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Tribological Characterization of Dental Materials

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Abstract

Tribology is the study of friction, wear and lubrication when two solids are in relative motion against each other.The tribological response of human teeth depends strongly on both microstructural orientation and location inside the same tooth. In order to evaluate the tribological properties of the human tooth, fretting wear tested were carried out against alumina under a loadof 1N for 2000 to 10,000 cycles. A variation in COF ranging from 0.12 to 0.55 was measured. The wear mechanism is dominated by fretting fatigue and adhesive wear, involving the formation of oxidized calcium phosphate based compounds and its subsequent transferfrom tooth to alumina surface. The experimental results also reveal that the human tooth is more susceptible to adhesion wear than abrasion or attrition at fretting contacts.

Key words: Enamel, Dentine, DEJ, Fratting wear, COF, Adhesion

Introduction

The two most important elements of the tooth, from tribological point of view, are the outer enamel layer and the dentine which lies underneath. The enamel is initially exposed to the loads and chemical environment within the mouth as a result of chewing, etc. If this layer is breached due to tooth fracture or wear the underlying dentine is left exposed. Enamel is thicker at the tip of each tooth (2-3mm) and reduces its thickness at the cemento-enamel (CEJ) junction[1].

Tooth enamel is a unique natural substance. This still cannot be effectively replaced by artificial restorative materials. Its most important attribute is a good wear resistance; despite sever working conditions, such as widely ranging loads, reciprocating movements, temperature shocks, impact of possible acid attacks[2]. Sound enamel under friction coming from mastication and biting loses only 30-40 µm thick layer per year [3], while average wear rate found for restorative dental materials in clinical conditions ranges from 8-9 µm per month [4]. This is the main reason why many researchers try to understand the good wear performance of enamel.

` Upon initial inspection, the tooth looks like a relativity simple design with an outer layer of enamel and an inner zone of dentin. The junction of these two materials is called the Dentin-Enamel Junction, or DEJ. In recent years, an increasing number of studies have been performed to uncover more information about the microscopic material properties and structure of enamel, dentin, and the DEJ.Enamel is known to be the hardest tissue in the human body. This is due to the fact that enamel is about 85 vol% mineralized [12]. Enamel is a ceramic-like material that is composed of parallel rods that start at the DEJ and run toward the outside of the tooth. Thus, enamel should be considered an anisotropic material. It provides a hard, brittle protective coating that is excellent for harsh wear, but also diverts any load through its depth to the under-lying dentin [11]. Dentin is a softer, bone-like material with considerably lower stiffness than enamel.

Dentin is composed of approximately 50 vol% mineral, 30 vol% organic components, and 20 vol% fluids [13].

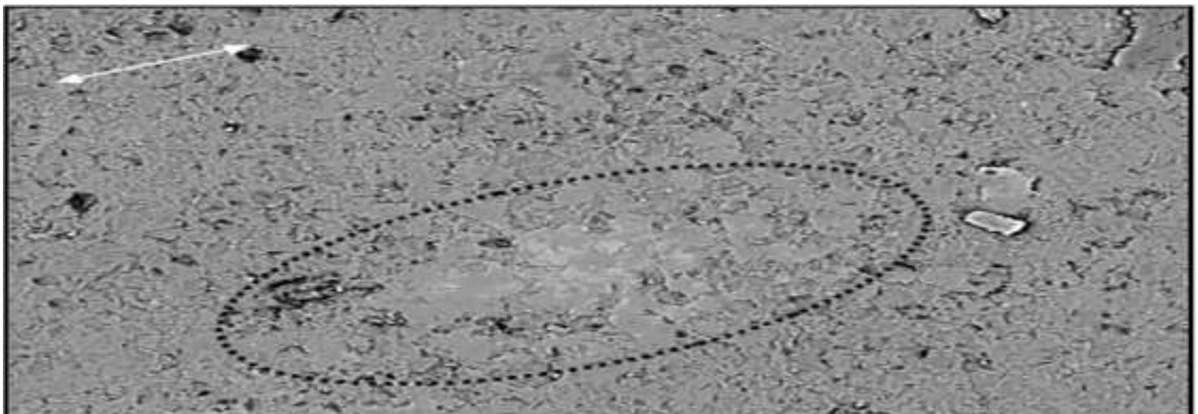
Tribology is the study of wear, friction and lubrication when two solids are in relative motion against each other. COF and wear rates were affected by the application of bleaching [5]. After initial increase, the enamel exhibited a recovery of properties when it was stored in artificial saliva during a week. The bleaching application caused an immediate dip in the wear resistance and friction properties. It seems that the enamel recovered both properties after being stored in artificial saliva. The final friction coefficient and wear rates were roughly similar to those characteristics of the enamel before bleaching agent was applied.

