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Bionic design perspectives based on the formation mechanism of dental anti-wear function

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Abstract

Human teeth are the important masticatory organ and therefore are subjected to friction and wear everyday. Both the loading condition and the environment are relatively complex in the mouth, however, normally human teeth can serve in mouth all their time with excellent wear resistance in most people. Obviously, through the process of human evolution, human teeth have become a natural anti-wear system that far outclasses the best engineering anti-wear systems at present. To understand the excellent anti-wear properties of human teeth, we need to look into what act as the wear resisting elements of human teeth. In this paper, based on the results obtained by the authors and from literatures, the formation mechanism of dental anti-wear function was summarized. Particular attention was paid to the multi-scale anti-wear mechanism caused by the unique hierarchical structure of human teeth, the self-repair mechanism by tooth remineralization, and the cooperating lubrication mechanism of salivary pellicle upon tooth surface and the hydration proteins within the tooth. Based on the formation mechanism of dental anti-wear function, some bionic design perspectives were discussed and future research directions are recommended.

Keywords: Human teeth; Anti-wear mechanism; Bionic design

1. Introduction

It was pointed out that friction consumes about one-third of energy, wear causes about 60% parts to fail, and more than 50% of equipment failures are induced by lubrication failure or excessive wear [1]. Wear has been widely considered to be the bottleneck to restrict the reliable running of instruments/ equipments. Therefore, the development of the machine parts with excellent wear-resistance plays an important role in upgrading the manufacturing level of equipments. Given that current theory of tribological design cannot meet the needs of the development of the instruments with excellent anti-wear performance, how to design excellent anti-wear systems still has been a worldwide puzzle for engineering researchers.

It is well known that the organs /organ surfaces of some natural organisms have unique anti-wear properties after billions of years of evolutionary. Thus, learning from nature, revealing the anti-wear function formation mechanisms of bio-specimens, and then establishing anti-wear and friction-reducing bionic design methodologies would promote the development of high performance anti-wear instruments/equipments significantly. As an important masticatory organ, the main physiological functions of human teeth are to cut and grind various foods. The wear of human teeth is really slight, only 20 to 38 μm per year [2], and for most people, their teeth can serve for several decades in body. Obviously, human teeth are natural friction pair with excellent wear-resistance, that is, a typical anti-wear bio-specimen. Therefore, understanding the formation mechanism of the anti-wear function of human teeth would not only has important application values to the prevention of excessive tooth wear and the developments of advanced dental materials, but also provide innovative insights into the anti-wear bionic design and then help upgrade the manufacturing level of equipments.

Considering that natural teeth are a living organ with individual differences and serve in a complex oral environment, dental biotribology has been regarded as highly challenging and

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rarely investigated for many years. Most related research focused on clinical observations of excessive dental wear and the wear loss measurements of dental restorative materials [3–5], while few systematic fundamental and applied studies have been conducted through regarding human teeth as a biotribological system and conjoining engineering with medicine. Hence, little is known about the tribological properties of human teeth and there still exist many puzzles. For instance, it has been accepted that human teeth and their peripheral tissues and environment have constituted a natural anti-wear system after evolution of millions of years, but what is the running mechanism of human teeth during friction process? What act as the wear resistance elements of human teeth to endue them with a long service life in the complex oral environment?

In order to explore the formation mechanism of dental anti-wear function of human teeth, authors have investigated the friction and wear behaviors of teeth in detail by laboratory simulation in vitro in the past decade. In this paper, based on the results obtained by the authors and from literatures, the formation mechanism of dental anti-wear function was summarized. Particular attention was paid to the multi-scale anti-wear mechanism caused by the unique hierarchical structure of human teeth, the self-repair mechanism by tooth remineralization, and the cooperating lubrication mechanism of salivary pellicle upon tooth surface and the hydration proteins within the tooth. Based on the formation mechanism of dental anti-wear function, some bionic design perspectives were discussed and future research directions are recommended.

