Wear 297 (2013) 1040–1044

Contents lists available at SciVerse ScienceDirect

Wear

journal homepage: www.elsevier.com/locate/wear

Dental tribology at the microscale

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ARTICLE INFO

Article history:
Received 22 June 2012
Received in revised form
23 November 2012
Accepted 28 November 2012
Available online 5 December 2012

Keywords:
Dental analysis
Friction
Wear
Microtribology

ABSTRACT

Dental wear caused by tooth care is a complex phenomenon that depends on the quality of the tooth material, the type of toothbrush and the brushing slurry. Tooth wear is commonly determined in abrasion experiments using a standardized toothbrush in contact with a radioactively labeled dentin sample (RDA method). The increase of radioactivity in the slurry is a direct and highly-sensitive indicator for wear. It is, however, detrimental that RDA provides an integral view of the tribological processes leaving microscopic issues undetected. Therefore, in this contribution the macroscopic system of brush versus tooth was reduced to a microtribological setup analyzing the contact between a single bristle (monofilament) and a tooth sample. This setup allowed to correlate friction and wear events to topography and structure of the tooth and will enable the evaluation of cleaning processes microscopically in the future. In addition, results of this work were related to the literature results of RDA experiments.

1. Introduction

Daily dental care is commonly pursued by brushing teeth using a toothbrush, some water and toothpaste. The toothpaste is mainly composed of cleansing particles, foamer, moisturizer, binding agent, sweetener, flavoring agent, preservative and fluoride containing ingredients. The cleansing particles serve as mild abrasives to remove stain and plaque from the tooth surface. As a consequence, besides attrition (wear due to direct tooth-to-tooth contact) brushing teeth using toothpaste is the most important wear process and the wear rate determines the lifetime of the tooth, especially the dentine [1,2]. Several studies simulated attrition [3–8] and brushing teeth using toothbrushes [9–13]. In these studies different materials were used, e.g. human enamel [3–6] or teeth [9,10], different restoration materials [4,6–8,11], bovine incisors [12] or PMMA [13]. The majority of tribological tests were carried out in natural or artificial saliva [3–8] using a mechanical setup with reciprocating motion [3–8,11,13]. Friction turned out to be lower in fluid media compared to dry environments [13]. Generally, the friction coefficient does not depend on fluid viscosity [5] and in this particular experiment [8] not on sliding velocity. The addition of small amount of particles to the fluid rapidly increases friction [4,8,13], while any further addition hardly impacts friction [13]. The action of particles was examined by the addition of food particles [3], Al_2O_3 particles [4,5], calcium pyrophosphate [10,11], calcium carbonate [11], calcite [13] or commercial products for dental care [9,10]. Particle shape was shown to have a great impact on abrasivity [14]. Lewis et al. [15] analyzed the trapping of particles in contact between filament and tooth as function of load, deflection of the filaments, particle size and particle hardness. Only some particles are trapped stochastically in the contact. After a few thousand brushing cycles different patterns of scratches caused by the filaments appeared [3,13].

In regard to wear on tooth enamel, literature reports on different influencing factors. Wear increases with increasing load [3,10,11,13], but decreases when the load reaches the point when the filaments spread [11]. Wear often correlates with friction energy [6] and increases with the number of brushing cycles [10]. Wear in fluid media is smaller than wear caused by dry friction. However, the addition of abrasives to the fluid causes strong wear [3–5,7,9]. Furthermore, abrasion is dependent on the type of abrasive and the composition of the toothpaste [10]. The American Dental Association proposes to use relative dentin abrasion (RDA) values to verify the abrasiveness of toothpastes [16–18]. By means of thermal neutrons, tracer atoms are generated in the enamel. Due to radiation, ^{31}P is transformed to ^{32}P.The dentin sample is then subjected to brushing in a standardized brushing apparatus. In the course of brushing, wear particles appear in the slurry. With the help of a highly-sensitive detector, the radioactive traces in the slurry are monitored. This technique is very similar to radionuclide technique, as used in mechanical engineering [19]. Abrasive wear and RDA value increase with decreasing filament diameter of the toothbrush [12].

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http://dx.doi.org/10.1016/j.wear.2012.11.066

Unlike previous studies, which used entire toothbrushes for the tests, this approach reduced the system to the microtribological contact between a monofilament of a toothbrush and a sample of human enamel. The intention was to identify friction and wear mechanisms of enamel in various media by reduction of external influences. The experimental setup allows us to correlate friction and wear effects with microscopic topography changes of the tooth surface.

