar and Ryge for the United States Public Health Service (USPHS), in which the wear of restorations was categorized as ‘alpha’, ‘bravo’ and ‘Charlie’ [12]. An ‘alpha’ score means there is no wear, ‘bravo’ means visible wear; however, it is still clinically acceptable, and ‘Charlie’ means excessive wear and the restoration must be replaced. The advantages of the chairside method of wear assessment are that it is readily available and does not require special equipment, whilst the disadvantages are that it is subjective and insensitive and takes a long time to get significant results [3, 69].

With replica models there are a number of measurement systems, the majority of which compare the replicas of restorations with standard reference models or calibrated reference steps [3]. Advantages of this method are that it is fast and inexpensive [69]; however, the major disadvantages are that it assesses only the wear at the restoration margin and, therefore, gives no indication of wear occurring at other sites [3]. In addition, it tends to underestimate wear [69]. Recently, it has been pointed out that the best method for measuring wear is by comparing sequential 3D images of the materials of interest [3, 33, 69], which is quantitative, accurate and providing storable 3D databases that can be compared with other 3D databases. However, considering that it needs to use expensive equipment [69, 33], few clinical studies have used 3D scanning technology to measure wear although it has been available since the mid-1980s.

### 4.2. *In vitro* laboratory simulation

Due to the mentioned disadvantages of *in vivo* methods, the quest for a wear machine which would predict clinical performance has been the dream of many material scientists with the ever increasing number of artificial dental materials available. Therefore, laboratory simulation methods were widely developed to mimic wear conditions in the mouth such as clinical masticatory cycle and oral environment and then used for *in vitro* evaluation of dental materials after the 1940s [40].

The wear testing devices used in *in vitro* studies were various, which include simplest pin-on-disc devices and a more complex ‘artificial mouth’ [17, 33, 92]. Several liquids are incorporated in these wear machines such as water, alcohol, acids, olive-oil, olive-oil/CaF slurry, artificial saliva, with or without the inclusion of bacteria [84]. A summary of the different test geometries used in dental tribology is shown in figure 7.

Generally three main mechanical approaches can be considered with different wear simulation techniques: toothbrushing machines, two-body wear machines and three-body wear machines. For toothbrushing machines, in general a toothbrush/dentifrice abrasion concept is used consisting of the following elements [84]: toothbrush, programmable brushing techniques and paths and medium (such as dry, wet and dentifrice abrasive slurry). A relative dentine abrasion (RDA) method developed by Hefferren is perhaps the most well-known *in vitro* method to study toothpaste abrasion and is widely used by manufacturers [16]. The literature survey shows that several two-body wear simulators were designed and used with varying degrees of success to imitate clinical wear [84], such as two-body abrasion single-pass sliding, two-body wear rotating countersample, Taber abraser, two-body machine sliding wear, pin-on-disc tribometer, abrasive disc, oscillatory wear test, modified polisher and fretting test. In addition, a number of three-body wear simulators have been developed to simulate masticatory abrasion, which include abrasive slurry that acts simultaneously with the surface contact. Examples of these devices [84] are ACTA wear machine, Oregon Health Sciences University Oral
Wear Simulator, four-station Leinfelder-type three-body wear device, Zurich computer-controlled masticator, Minnesota MTS wear simulator (also called ‘artificial mouth’), BIOMAT wear simulator and Willytec Munich and Muc3.

It has been accepted that in vitro testing offers researchers much more control over experimental variables and the opportunity to take far more accurate measurements than in vivo testing and therefore shows many advantages in the study of wear mechanism of natural teeth and artificial dental materials [33]. Moreover, in vitro evaluation of dental materials can be examined over relatively short periods of time in comparison with clinical trials. However, the oral environment is very complex and has many variables; therefore all in vitro models cannot replicate the oral environment with all its biological variations [82]. And extrapolation to the oral environment is impossible to calculate. As a result, only trends and indications as to the true extent of wear can be obtained by in vitro methods [3]. In addition, the results of in vitro studies would be credible provided that the most influencing parameters have been identified and can be used and controlled in the test rigs [33]. To be of value, wear simulation must produce clinically relevant results [69]. It should be noted that nowadays most of the in vitro studies have been carried out on different test rigs with differing contact geometries, loads, sliding speeds, lubricants, etc, which make it difficult to compare wear results obtained by different machines.

4.3. In situ testing

Whatever in vitro method is employed, it is difficult to extrapolate findings into a clinical meaning, particularly since the wear of teeth is multifactorial and physical and chemical processes interact [82]. Indeed, it is this multifactorial aetiology of toothwear which has hampered the development of in vivo methods to study the tribology of dental materials. As a result, in situ methods were developed by West et al in 1998 [93]. During in situ testing, specimens are mounted in devices worn in the mouth and finally removed for ex vivo measurements [33]. Therefore, specimens can be exposed to the real oral environment. In a word, in situ testing provides a partial compromise between the in vivo and in vitro conditions [6].

