Journal of the Mechanical Behavior of Biomedical Materials 80 (2018) 77–80

Contents lists available at ScienceDirect

Journal of the Mechanical Behavior of Biomedical Materials

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

Role of particulate concentration in tooth wear

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ARTICLE INFO

Keywords:
Enamel wear
Wear rate
Silicate particles
Microcracking

ABSTRACT

Results are presented for wear tests on human molar enamel in silica particle mediums. Data for different particle concentrations show severe wear indicative of material removal by plasticity-induced microcrack formation, in accordance with earlier studies. The wear rates are independent of low vol% particles, consistent with theoretical models in which occlusal loads are distributed evenly over all interfacial microcontacts. However, perhaps counter-intuitively, the wear rate diminishes substantially at higher vol%. This is attributed to a greater proportion of lower-load microcontacts transitioning into a region of mild wear, where microcracking is suppressed. Implications of these results in relation to evolutionary biology and dentistry are explored.

1. Introduction

It is well documented that ubiquitous micrometer-scale silica particles in the food source, atmosphere and ocean can cause deleterious wear in the tooth enamel of mammals (Dean et al., 1992; Damuth and Janis, 2011; Fortelius, 1985; Fortelius and Solounias, 2000; Grine, 1981; Grine and Kay, 1988; Janis and Fortelius, 1988; Lucas, 2004; Lucas et al., 2008; Lucas and Omar, 2012; Sanson, 2006; Scott et al., 2006; Teaford, 1988; Teaford and Ungar, 2000; Ungar, 1998, 2010; Ungar and Sponheimer, 2011; Walker et al., 1978). How such particles determine microscopic dietary signals has generated some debate (Lucas et al., 2013; Merceron et al., 2010, 2016; Rabenold and Pearson, 2011; Ungar and Sponheimer, 2011), but it is generally acknowledged that they greatly accelerate the rate of macroscopic wear (Cuozzo and Sauther, 2006; Fortelius and Solounias, 2000; Janis and Fortelius, 1988; Logan and Sanson, 2002). Recently, models based on fundamental indentation mechanics have been developed to quantify dental wear rates in terms of particulate morphology, oral lubricant medium, occlusal bite force, and enamel material properties (Arsecularatne and Hoffman, 2010; Borrero-Lopez et al., 2014, 2015; Constantino et al., 2016; Xia et al., 2015). Cumulative microwear damage from many individual particle microcontacts manifests itself as macrowear. Severe macrowear has negative health implications by limiting the useful lifetime of the dentition, from either excessive chewing conditions, most notably in herbivorous animals, or bruxing in humans. Once the wear is sufficient to remove the enamel cap, the rate of wear through the soft dentin interior accelerates and the risk of infection increases. Accordingly, dental wear rates are of considerable interest to evolutionary biologists and dentists alike.

A principal finding from the previous micromechanical studies was the strong sensitivity of enamel wear rate to the ubiquitous presence of even small quantities of third-body silicate particles in the lubricant medium. The wear can be mild or severe depending on whether individual indentation plastic zones lie below or above a threshold for microcrack initiation in the enamel (Borrero-Lopez et al., 2015; Constantino et al., 2016). Within each of these wear regimes, the wear rate closely obeys a relation akin to Archard's law, with a wear coefficient directly proportional to volume removed and to enamel hardness, and inversely proportional to net occlusal load and sliding distance. The wear coefficient depends also on particle modulus and angularity. An interesting aspect of the wear rate relation is its independence of particle concentration, at least within any given mild or severe domain, following the notion that increasing the number of microcontacts simply distributes a smaller load to each individual particle, with a consequent null outcome.

The last assertion is of great significance in the context of dietary influence, since it suggests that the density of particulate matter is unimportant—all that is needed is a sufficient number of microcontacts to support the occlusal bite force, so a rigorous particle count is not required. The present study examines this issue by conducting sliding macrowear tests on human dental enamel specimens in a conventional ball-on-flat wear test in suspensions of four concentrations of silica particles in a water environment (Borrero-Lopez et al., 2015). The results are analyzed within the framework of the previous microcontact models. While it is confirmed that particle concentrations are not a factor if they are maintained at sufficiently small levels, wear rates can

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https://doi.org/10.1016/j.jmbbm.2018.01.024
Received 23 November 2017; Received in revised form 31 December 2017; Accepted 22 January 2018

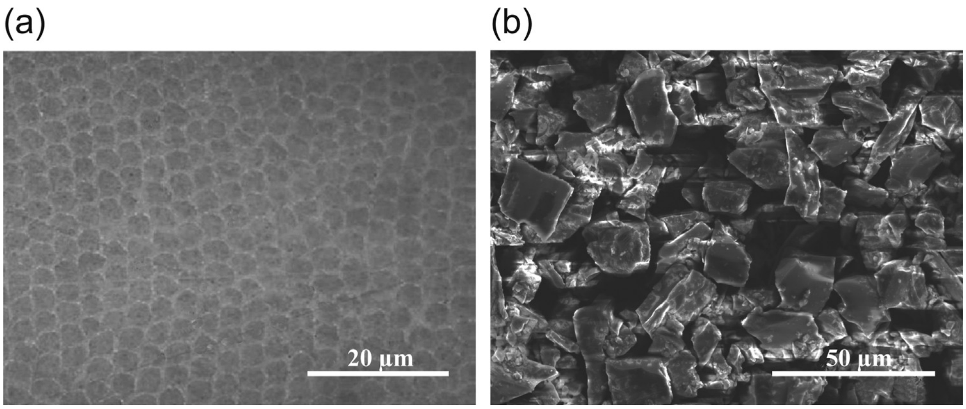

Fig. 1. (a) Polished surface of slice from human molar normal to tooth axis, showing emergence of rods on surface. (b) Silica particles used in the wear tests. Note sharp angular corners.

actually become somewhat suppressed if the particle density exceeds a certain limit.

