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Mechanics of microwear traces in tooth enamel

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ABSTRACT

It is hypothesized that microwear traces in natural tooth enamel can be simulated and quantified using microindentation mechanics. Microcontacts associated with particulates in the oral wear medium are modeled as sharp indenters with fixed semi-apical angle. Distinction is made between markings from static contacts (pits) and translational contacts (scratches). Relations for the forces required to produce contacts of given dimensions are derived, with particle angularity and compliance specifically taken into account so as to distinguish between different abrasives in food sources. Images of patterns made on human enamel with sharp indenters in axial and sliding loading are correlated with theoretical predictions. Special attention is given to threshold conditions for transition from a microplasticity to a microcracking mode, corresponding to mild and severe wear domains. It is demonstrated that the typical microwear trace is generated at loads on the order of 1 N – i.e. much less than the forces exerted in normal biting – attesting to the susceptibility of teeth to wear in everyday mastication, especially in diets with sharp, hard and large inclusive intrinsic or extraneous particulates.

1. Introduction

The wear of teeth by small particulates is of great interest to evolutionary biologists because of its utility as an indicator of diet. This interest is manifest in the extensive field of dental microwear [1–14]. Conventional wisdom has it that hard foods are fractured in compression (normal, axial loading), leaving residual pits on the enamel surface, whereas soft foods are ground down in shear (sliding, translational loading), leaving scratches. Individual microcontact signals typically occur on a width scale of 1–20 μm [5,7]. The ratio of pits to scratches is taken as a measure of diet: some teeth show either scratches or pits, suggesting specialist diets; others show both scratches and pits, suggesting more omnivorous diets. Most advances in interpretation are based on quantifying this ratio, using ever more sophisticated methodologies in imaging and digitizing techniques [14]. Microwear patterns tend to be transient, so that they are indicators of recent food intake rather than a full dietary history.

What is missing from dental microwear is a first-principles account of the basic contact micromechanics of pit and scratch formation. This deficiency provides the rationale for the current study, i.e. a strong physically based analytical footing for describing individual microwear events in a hitherto empirical field. Wear can be life-limiting in some species of animals, especially grazers and browsers, where the work rate is high and continual. In humans, wear can be sufficiently severe (bruxing) to necessitate treatment by a dentist. A recent paper by Lucas et al. [15] set a precedent for an understanding by examining the nature of individual wear tracks produced by translating individual particles glued to a nanoindenter tip. The principal consideration in that study was the competitive roles of silicate-based phytoliths in vegetable matter [16], quartz dust in the atmosphere [10] and even enamel particles, typically 1–100 μm in diameter. It was suggested that incursive particulates should be at least as hard as enamel and should have a sufficiently high attack angle in order to cause significant tooth wear. However, the Lucas et al. study focused almost exclusively on the ultra-low load (mN) region, whereas the type of material removal process that leads to accelerated tooth wear involves much more deleterious microfracture [17,18]. Such differentiations in removal processes are well understood by tribologists and ceramic machinists as a transition between polishing and abrasion [19], and are a manifestation of an intrinsic ductile–brittle transition with increasing contact load and dimension [20,21]. This transition, along with the roles of particle compliance and sharpness, remains to be quantified in the context of dental microwear.

Accordingly, in this paper, microwear in tooth enamel is examined using the well-established methods of indentation mechanics [21–24] as the basis for modeling the action of angulate, compliant

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particles in food diet. First, controlled indentation experiments in axial and translational loading are employed to simulate individual pits and scratches. Distinction is made between polishing and abrasion damage modes by identifying the loading conditions under which the microcontact undergoes a plastic to brittle transition. For modeling, the particles are considered to be "sharp", i.e. with fixed-angle profiles, as opposed to "blunt", with fixed-radius profiles. (Some consideration has been given to blunt contacts in an earlier analysis of the role of food size in tooth fracture [25,26], but sharp contacts are more deleterious and thereby serve as a worst case.) This type of indentation-based analysis has been pre-empted in a preceding model of macrowear, in which tooth occlusal wear rates were determined by integration of individual microwear events over a macroscopic contact area over time [18]. However, that earlier model was generic, without attention to individual contact micromechanics. The roles of particle angularity, compliance, size and number are now elucidated. The prospect of using trace dimensions, specifically track width and depth, to infer corresponding microcontact conditions in naturally occurring microwear tracks is examined. It is demonstrated that the contact loads lie in the region of 1 N, i.e. two to three orders of magnitude below the nominal bite forces for humans and other hominid species. The implications of the analysis concerning dietary characteristics are explored.