2. Experimental procedure

2.1. Microtribometry

The head of a toothbrush holds usually more than 1500 single bristles, the so-called monofilaments. To determine the adequate normal force for the Pin-On-Disk (POD) microtribometer experiment using a TetraBASALT-PT®, the average force acting on a toothbrush was divided by the number of monofilaments. It turned out that a normal force range between 1 and 5 mN generates a contact pressure similar to that for a single filament in an entire brush [20]. Thus, the complex macroscopic system was successfully replaced by a microtribological setup consisting of a single filament and a flat piece of human enamel with an interferometer-determined average roughness of 20 nm measured over an area of 1 mm × 1 mm. For this work a monofilament of a cylindrical toothbrush (elmex inter X, GABA International AG, Switzerland) with a diameter of approximately 0.2 mm ± 0.02 mm and a length of 5 mm was used. The filament was shortened to improve the signal to noise ratio by reducing lateral fluctuations. The tooth sample was placed inside a container filled with water or toothpaste slurry. The container was situated at the center of a disk connected to a drive to rotate the disk and specimen at a constant velocity (0.75 cm/s). Loads and brushing speeds used in the tests were based on reported measurements. Typical loads ranged from 2.4 mN to 8.8 mN and brushing speeds from 30 mm/s to 150 mm/s [21,22]. The pin, i.e., the monofilament, was attached to a double leaf spring, which was placed outside the water above the container. The separation between the filament and the tooth sample was controlled by a vertical drive. Upon down-motion of the spring the contact was established. Continued approach sets the normal force by deflecting the leaf spring in normal direction. The spring was fabricated from steel with a spring constant in tangential direction of 195 N/m and in normal direction of 162 N/m. The experimental setup is shown in Fig. 1.

The microtribometer was used to gather data about the long-term behavior of the system. For the dry contact, distilled water coverage and toothpaste slurries with different RDA values (toothpaste provided by GABA International AG) 8000 revolutions were recorded. The friction values were averaged over 200 revolutions to give one data point in the diagram.

In order to measure time-resolved friction coefficients along a single linear path across the enamel, a nanoindenter (Nano Indenter G200, Agilent Technologies) was used at low sliding velocity (25 μm/s). This kind of approach allowed us to analyze the interaction at the tip of the filament. The device is sensitive enough to detect subtle effects. The water film thickness was 2 mm in both the types of experiment. Thus the amount of fluid was sufficient to fully lubricate the system. However, the system was operated in boundary lubrication this means that the tip of the filament was always in contact with the tooth and/or trapped particles. Since this is a stochastic process, it cannot be ruled out that situations exist where no particles are entrained between the tip and tooth.

2.2. Samples

All experiments were carried out with human teeth, obtained from human third molars. First the teeth were mechanically cleaned to remove adherent tissue. Then the samples were disinfected with hydrogen peroxide at 5 wt% and cleaned in an ultrasonic bath. The teeth were stored at 4 °C in double-distilled water with additions of ethanol and thymol. With a minitome (Struers) the roots of the teeth were cut off. One tooth crown was separated into 8 pieces which were separately embedded in acrylic resin. These samples were ground with wet abrasive paper with decreasing grit size (P500, P1200, P2500, P4000) and samples were kept in a cool place in distilled water until the beginning of the measurements. The topography of the samples was evaluated before and after the tests with a confocal laser scanning microscope (CLSM, Leica TCS SL from Leica Microsystems CMS GmbH, Germany) and a scanning electron microscope (SEM, Quanta 3D FEG from FEI, Netherlands). The depth of scratches caused by the monofilament provided information about wear.

The experiments were carried out in different fluids, i.e., distilled water and three toothpaste slurries and compared to dry sliding. The different toothpastes (toothpaste 1: RDA 30, toothpaste 2: RDA 75 and toothpaste 3: RDA 165) were mixed with distilled water to obtain a slurry with a ratio of 1:2 w/w. Five samples per treatment were tested.

2.3. Characterization of abrasives

In order to extract the abrasive from the toothpaste formulation, ethanol was used to remove the binding agents which are ingredients of toothpastes 1–3. About 5 g of the toothpaste were applied to a test tube with 50 ml of ethanol and mixed. The separation was achieved by sedimentation and centrifugation of the suspension. Before taking out the solid material from the test tube, this procedure was repeated three times. Afterwards, the remaining solid components were air dried. The abrasives were investigated by SEM (same instrument as mentioned above).

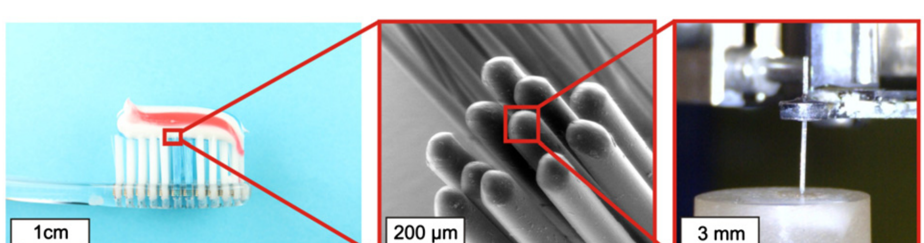

Fig. 1. Toothbrush, set of filaments and tribological pairing. The right photo shows the monofilament attached to the spring in contact with the tooth sample.