Wear behaviour

Wear of a human tooth is a natural and unavoidable process, which occurs as a result of physiological and pathological function in the oral cavity. Excessive wear may lead to a lack of perfect contact between opposing teeth, disturbance in the efficiency of the masticatory system, and obliteration of chewing surfaces. During the chewing process of human beings, the magnitude of masticatory force in the oral cavity ranges from 3 to 36N [6]. In order to understand the dominant wear mechanisms of tooth/alumina fretting couple, SEM EDS analysis of worn surface of both tooth ball and alumina base plate was carried out.

Fig. 1A presents the overall topography of the as-worn surface on Al_2O_3, after fretting against a tooth ball for 8000 cycles. The boundary of damaged zone is also indicated on Fig. 1A. It was observed that a fractured tribolayer adhered to the central region of alumina worn surface for all the five experiments. Besides the occasional presence of a tribolayer, no noticeable abrasive groove was found on a worn Al_2O_3 surface.In Fig. 1B, the details of the tribolayer are presented. A number of microcracks can be clearly observed. The contrast between the tribolayer and unworn (virgin) Al_2O_3 surface in Fig. 1A indicates a difference in chemistry. EDS analysis indicates a strong presence of Ca, indicating that the tribolayer is a Ca-rich compound. Considering the composition of the mating counterbody (human tooth),it is evident that

A



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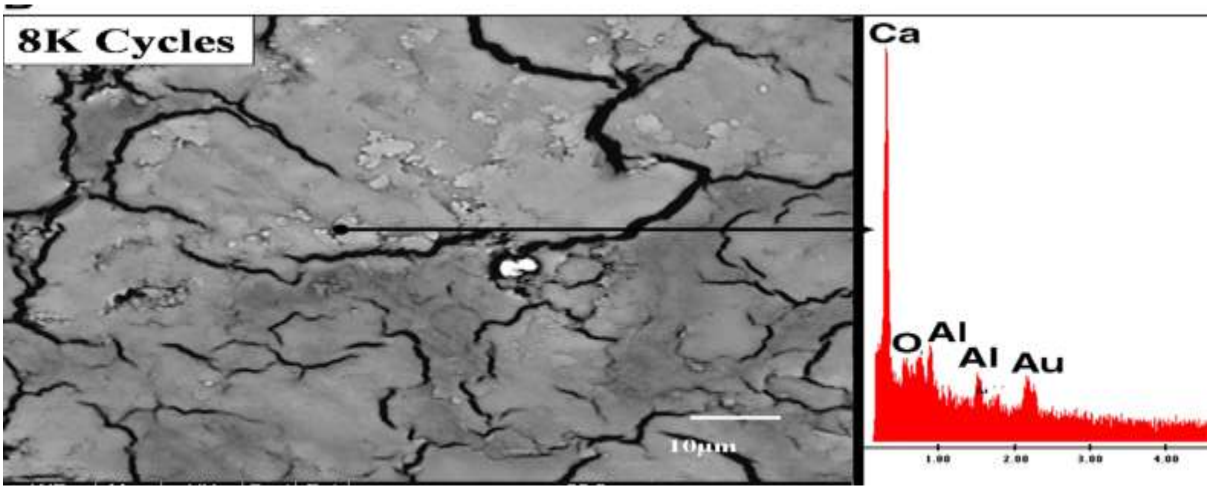
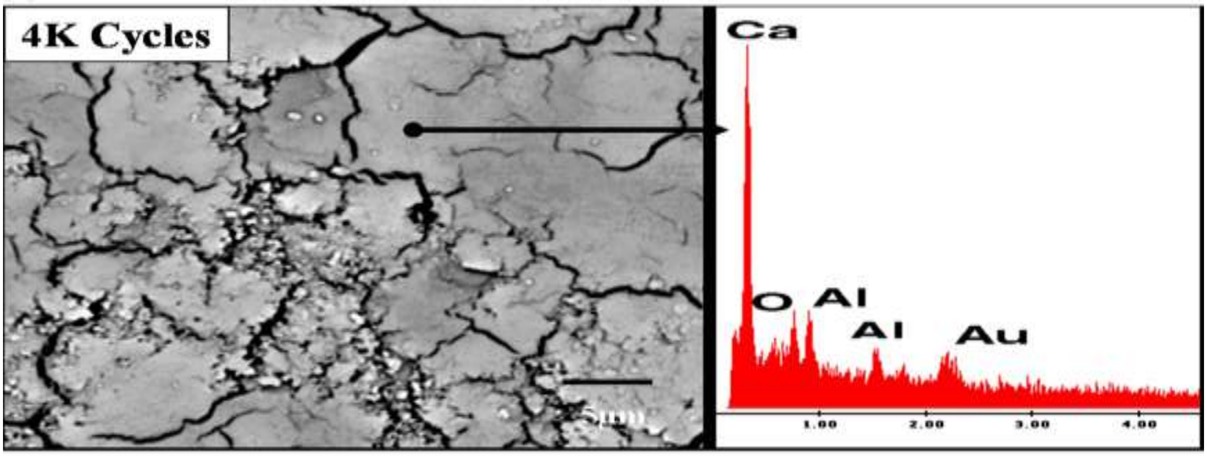