2. Materials and methods

Tooth enamel specimens were fabricated from extracted human molars supplied by local dentists and subjected to wear tests (Borrero-Lopez et al., 2014). Flat slices parallel to occlusal facets were polished to 1 µm finish (Fig. 1a). Sliding wear tests were conducted in a ball-on-three-specimen tribometer (Falex Multi-specimen, Faville-Le Valley Corp., Bellwood, IL) using a rotating silicon nitride sphere of radius 6.35 mm (Cerbec NBD 200, CoorsTek, Golden, CO) in a tetrahedral loading configuration. Silicon nitride was chosen simply because it is harder and stiffer than the specimen enamel, and so can last through a full testing cycle without itself wearing out. The normal load on each specimen was 30 N and the sliding speed was 10 mm s^{-1}. Prior to testing, suspensions of hard, angular silica particles of mean size 20 µm (Fig. 1b) in a water slurry were introduced between contact ball and specimens in concentrations of 0.1, 0.5, 1 and 5 vol%. Some tests were run in particle-free water as a control.

The tests were interrupted at prescribed intervals and the specimen holder removed for inspection. The ensuing near-circular wear scar diameters and depths on the enamel test surfaces were measured by profilometry (Surftest SJ-400, Mitutoyo, Kanagawa, Japan) and used to calculate macrowear volumes according to a geometrical formula for sphere-on-flat contacts (Hsu and Shen, 1996). The maximum depth of removal was 100 µm, relative to the enamel thickness 1.5 mm. A precision location fixture enabled the specimen holder to be replaced in its original position, at which point the abrasive suspension was replenished and the test resumed. In this way wear volumes could be recorded as a function of test time, thence sliding distance. The wear scars on water-rinsed and dried test surfaces were then examined by optical and scanning electron microscopy.

3. Results

Fig. 2 plots enamel scar wear volume V as a function of sliding distance L for tests at normal load $P = 30$ N in aqueous suspensions with concentrations of 0.1, 0.5, 1 and 5 vol% silica particles, as well as in pure water medium. Data points are mean and max/min bounds for the three enamel specimens in each test. In all cases an initial run-in stage is observed, until at sufficient depth the contour of the wear scar matches that of the sliding ball. Subsequently, the data approach a stage of near-linear dependence, corresponding to a steady-state wear rate given by (Borrero-Lopez et al., 2014)

$$VH/PL = K \tag{1}$$

where H is the specimen hardness and K is a wear coefficient. Of special note is that the data for 0.1, 0.5 and 1 vol% particles overlap, within scatter, consistent with the absence of particle concentration in Eq. (1).

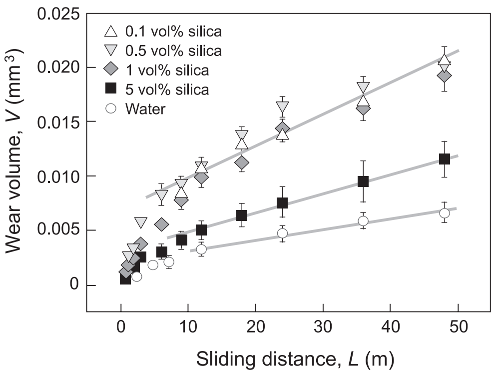

Fig. 2. Wear volume of tooth enamel as function of sliding distance for ball-on-three flat test configuration, for different silica particulate densities, tests with silicon nitride balls of radius 6.35 mm at normal load 30 N on each surface. Sliding distance measured from rotational speed and test duration for the given sphere radius. Data for tests in particle-free water included for comparison. Each data point represents mean values and data bounds for the 3 specimens. Solid lines are asymptotic linear fits to the data sets, with wear coefficients K evaluated from the slopes.

This in turn is consistent with a common material removal process for these three particle concentrations. Perhaps seemingly counter intuitively, the data for the higher 5 vol% concentration show a relative decrease in wear rate over the entire sliding distance range, closer to the data for control tests in particle-free water.

Quantitative evaluations of the wear coefficient K in Eq. (1) are useful to establish whether the wear process lies in the mild or severe region. The slopes of the linear fits in Fig. 2, together with $P = 30$ N on each specimen and $H = 4$ GPa for enamel hardness, yield a mean $K = 4.0 \times 10^{-5}$ for the 0.1, 0.5 and 1 vol% concentrations, $K = 2.3 \times 10^{-5}$ for the 5 vol% concentration, and $K = 1.3 \times 10^{-5}$ for the water medium. These values lie just above the previously estimated transition point $K > 1 \times 10^{-5}$ for severe enamel wear in silicate-rich environments, suggesting material removal principally by microcracking associated with otherwise microplastic contacts (Borrero-Lopez et al., 2014).

Fig. 3 shows comparative scanning electron microscope images of surface damage within wear tracks in (a) 0.1 and (b) 5 vol% silica particle concentrations. Both images show distinct microcontact tracks from individual particles, but the width and density of these tracks measured by profilometry differ substantially: the specimens tested with 0.1 vol% particle suspension reveal fewer tracks, but with larger half-widths of 3.0 ± 0.2 µm; those with 5 vol% particle suspension reveal more tracks, with smaller half-widths of 0.4 ± 0.1 µm. There is clear evidence of local microcracking along the tracks in Fig. 3a, less so in Fig. 3b, consistent with the data shifts in Fig. 2.

4. Discussion

Our wear experiments on human molar enamel have been