For most in situ methods the conditions of any experiment can be carefully controlled so that the effects noted can be ascribed to the agent under test [82]. In situ studies can use sensitive equipment such as profilometer and scanning force microscopy, to measure the loss of materials surface due to various factors so that experiments could be conducted over comparatively short time periods. Initially in situ methods were used mainly to measure the erosion of dentine and enamel by soft drinks and were then gradually used to study a variety of phenomena in the mouth including abrasion of dental materials by toothpastes [33, 82].

5. Tribological behaviour of natural teeth

As mentioned above, friction occurs during normal oral functions; therefore, toothwear, a cumulative multifactorial lifetime process, is irreversible to a large extent [94–96]. It has been shown that the rate of toothwear may be associated with factors such as age, gender, occlusal conditions, parafunction, gastrointestinal disturbances, excessive intake of citrus fruits or beverages with a low pH, environmental factors, salivary factors and congenital anomalies of dental tissues [97].

5.1. Effect of tooth microstructure

Tooth enamel is one of those unique natural substances which still cannot be substituted effectively by artificial restorative
materials. The most important feature of enamel is its excellent wear resistance. Mass [98] pointed out that the variation in the crystallite orientation of prismatic enamels may contribute to optimal dental function through the property of differential wear in functionally distinct regions of teeth.

Zheng and Zhou studied the friction and wear behaviour of enamel and dentine against titanium balls by using a reciprocating wear test apparatus with the lubricant of artificial saliva [99]. Results showed that the enamel zone exhibited a lower friction coefficient and better wear resistance in comparison with the dentine zone in the same tooth, and the hardness and wear depth decreased as the test locations move through the outer enamel to the inner dentine, as shown in figures 8 and 9. The wear of enamel resulted mainly from delamination, whilst dentine wear as a result of ductile chip formation and plenty of strong ploughs appeared on the worn surface (figure 10). In addition, the depth of wear scar varied with test orientations (figure 11). Therefore, they concluded that the excellent tribological property of enamel was closely associated with its high hardness and the presence of prisms, and the tribological behaviour of natural tooth may interact strongly with microstructure orientation.

Some researchers pointed out [100, 101] that due to different microstructures and mechanical properties, wear rates of enamel and dentine showed different increasing tendencies as the load increased. High mineral content and corresponding hardness result in relatively low wear rates of enamel at lower loads; however, the brittle nature of enamel contributes to a high wear rate at higher loads. In contrast, dentine has higher organic content and relative softness, which makes it less prone to fracture under oral conditions; as a result, it shows a high wear rate at lower loads but a low wear rate at higher loads. It was reported that the differential wear rate between dentine and enamel occurring in areas of exposed dentine may be a cofactor in the formation of some Class VI lesions [102].

It was reported that sound enamel under friction by mastication and biting lost only a 10–40 µm thick layer per year [103]. Two stages of the wear of enamel have been observed by several researchers with different wear apparatus [100, 104, 105], which is also consistent with the results of clinical traits [106]. Clinical studies described the primary and the secondary phases as running-in wear and steady-state wear, respectively. The initial stage appeared to last for a period of 2 years before the transition to a slower second stage. In addition, the wear of enamel was reported to be controlled by the mechanical removal of materials without obvious changes in the composition and crystal structure of enamel [105].

Considering that the gradual wear of human teeth with age is an inevitable and irreversible process, the structure and property of the tooth surface exposed in the mouth could vary with ageing. Zheng and Zhou [107] found that there existed differences in both the evolution of the friction coefficient and the wear behaviour between teeth at different ages against the titanium alloy. Although delamination and ploughing mechanisms were dominant for the wear of human teeth, more severe wear was observed for primary teeth and permanent teeth in old age accompanied by remarkable fluctuation in the friction coefficient. Figure 12 shows the relationship between the hardness–depth of wear scar and tooth ages. Permanent teeth throughout their life exhibited higher hardness and lower wear depth than primary teeth. Moreover, the hardness and wear depth of permanent teeth varied with ageing, and the permanent teeth in old age showed obviously higher wear depth than the permanent teeth in young and middle ages. It was suggested that the permanent teeth in young and middle ages have better wear resistance in comparison with primary teeth and permanent teeth in old age.

5.2. Chewing effect

Toothwear resulting from mastication has been reported to be closely associated with occlusal conditions (such as occlusal surface roughness and load) and the properties of food particles (such as texture and size) [6, 33].

During the closed phase of mastication, food particles are trapped between opposing tooth surfaces and then crushed and
Figure 10. Two types of human tooth wear scars observation parallel to the occlusal section (versus titanium ball): (a) at the enamel zone and (b) at the dentine zone. (Reprinted with permission from [99]. Copyright 2003, Elsevier.)

Figure 11. A comparison of tooth wear depth between different contact zones for two different orientations (versus titanium ball). (Reprinted with permission from [99]. Copyright 2003, Elsevier.)

ground, which can cause abrasion to the occlusal surfaces. The entrapment of particles is clearly influenced by the nature of the contacting surfaces. Rough surfaces may trap more particles than smooth ones. It was indicated that scratches in the occlusal surfaces resulting from thegosis may act as particle traps during mastication [71].