Fig.1 – A) SEM image, illustrating the overall fretting damage experienced by alumina plate, after tested against human tooth ball at 1 N load for 8000 cycles. B) SEM image, revealing the details of the tribolayer on the worn alumina as well as EDS compositional analysis of the tribolayer. The dotted line and reciprocating arrow in (A) indicates the boundary of the fretted damage zone and the fretting direction, respectively [10].

it is evident that the worn material from the tooth surface has been transferred to the alumina base plate during the fretting process. It has been also observed that alumina hardly experiences any fretting damage, which is understandable because of the much higher hardness of alumina compared to a human tooth.In order to illustrate damage at a lower number of fretting cycles, the evidence of cracked tribolayer formation is presented in Fig. 2. From Fig. 2A, it should be clear that tribolayer formation took place at the early stages of fretting wear. Also, the appearance of the tribolayer indicates that it is rather thin. A comparison of Figs.2 and 1 further reveals that similar wear mechanisms are operative, irrespective of the fretting duration. A SEM image, revealing the overview of the damage experience by human tooth is presented in Fig.3A.

A



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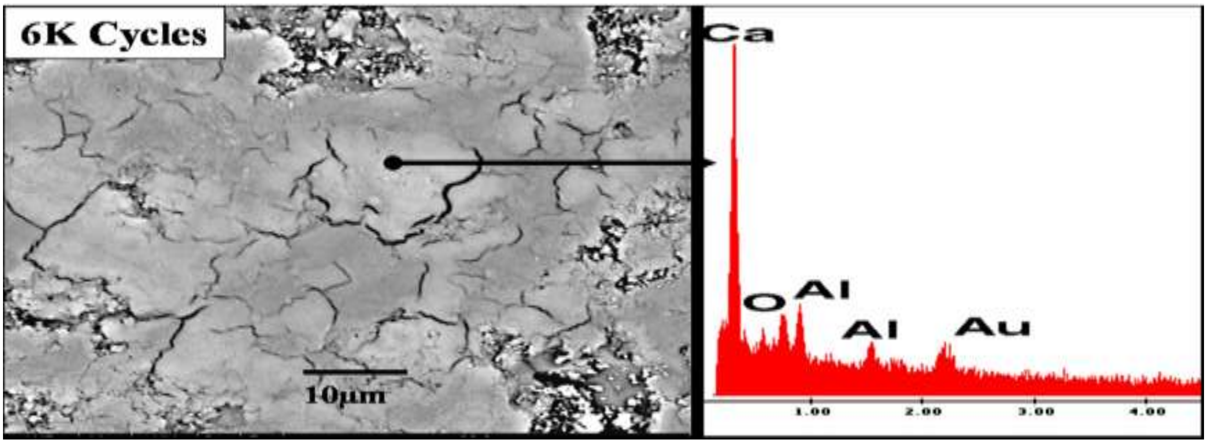
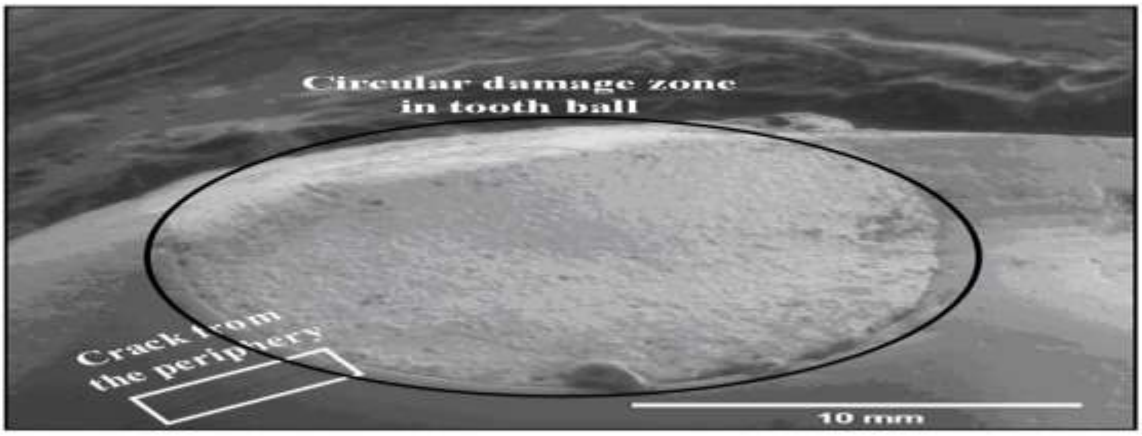


Fig. 2 –SEM images revealing the details of the tribolayer as well as EDS compositional analysis of the tribolayer on the worn alumina, after it was fretted against the human tooth ball at 1 N load for various durations: (A) 4000 cycles and (B) 6000 cycles [10].

A



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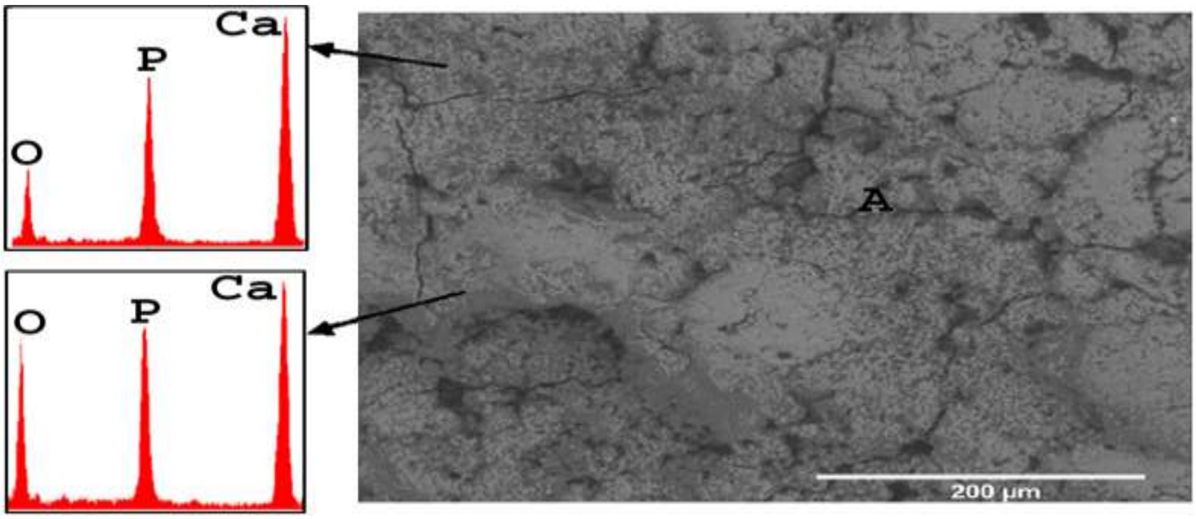