2. Anti-wear mechanism of human teeth

From the proffered information obtained by the authors and from literatures, it could be confirmed that the excellent anti-wear properties of human teeth are mainly resulted from dental hierarchical structure, synergistic lubrication, and self-repair.

2.1. Multilevel anti-wear mechanism of dental hierarchitecture

2.1.1. Macroscopic anti-wear structure

At macro-scale, human tooth is mainly composed of outer enamel and inner dentine (Fig. 1). Reciprocating wear testing results demonstrated that the friction coefficient of the occlusal surface of enamel was low and kept stable at the early stage [6], as shown in Fig. 1.a, suggesting that tooth enamel possessed good wear-resistance. With the contact interface being moved from outer enamel to inner dentin, the friction coefficient increased rapidly. The micro-hardness decreased but the wear depth increased from outer enamel to inner dentine (Fig. 1.b). Microscopic examinations indicated that the wear mechanism of enamel was mainly dominated by mechanical removal due to brittle delamination and almost no tribochemical process occurred [6,7], while obvious ploughs as a consequence of plastic deformation occurred to the dentin. Both delamination and ploughing traces appeared on the worn surface of dentin-enamel junction without the detachment of enamel and dentine. No crack mechanism happened to tooth wear. Obviously, human tooth has gradient mechanical properties, and there exists excellent bonding strength between outer enamel and inner dentine.

Enamel is the hardest tissue with a hardness of about 360 (HV50g) in body, while dentine is usually considered to be elastic and soft with a hardness of about 60 (HV50g) [6]. The hardness (HV50g) of DEJ zone varies from about 300 to 60. Generally the enamel of a thickness of 2–3 mm acts as occlusal surface and then suffer fiction and wear during mastication process. The high surface hardness of enamel endues it with excellent wear-resistance, while the soft inner dentine is involved to spread normally compressive stress over a much larger volume and produce large plastic deformation so as to dissipate friction energy and then prevent enamel surface from cracking. The gradient mechanical properties of enamel also contribute to energy dissipation. It seems that the hard enamel layer with gradient mechanical properties and the organic integration of hard enamel and soft dentin act as the anti-wear structure of human teeth at macroscale.

2.1.2. Mesoscopic anti-wear structure

At meso-scale, enamel rods are combined tightly and orderly with the surrounding inter-rod enamel within the enamel [8] (Fig. 2). Both the hardness and elastic modulus of enamel rod were found to be higher than those of the inter-rod enamel, and they were heterogeneous over their occlusal cross-section [8,9]. For a single enamel rod, the hardness and Young's modulus were higher in the central head area, and tended to be lower in the edge area, especially in the tail area, as shown in Fig. 2.b. The inter-rod enamel was demonstrated to be the weaker phase that was easily worn out during the friction and wear process as compared to enamel rods [7,10]. The worn surface of enamel was mainly characterized with obvious zigzag morphology, and the enamel rod was higher than the surrounding inter-rod enamel (Fig. 2.c). No detachment between the rods and inter-rod enamel occurred. Obviously, during the friction process, enamel rods with excellent mechanical properties act as a load-bearing shoulder, while the soft inter-rod enamel can produce large plastic deformation to provide stress-buffer effect to a certain degree.

Human tooth enamel is typical fibre-reinforced composite. As shown in Fig. 6, keyhole-like rods (6–8 μm in diameter), aligned in parallel, are embedded in inter-rod enamel, the matrix which has a thickness of 800–1000 nm [7,8]. Enamel rods are over 95% mineralized and thus have high elastic modulus and hardness, while inter-rod enamel is rich in protein and soft. The rod sheath is a natural coupling agent locates where enamel rods meet inter-rod enamel. As a result, there exists compact and orderly alternate arrangement of hard enamel rods and soft inter-rod enamel with the enamel. When occlusal stress is applied on the enamel during chewing, it is carried mostly by the high hard rods, producing little plastic deformation and then low wear loss, while the inter-rod enamel may dissipate partial stress and produce large deformation, preventing the rods from damage. The heterogeneous