The effect of occlusal load on mastication abrasion has also been investigated. In vitro compression tests, which were conducted by Mass to examine the microscopic wear features on the occlusal surfaces as a result of abrasion by food particles [108], indicated that wear seemed to be independent of load. The results were quite different from a study conducted by Zheng et al [109]. Zheng and Zhou used a reciprocating wear test apparatus to study the friction and wear behaviour of enamel under different wear conditions, which should simulate more what actually occurs during chewing [109]. They found that the wear volume of enamel resulting from abrasion by food particles increased progressively with normal load, which was consistent with other studies [99].

At the population level, the abrasive properties of foods are the prime determinants of the wear rates of teeth and restorations [110]. It has been implicated that the very common high toothwear rates of ancient human beings mainly resulted from the fact that their diet was very coarse and abrasive because hard particles were often incorporated in their food. These particles may be intrinsic components such as bone fragments or collagenous material of fish or meat, cellulose or phytoliths of plant foods and those which were inadvertently introduced as contaminants during food preparation or processing, for example, mineral grit was introduced during the grinding of cereal grains. In contrast, reliance on factory-processed foods, so-called delicate foods, has resulted in very low rates of toothwear in contemporary populations. In addition, results of in vitro compression tests [108] showed that larger particles produced fewer, larger wear features on the surfaces of teeth than smaller ones, and total wear increased with the particle size.

5.3. Pathological factors

Clinical reports show that pathological factors such as erosion, bruxism, xerostomia and tetracycline can result in excessive toothwear, which sometimes needs necessary intervention for cosmetic or functional purposes. Erosion is probably the most significant factor because various surveys have shown a high prevalence of erosion all over the world, which is likely to increase with the increasing consumption of acidic drinks.

5.3.1. Chemical effects. As stated above, tooth erosion is defined as an irreversible loss of dental hard tissues due to a chemical process without the involvement of
microorganisms [63], which can be caused by either extrinsic or intrinsic agents [3, 33, 80]. Extrinsic agents include acidic substances, beverages, snacks or environmental exposure to acidic agents. Intrinsic causes of erosion include recurrent vomiting as part of anorexia or bulimia or the regurgitation of gastric contents. The pattern and distribution of erosion lesions differ according to the acid sources [111]. Dietary erosion affects the labial and palatal surfaces of the upper anterior teeth, while regurgitation erosion typically affects the palatal surfaces of the upper anterior teeth as the tongue directs the vomit forwards during vomiting. Airborne acid affects the upper and lower anterior teeth.

Erosive substance loss of enamel is a dynamic process with demineralization and remineralization periods [112]. In the initial stage, the softening of enamel occurs due to partial demineralization of the surface. At this very early stage of the process, when the pH of saliva returns to neutrality, remineralization is in theory still possible as the remaining tissue could act as a scaffold [113]. At a more advanced stage the mineral of the outer enamel is totally lost and repair is not possible, while the remaining softened enamel beneath the lost hard tissue is probably remineralizable. A substantial loss of dental hard tissue must be expected when softening is followed by friction processes such as mastication and toothbrushing [33, 89], and there is evidence that the acid-eroded enamel is more susceptible to abrasion and attrition than the intact enamel [114]. It was reported that the type of acid, pH value, acid concentration and temperature are all relevant to the wear of teeth [89, 115]. Toothwear caused by erosion observed clinically is the combined effect of demineralization of the tooth surface by an erosive agent and abrasion of the demineralized surface by the surrounding oral soft tissues, food mastication and toothbrushing [90]. Patients with clinically evident palatal erosion showed a ten-fold greater wear rate (median 6 µm/month) than those without any evidence of abnormal wear (median 0.6 µm/month) [112].

For most people, avoidance of erosive foods will well prevent toothwear caused by erosion. Studies also proposed that immediately following an acidic challenge, a remineralizing agent, such as fluoride mouthrinses, fluoride tablets, fluoride lozenges or dairy milk, should be administered to enhance rapid remineralization of the softened tooth surface as well as to serve as a mouth refresher or as an alternative, a neutralizing solution should be used [64]. In addition, it has been increasingly emphasized that modifying the composition of soft drinks is an important concept in the prevention of toothwear due to erosion and should be further developed [115, 116].

5.3.2. Bruxism. Bruxism, a very common parafunction of the masticatory system, may be defined as rhythmic, habitual tooth clenching or grinding movements that would occur either when awake or during sleep [117–119]. Examples of the consequences of bruxism often mentioned in the dental literature are toothwear, muscular pain, toothache, mobile teeth, various problems with removal and fixed prostheses, and so on. The aetiology of bruxism has long been a controversial issue and theories have invoked occlusal, physiological, genetic and stress factors [120].

In general bruxism can cause abnormal attrition at sites of occlusal contact (OCA) and then result in excessive toothwear. It was reported that patients with bruxing habits can apply occlusal loads of approximately 1000 N [75], while for normal people, as discussed above, the maximum biting load at the incisors is 100 N, gradually increasing as one moves posteriorly to reach around 500 N at the molars. In addition to these increased loads, bruxists have a total tooth contact time of 30 min to 3 h in a 24 h period. For a nonbruxist, the tooth contact time is about 10 min. As a result, wear due to extensive bruxism could be very severe. The vertical loss of dental hard tissues in patients with bruxism habits has been reported to be 3 to 4 times higher than that in normal people [119].