Fig. 3 – (A) SEM image (BSE mode) illustrating the overall damage experienced by human tooth after the initial 2000 fretting cycles. A crack can be seen to propagate from the periphery of the

damaged zone. (B) Higher magnification SEM image (BSE mode), revealing the formation of a tribolayer along with the EDS analysis obtained from different parts of the worn surface [10].

A large circular damage zone with diameter of around 15–20 mm can be clearly seen. This indicates that the human tooth experiences extensive fretting induced damage. Such observation should be correlated with the much lower hardness of a human tooth, in comparison to Al_2O_3counterbody. Some important details of the worn surface are illustrated in Fig.3B. The presence of many longer cracks, as well as a dense tribolayer is the common features of the worn surface. EDS analysis reveals much stronger P and O peaks from the tribolayer, indicating the dominant formation of Ca–P compounds. Based on the surface topography analysis of worn surfaces, it can be summarized that during the initial stages of fretting cycles, the tooth surface, being softer of two counterbodies, is worn away faster involving oxidation of the tooth surface. Also, a comparison of Figs. 1, 2, and 3 indicates that a much thicker tribolayer forms on the tooth surface. From the above observations, it can be said that fretting fatigue seems to be a dominant wear mechanism, which involves cracking and material transfer to a softer counterbody. Once the transferred material fragments adhere to the opposing mating solid, the contact scenario changes to tooth–enamel and the adhered enamel contact. Such a phenomenon has influenced the frictional behavior in the present case.

Friction behaviour

The experimentally measured coefficient of friction (COF) against the number of fretting cycles, when teeth balls are rubbed on the sintered alumina isploted in Fig. 4.