2. Morphology of pits and scratches

Extracted molars from healthy adults were obtained from local dentists, and were disinfected using an ethanol solution (70%) and stored in distilled water under refrigeration. Those with any surface damage were discarded, and four others were embedded upright in a resin mold, as depicted in Fig. 1. The top surfaces were lightly ground to produce island facets 2–3 mm in diameter on the cusps, and then finished in an automatic polishing machine (Phoenix 4000, Buehler, Lake Bluff, IL) using diamond particle suspensions down to 1 μm. The maximum depth removed below the original occlusal surface was 100 μm, i.e. small compared with the thickness ~1.5 mm of the enamel. Preliminary Vickers indentations (HSV-30, Shimadzu, Kyoto, Japan) at a load of 10 N on the polished surfaces yielded hardness values $H = 4.0 \pm 0.2$ GPa (mean and standard deviation, 10 indents).

A conical Rockwell diamond indenter with included angle $\psi = 60^\circ$ and tip radius 25 μm (Nanotest, Micro Materials Ltd., Wrexham, UK) was selected in an attempt to simulate wear events in a particle-rich diet. The indenter had some surface imperfections on a scale of ~3 μm in the near-tip region, but, in the context of the irregular geometries of natural particulates, this was considered to add a touch of realism. Tests were run in both normal axial and lateral sliding contact over a load range of 0.1–3 N on the polished surfaces, which were kept moist during the testing. In the axial tests, the loads were ramped up monotonically to maximum load and held for 5 s before unloading. In the sliding tests, the specimens were translated at 2 μm s^{-1}, with load applied linearly at 5 mN s^{-1} to its prescribed maximum and then held steady over a further translation distance of 200 μm. The indentation sites were examined and photographed by optical microscopy (Epiphot 300, Nikon, Tokyo, Japan). Some specimens were sputter-coated with a gold layer and then examined by scanning electron microscopy (SEM; QUANTA 3D FEG, FEI Company, Hillsboro, OR) using secondary electrons at low voltage (5 kV). All tests produced residual impressions, indicating that the Rockwell indenter can be considered effectively sharp.

Optical microscope images of the indentations in axial contact are shown in Fig. 2 at normal loads of 0.25, 0.5, 1 and 2 N. The impressions have somewhat irregular edges, attributable to the aforementioned imperfections in the shape of the indenter tip, but are otherwise near-circular. Radially extending cracks are clearly evident at the higher loads in Fig. 2, but not at the lower loads, consistent with the existence of a plastic-to-brittle threshold contact dimension [20]. Also faintly visible is some peripheral microcracking at the highest load.

Analogous optical images of indentations in translational motion are shown in Fig. 3 at loads of 0.25, 0.5, 1 and 2 N. These images are reminiscent of scratches in a broad range of brittle solids [27]. Once beyond the initial load ramp, the linear traces in Fig. 3 assume a constant steady-state width. Again, outward extending cracks, similar to those observed in Fig. 2, but with a tendency to propagate more in the direction of translation, are evident at the higher loads. Peripheral microcracking is more pronounced than in static loading, coalescing in places into lateral cracks [28]. The incidence of cracking of any type becomes more evident at the higher loads, again indicative of threshold behavior. Note the apparent absence of any cracking within the tracks, consistent with a surface smearing action of the moving contact.

Higher magnification SEM images of the contact sites at the upper end of the load range are pictured in Fig. 4. It is apparent that

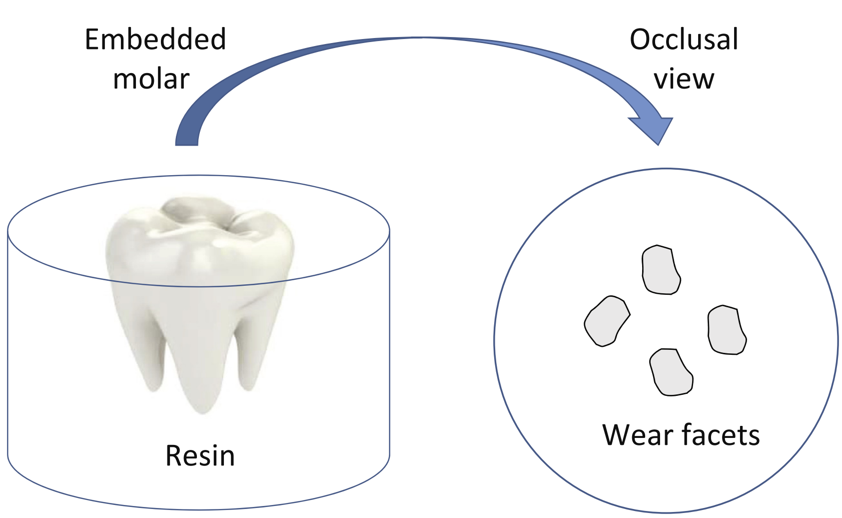

Fig. 1. Schematic diagram showing the embedment of a molar tooth into a resin mold. Grinding and polishing of the top surface produces smooth planar test facets for testing.