5.3.3. Other factors. Clinical reports have shown that a large number of people suffer from impaired salivary functions [121, 122], displaying symptoms such as ‘dry mouth’ (also called xerostomia). Xerostomia is a condition characterized by a reduction or loss in salivary flow, often with a concurrent change in the composition of the saliva, resulting in dryness of the oral cavity and then difficulties in speaking, masticating, swallowing, etc [121]. As mentioned above, saliva plays an extremely significant role in decreasing the friction and wear of teeth to prevent those lesions; therefore, if not treated, people could suffer excessive toothwear from xerostomia. The most common option for xerostomia treatment is the use of an artificial saliva or saliva substitute (oral lubricants).

Recently authors investigated the tribological behaviour of human teeth at different tetracycline stained extents against titanium alloy by using a reciprocating sliding wear test machine. The results showed that the friction and wear behaviour of lightly tetracycline stained teeth were similar to those of normal teeth, and the worn surface is characterized by scratch and slight plough. However, for heavily tetracycline stained teeth, significant plough and delamination were dominant accompanied with strong discontinuities in the evolution of the coefficient of friction and the rather high stable friction coefficient, and their tribological property was obviously inferior to normal teeth. It was suggested that the wear resistance of human teeth decreases with increasing tetracycline stained extent due to the variation of the tooth microstructure (figure 13).

Gil et al [123] reported that the accumulation of lead in teeth was associated with dental health factors, such as dental plaque, salivaris lactobacilli number, dental colour, dental abrasion and toothbrushing frequency. Coloured teeth and teeth subject to abrasion showed the highest lead content. Teeth obtained from irregular brushers presented higher tooth lead content than subjects with regular toothbrushing frequency.

In addition, a clinical survey conducted by Judith et al showed that to a lesser extent, difficulty in relaxation, pain and distress and avoidance of going out are associated with tooth loss and/or denture wearing [124].
5.4. Effect of tooth flexure

During mastication or bruxism, occlusal loading can cause tooth flexure [15, 75, 80] and generally result in shear stress in the cervical region of a tooth where the enamel has been found to be less resilient. Once the shear stresses resulting from tooth flexure exceed the failure stresses of enamel, cracking and subsequent enamel loss can occur in the cervical region (around the cemento–enamel junction), which is clinically called noncarious cervical lesions (NCCL) by abfraction. Fracture of the cervical enamel by abfraction is most likely to occur along the boundaries of the hydroxyapatite crystals.

Levitch et al reported that the number, size and depth of cervical lesions increased with age [75]. Cervical lesions by abfraction were seen more commonly on maxillary (upper jaw) incisors in clinics, possibly because these small teeth were less able to withstand the applied occlusal load. A finite element study conducted by Rees et al suggested that stresses in maxillary incisors were several times larger than those in canines and molars [125], which explained these clinical observations. Clinical studies have also shown that abfraction lesions are common in people with parafunctional habits, especially bruxists [75], as mentioned above, who apply large eccentric occlusal loads.

5.5. Effect of toothbrushing

Teeth are usually cleaned using a filament-based toothbrush and a toothpaste. Toothbrush and toothpaste can be traced back 1000 years [77], and toothbrushing with toothpaste is arguably the most common oral hygiene habit in developed countries. The oral dental health benefits of toothbrushing with toothpaste are recognized and reviewed in a large number of publications: plaque removal, the control of extrinsic stain and the delivery of preventive and therapeutic agents for dental and gingival diseases or conditions [82].

The chemical composition of a typical toothpaste is as follows [126]: abrasive particles, peroxides, enzyme systems and absorbents, saccharin and peppermint flavouring and water. Toothpaste abrasive particles are made from materials such as calcium carbonate, sodium bicarbonate, precipitated silica, pumice and perlite, which are used to obtain optimum stain removal during toothbrushing. Peroxides can either dissolve or bleach the particle stain. Enzyme systems and absorbents are used to soften the pellicle easing the removal process. In addition, generally fluorides are added to toothpastes to prevent caries and tooth erosion. Due to different geometries, nature and contents of abrasive particles, toothpastes can manifest different abrasivities [126, 127], which is normally described by the relative dentine abrasivity value (RDA value). Although optimum stain removal is desired from a toothpaste abrasive it is important that during the cleaning process the enamel or dentine or soft gum tissue is not damaged.

Various studies have been carried out to study the effects of the type of toothbrush and the composition, especially the abrasivity of the toothpaste on toothwear caused by toothbrushing. Traditionally studies on toothbrushing were conducted in vitro by using various wear simulators, whilst more recently, in situ methods have been frequently used [82]. Although toothbrushes alone or combined with toothpaste have been proposed to both cause tooth wear, abrasion of gingival tissues and gingival recession, and be involved in the aetiology of dentine hypersensitivity [77], toothbrushing alone appears to have no obvious effect on the wear of enamel and very little on dentine [33]. Most, but not all, toothpastes have low relative enamel abrasivity values and are implicated to have a minimal effect on enamel and in normal use would not cause significant wear of dentine in a lifetime of use [77]. However, it should be noted that dentine is considerably more susceptible than enamel to abrasion caused by toothpaste abrasive, and dentine loss appears to correlate with toothpaste abrasivity [127]. Overuse or abuse of toothbrushing with toothpaste would only be relevant to dentine and not enamel wear unless high relative enamel abrasivity toothpastes were in use and as stated these are unusual [77]. Therefore, toothpaste with lower abrasivity might be advisable for daily oral hygiene practice of patients with excessive toothwear.