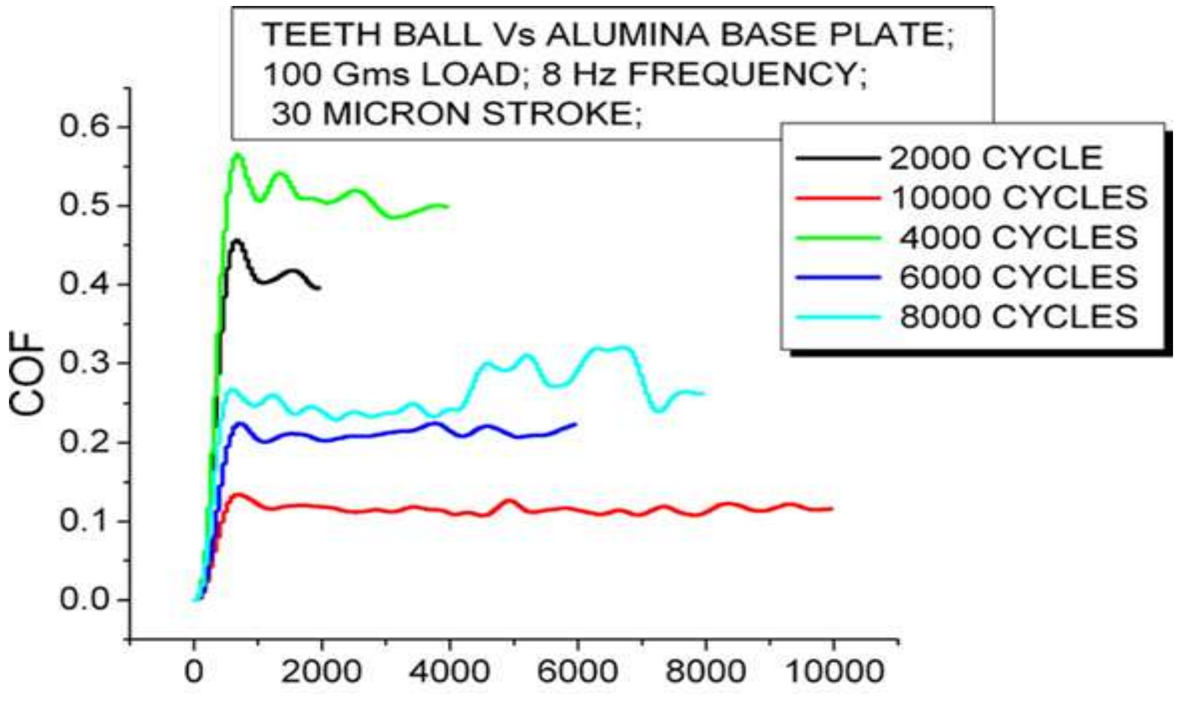

Fig. 4 – Variation of COF with number of cycles, when human teeth are balls fretted against sintered alumina plate at 1 N load, 8 Hz frequency under unlubricated conditions. The tooth samples were extracted from five different subjects of varying age, sex and dietary habits [10].

It has been observed that for all the different experiments, the COF increases initially up to around 1000 cycles and then remains almost constant, with certain fluctuations of the steady state COF value. An interesting point to note here is that a range of COF values, with a maximum measured steady state COF of 0.55 and the lowest measured at 0.12, have been recorded. For certain instances, such as the tooth sample tested for 8000 cycles, larger fluctuations in the otherwise steady state frictional stage do appear. The general observation of a sharp rise in COF within the initial fretting cycles can be explained by the possibility of the asperities getting knocked off due to abrasion during the running-in-period. It can be mentioned here that Li et al.[7]performed the wear study of a human tooth against titanium on a conventional pin-on-disc machine in both dry and artificial saliva conditions and found that the coefficient of friction is slightly lower (0.2) in artificial saliva conditions, compared to dry condition (COF≈0.3). It was also observed in the work of Li et al. that the dental tissue is less burnt and carbonized in artificial saliva condition. This is because artificial saliva plays a role, not only as a lubricant, but also as a coolant.

An important observation from Fig 4is that, no definite relation between the COF and the number of testing cycles is found. The initial increase in the COF may be attributed to the high hardness of enamel that is being worn with time and adhered to the alumina base plate, so that after the initial 1000 cycles, the tribocontact is no longer between the tooth and the alumina, rather it becomes enamel being rubbed over the enamel layer on alumina. This is possibly the reason for measuring the slight decrease and subsequent attainment of steady state COF value. The experimental measurements in Fig. 4 can be further comprehended when we consider the fact that the mechanical properties of a tooth depend strongly upon individual differences (e.g. age, sex, physical condition) and also, on the location of the contact zone inside a single tooth [8]. Zheng et al. [7] also observed that tribological behavior of a tooth is strongly sensitive to the microstructural orientations and it changes from location to location for the same tooth. Therefore, a difference in hardness as well as in the tribological behavior in the present work is expected in the tested teeth, which have been taken from five different subjects. Furthermore, in spite of our great effort to produce the teeth balls with similar geometry and location of the teeth sections, it is quite possible that point contacts between the balls and the alumina base plate were different in different testing conditions. All these facts may explain the discrepancy in the relation between the measured COF and the number of cycles, during the fretting test.

The COF of both scratch directions parallel and perpendicular to the rod axis from enamel surface toward DEJ gradually increases. It can be evaluated using

$$\mu = \frac{F_L}{F_N}$$

where F_L and F_N are the lateral force and normal force acting on the tip respectively μ is COF. The COF in the direction parallel to the rod axis increases from 0.108 ± 0.006 to 0.123 ± 0.006 (enamel surface to the DEJ), while they were 0.111 ± 0.002 to 0.134 ± 0.003 in the perpendicular direction [9].

Conclusion

Tribological properties (wear and friction) gradually increase with increasing distance from outer enamel surface toward the DEJ.In tribological experiments, human tooth/alumina tribocouple exhibits steady state COF, varying in the range of 0.12-0.55 for varying number of cycles under the unlubricated fretting conditions. No definite correlation could be made between steady state COF and the number of cycles.The values of friction coefficient obtained in a direction perpendicular to the longitudinal axis of the rod are higher than those obtained in the parallel direction. This suggests that the friction coefficient depends on the direction and orientation.

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