Wear of enamel and dentine can be dramatically increased if toothbrushing follows an erosive challenge [77], which may result in noncarious cervical lesions [128]. Attin et al suggested that for protection of dentine surfaces at least 30 min should elapse before toothbrushing after an erosive attack [129]. It is interesting to note that a recent study carried out by Hooper et al showed that toothbrushing with fluoride toothpaste containing sodium hexametaphosphate before meals could provide significant erosive protection in susceptible individuals [67].
6. Tribological behaviour of artificial dental materials

In dentistry, as discussed above, metals and alloys, ceramics and composites are generally applied to restorations and implants. Considering the inter-oral complex environment and biomechanics, wear processes of artificial dental materials are very complicated, which normally include abrasion, attrition, corrosion, fretting wear and fatigue [3, 5]. These processes occur in various combinations to cause surface loss of materials in the mouth. Excessive wear may lead to premature failure and replacement of dental restorations and implants.

Wear resistance of artificial dental materials is clinically important for clinical longevity, aesthetics and resistance to dental plaque [3, 5, 80]; therefore, a large number of studies have been carried out on their tribological properties. Commonly their research interests are as follows [6]: (1) the wear resistance of artificial dental materials and (2) the predisposition of restorative materials to create wear on the opposing structures, especially the opposing enamel.

6.1. Metals and alloys

Corrosion has been considered the most important factor in the selection of metallic materials in dentistry because poor biocompatibility and cytotoxicity of their corrosion or wear products may make the materials worse for either restoration or implantation purposes in the mouth [34, 130]. It has been reported that the presence of a metal restoration is the most commonly cited reason for an adverse reaction [130]. There is a vast amount of literature concerning the corrosion of dental alloys, and from the proffered information it emerges that leaching of metallic ions and food habits are the main causes of corrosion of metallic restorations and implants [34]. The purity, casting and melting techniques also affect the corrosion behaviour of metal alloys. In general the nature of metal alloys plays a major role in the initiation and propagation of corrosion. Recently Liu et al reported that the wear and corrosion resistance of nickel-based and chromium-based dental alloys could be improved with the presence of titanium aluminum nitride films [131].

Generally, most metals are strong enough to withstand maximum possible oral forces. However, with the life quality increasing significantly, the appearance of dental materials may be the most important factor to be considered for many patients. As a result, nowadays, metals and alloys have increasingly been applied to orthodontic appliances and dental implants.

Friction in fixed orthodontic appliance systems is recognized by most clinicians to be very harmful to tooth movement [132, 133]. Various factors affect the friction resistance process of orthodontic bracket–wire combinations, such as archwire and bracket materials, their size and shape, width and slot dimensions and the surface composition, roughness and cleanliness. Other important parameters are the bracket-to-wire positioning in a three-dimensional space, the ligature force and type of ligation, the interbracket distances and lubrication. Fretting tests of stainless bracket–wire combinations during sliding processes, carried out by Willems et al [132], indicated the significant role of the centred positioning method on the friction value. In addition, the slot-filling, bracket–wire combination resulted in an increased coefficient of friction and therefore is not recommended for sliding systems. It is also notable that pain and discomfort of the oral mucosa can often be experienced as a result of trauma from the metallic appliance caused by increased friction between mucosa tissue and the surface of the brackets [134], on which few research works have however been conducted.

Fretting wear has been frequently mentioned by clinicians as a possible failure cause of dental implants [86, 87]. Yu et al investigated tangential fretting behaviour of pure titanium (TA2) and its alloy (TC4) against the human thighbone cortical bone [87]. Results showed that friction logs transformed from a partial slip directly to a gross slip without a mixed regime, and the friction coefficients in each fretting regime went up with the displacement. The wear depths on the Ti ball were only to the extent of several to tens of micrometres, which were much less than those of the bone. In addition, the friction coefficient of the bone–TC4 pair was higher than that of the bone–TA2 pair, and the maximum wear depth on the bone against TA2 was about 40% the value of that on the bone against TC4. Therefore the wear adaptability of bone–TA2 pairs was better than that of bone–TC4 pairs. Abrasive wear features and various microfractures were observed on the worn cortical bone surfaces. It was suggested that some surface modification techniques of titanium be adopted to reduce the fretting damage to bone.

It should also be noted that commercially pure (CP) titanium and its alloys have been increasingly applied to dental restorations, especially implants, in place of other metals due to their excellent biocompatibility, corrosion resistance and light weight [135–139]. One of the disadvantages of titanium for structural applications is its poor tribological characteristics [135]. Clinical trials [136] showed that cast CP-Ti dental restorations underwent the greatest amount of wear in comparison with conventional dental alloys. Alloying may be a possible method to improve the wear resistance of CP-Ti [137–139]. Ohkubo et al [137] indicated that among the different types of titanium alloys, α + β alloys exhibited the best wear resistance due to increased resistance to plastic deformation resulting from the existence of α needles in the retained β matrix, which was consistent with that given by Khan et al [136]. It was also found that alloying with copper [138], which introduced the α′ Ti5Ti2Cu eutectoid, seemed to improve the wear resistance of titanium alloys. Iijima et al reported that Ti–6Al–7Nb alloys can be used for dental restorations because they exhibited lower wear loss and a much smoother worn surface than CP-Ti [139].

6.2. Ceramics

The advantages of ceramics in dentistry are their natural appearance and their durable chemical and optical properties. Normally ceramics possess relatively high resistance against wear. However, clinical trials show that there may exist
two major problems encountered in their dental use [46]: (1) most ceramic restorations may be abrasive and potentially destructive to the opposing natural teeth or restorations and (2) brittle fracture plays a major role in the wear of some ceramics during the friction process in the mouth, which could cause disastrous results clinically. Therefore, the use of less abrasive ceramics would offer excellent aesthetics whilst minimizing the wear of opposing natural teeth and would be a valuable addition to the dentists’ selection of materials [6].

Many researchers have focused on investigating the abrasive potential of various dental ceramics to opposing dentition, especially opposing enamel. Literature survey shows that the wear of enamel and ceramic appears to be closely related to the ceramic microstructure, surface characteristics (such as smoothness or glaze) and environmental influences [4, 140, 141].

Internal porosity and other surface defects, which are produced by an inadequate firing technique, act as stress concentrators and result in greater wear [4]. Glazing and/or polishing can lower wear at the early stage of contact, but the positive effect of a glazed/polished ceramic surface is quickly lost when the material is placed in function. The internal characterization of ceramics is recommended because shading materials contain abrasive metal oxides. The application of external stains should be limited to the noncontacting surfaces of aesthetic restorations. Moreover, etching the inner side of the porcelain veneer, which is often needed clinically, can cause microcracks which may slightly weaken the wear resistance of the porcelain.

An acidic and/or alkalic chemical attack caused by dietary habits and intrinsic diseases may result in the degradation of ceramic surfaces in the mouth [4]. Load has a significant effect on the friction coefficient and wear loss of dental porcelains [141]. Thus, if a degraded ceramic surface is further subjected to dysfunctional occlusion or parafunctional habits such as bruxism, the wear process may be accelerated. More recently, Akihiko et al reported that porcelain showed significantly less wear loss and was less abrasive to opposing enamel or composite resins in three-body conditions compared with two-body conditions, regardless of its surface conditions [140]. In addition, abrasion of toothbrushing is a possible cause of the wear of dental porcelains. Anil et al reported that significant material loss and decrease in roughness occurred in the surface of porcelains as a result of the equivalent of 8.5 years of toothbrushing [142].

In order to minimize the damage by brittle fracture, many efforts have been made to develop high-toughness dental ceramics in the past decades. Recently, yttria-stabilized tetragonal zirconia polycrystal (Y-TZP), a high-toughness zirconia ceramic, has been developed as an alternative to porcelains or glass-ceramics in posterior restorations [143, 144].

### 6.3. Composites

The main problem involved in the dental application of composites is their inadequate resistance against wear when used as posterior composite restorations, resulting in a loss of anatomic form under masticatory abrasion and attrition. Many efforts have been made continuously to optimize the composites in order to have better wear resistance since they were widely used in dentistry. Nowadays, many dental composites do not show excessive wear anymore, and wear is more likely to occur at occlusal contact areas than on contact-free areas [19, 145].

Wear mechanisms of dental composites were associated with wear conditions [6]. Abrasion and chemical degradation appeared to be dominant in the contact-free areas clinically, while fatigue and adhesive wear were generally associated with occlusal contact wear [3]. Nagarajan et al [50, 146] investigated the two-body wear of three medium filled composites and one highly filled one. Wear was found to occur by simultaneous processes consisting of tribochemical reactions between filler particles and water, dissolution of hydrated products, formation of surface films containing a mixture of filler fragments and reaction products and mechanical detachment of the surface films.

Generally, the wear process of composites is associated with both material and oral factors [145]. Material factors normally relate to the characteristics, content and distribution of filler, the degree of conversion, the nature of the matrix and the interfacial bond strength between filler and matrix.

Filler characteristics, such as size, shape, hardness and brittleness, play an important role in the wear process of dental composites. The wear resistance of composites is better with higher filler loading but smaller particle size [145, 147]. Hard filler particles could protect the soft matrix and enhance the material’s overall resistance to abrasion [145]; however, the hardness of filler particles must not be higher than that of hydroxyapatite crystals of human enamel. An ultra-fine filler size will reduce the impact of the filler hardness. Compared with composites containing large filler particles (>1 μm) [2, 36, 145, 148], microfilled and small–particle hybrid composites were frequently mentioned to have a tendency to display better abrasion resistance because of their smoother surface, decreased inter-particle spacing and decreased friction to food particles. In contrast to sharp and pointed particles, the presence of spherical and irregular particles could benefit both the composite wear and the opposing enamel wear [149].

An additional aspect to be considered is filler brittleness [145]. Under high stress, brittle filler particles will easily fracture and cause rapid abrasion of the material itself, but a less antagonistic engagement. It is well accepted that a smooth surface provides reduced frictional wear at the occlusal contact area, which will lessen the wear of both composite and antagonistic enamels. Whenever filler particles protrude and are big and extremely hard, there can be high antagonistic wear rates that could cause catastrophic loss of the tooth substance in time [145, 150].

Obviously, the ability of a resin composite to resist abrasive action depends on filler–matrix interactions. Therefore, the filler content and distribution and inter-particle spacing significantly influence the physical properties and then the wear resistance of dental composites [145]. As the filler volume increased, wear was reduced regardless of the filler treatment [145, 151]. Wear resistance of microfilled
Composites was remarkably enhanced by the filler volume with an increase from 25 to 30 vol%. Filler particles situated very close can protect the softer resin matrix from abrasives, thus reducing wear. It was reported that the use of finer particles for a fixed-volume-fraction of filler resulted in decreased inter-particle spacing and reduced wear [145]. Moreover, even at a low microfiller level, well-distributed fillers can achieve good wear resistance for small-particle hybrid composites.

Clearly a weak, incoherent matrix can invoke phenomena such as plucking out of filler particles and excessive wear of the matrix and thus reduce the abrasive capacity of composites. As a result, wear can be reduced significantly as the degree of cure, strength and toughness of the resin matrix increases. In general the degree of cure, strength and toughness of the matrix is associated with its composition and cure conditions. High-intensity curing units and postcuring can result in a high degree of conversion and then enhance the fracture toughness and strength [152, 153].

Another key factor in the wear of composites is a good interfacial bond between the filler and the matrix. Good filler/matrix adhesion was indicated to enhance stress-transfer ability, protect the matrix and interfere with crack propagation at higher filler levels and accordingly reduce wear [145, 154]. Silane coupling agents are thought to play a major role in enhancing the adhesion of the interface between the inorganic filler and the organic resin. It is important that the microfillers need to be kept well dispersed to achieve the full effect of protection. In addition, contamination of the filler might disturb silanization and reduce filler–matrix coupling. Another advantage of the use of a coupling agent in dental composites is that it, at least to some extent, protects the filler against hydrolytic degradation.

Oral factors, in particular oral chemical environment, have a significant effect on the wear process and in vivo degradation of composite restorations. The resin matrix can be softened and fillers can be leached out when composites are exposed to certain chemicals/food simulating liquids [52, 145], thus reducing the resistance against wear to a considerable extent. A high degree of cure of the composite matrix could decrease its degradation in long-term exposure to water. It should be noted that there is a rising failure rate of posterior resin composite restorations due to interproximal wear [145, 154]. Furthermore, wear of crowns and bridges made of composites is generally greater than that of fillings if they are analysed after longer periods of service [19].

In summary, normally different dental materials encounter different tribological problems in their clinical uses, as shown in Table 7. It can be seen that both material property and oral factors can significantly influence the friction and wear process of restorations in the mouth. An additional aspect to be considered is the clinical operation technique. Wear resistance of restorative materials tends to increase as the cavity size decreases. The restorations placed should be as small as possible in order to benefit from the strong support of, and full protection by, the surrounding natural tooth structure [4, 140, 145]. Ideally, the wear of a dental material should be similar to that of human enamel because enamel has extremely excellent wear resistance despite fairly bad working conditions in the mouth, such as widely ranging load, reciprocating movements, temperature shocks or possible acid attacks. To date, however, this property may only be found in ceramic materials and particular metal alloys [19]. The wear of amalgam is higher than that of enamel but lower than that of composite resins. Although significant improvements have been achieved, many resin composites still exhibit considerable in vivo wear in the long run [6, 155].

### Table 7. Dental materials and their tribological problems in clinics.

<table>
<thead>
<tr>
<th>Materials</th>
<th>Main tribological problems</th>
<th>Influencing factors</th>
</tr>
</thead>
<tbody>
<tr>
<td>Metals and their alloys</td>
<td>Wear–corrosion, friction in fixed orthodontic appliance systems, fretting wear</td>
<td>The nature of metal, alloying, oral factors</td>
</tr>
<tr>
<td>Ceramics</td>
<td>Abrasive potential to the opposing enamel, brittle fracture</td>
<td>Ceramic microstructure and surface characteristics, oral factors</td>
</tr>
<tr>
<td>Composites</td>
<td>Excessive wear in posterior composite restorations</td>
<td>Characteristics, content and distribution of filler, the degree of conversion and the nature of matrix, the interfacial bond strength between filler and matrix, oral factors</td>
</tr>
</tbody>
</table>

7. Concluding remarks

In dentistry, the tribological behaviour, in particular the wear of teeth and restorative materials, is a particular clinical problem. Wear is an important consequence of occlusal interaction. However, if not controlled, wear could lead to poor masticatory function and various treatment problems with a concomitant reduction in the quality of life and possible deterioration of systematic health. As a result, tribology of dental materials, which concerns the understanding of the mechanisms and controlling factors in dental wear, is critically important. As discussed above, inter-oral friction and wear of dental materials are extremely complex; therefore, there appear some problems in current research, some of which should be focused on in future work.

The literature survey shows that for the wear of human teeth more clinical observations have been reported than in vitro studies. In other words, many studies have focused on the aetiology of toothwear but the wear mechanism is far less understood. Take tooth erosion for instance. Toothwear by erosion is paid increasing attention and accordingly a great number of papers on the chemical effect has become available recently (table 1). However, most studies focused on the
Fewer studies have been carried out on its mechanism in detail. It is also found that few research works have focused on the effect of bioactivity and biomechanics of human teeth on their tribological behaviour. Nevertheless, the lack of these aspects may be one of the main obstacles hindering the development of dental materials because, as discussed above, the tribological properties of ideal restorations and implants should not only be similar to human teeth but also exhibit individual differences such as age and sex. For artificial dental materials the same situation is encountered. Most studies have focused on providing comparative ranking of various dental materials using wear test machines simulating the oral conditions, whilst only a few in vitro studies have been carried out on their wear mechanisms. Future in vitro wear testing should be aimed at an understanding of the fundamental underlying wear mechanisms involved, which will lead to a better understanding of in vivo failure patterns.

Little is known about the systemic effects of artificial material components, such as the clearance of the worn material, adverse effects, chemical reactions or a possible incorporation of worn material into body cells or tissues. With composites there is a certain amount of concern that, besides the leaching of monomer components, micro- and nanosized inorganic filler particles of composite resins that are worn, swallowed or inhaled and accumulated into tissues could be linked to diseases of the liver, kidney and intestine. It is also found that the role of interproximal wear in the loss of dental tissues and restorative materials has attracted less attention. Moreover, less attention has been paid to fretting wear of dental implants which can cause the loosening of metallic implants and subsequently result in these failures. In addition, few studies have focused on the effect of tooth location on its tribological behaviour. It is worth noting that much emphasis has been placed on the wear of dental materials, but efforts to explain and understand their friction behaviour in the mouth remain much fewer. This indicates that in the past the importance of friction as a factor in the wear of brittle dental materials may not have been fully appreciated. Friction forces play a major role in the oral wear process of dental materials. Stolarski noted that when friction is present the critical depth of just a few micrometres is sufficient to alter friction which will therefore affect the wear. Clearly works devoted to this field will promote tribology of dental materials.

As mentioned above, in vivo studies have some advantages in observing clinical manifestation and predicting risk factors for oral tribological behaviour, rather than investigating their mechanisms. In contrast, the marked advantage of in vitro testing is to analyse the fundamental mechanisms, which may lead to a better understanding of in vivo failure patterns. Many in vitro methods have been developed since the 1990s, on which Roulet commented that ‘there were almost as many wear testing devices as there were scientists who are interested in wear’. So the question has arisen whether these devices and methods fulfil the standards for qualification and validation that are already in place in other fields of medical product testing. Some researchers have observed that, firstly, comparison of the results obtained by different devices was difficult; secondly, the experimental results were best characterized as inconclusive; thirdly, some laboratory studies lack correlation with clinical trials. An important point to be kept in mind with future in vitro testing is that wear test machines need to simulate the oral condition and biomechanics as closely as possible, otherwise, the lack of correlation between the results of in vitro and in vivo studies will be inevitable. And an efficient and universally accepted in vitro tribological test would undoubtedly promote and assist tribology of dental materials.

There exists a state of confusion in assessing the wear of dental materials. Three parameters, ‘wear volume’, ‘wear depth’ and ‘wear area’, have been used by various researchers, respectively. Generally there are significant differences between the wear assessments of the same sample measured by different parameters. Volume was reported to be the preferred parameter because wear is defined as the volume of the material removed. The disadvantages of the other two parameters are that they represent indirect wear measures, depend on occlusal factors and vary with time. Moreover, depth is not a good parameter for comparing wear because its magnitude depends on where the depth is measured and the direction from which it is measured. In addition, evaluating the wear of dental materials requires that both the material of interest and the opposing material be considered because materials may be worn by the antagonist or they may cause aggressive wear of the antagonist. Clinically, it is the combined wear or total wear that is important; especially if the opposing material is enamel.

In addition, modelling dental tribology is proposed to be started. Almost no attempt has been made at modelling any dental tribological behaviour. This is probably because of the complexity of the oral environment and biomechanical functions. However, sometimes simple models, while they may not give a completely accurate representation, can be useful in comparing and contrasting the situations of oral lubrication, friction and wear.

Due to the fact that tribology of dental materials is involved in many subjects such as dentistry, materials and engineering, there is still a poor understanding of tribology behaviour of dental materials. Even through a lot of progress has been made, much remains to be done. It is evident that collaboration among clinical dentists, materials researchers and tribologists will help to advance this research area of strong current interest.

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