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A simple model for enamel fracture from margin cracks

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Abstract

We present results of *in situ* fracture tests on extracted human molar teeth showing failure by margin cracking. The teeth are mounted into an epoxy base and loaded with a rod indenter capped with a Teflon insert, as representative of food modulus. *In situ* observations of cracks extending longitudinally upward from the cervical margins are recorded in real time with a video camera. The cracks appear above some threshold and grow steadily within the enamel coat toward the occlusal surface in a configuration reminiscent of channel-like cracks in brittle films. Substantially higher loading is required to delaminate the enamel from the dentin, attesting to the resilience of the tooth structure. A simplistic fracture mechanics analysis is applied to determine the critical load relation for traversal of the margin crack along the full length of the side wall. The capacity of any given tooth to resist failure by margin cracking is predicted to increase with greater enamel thickness and cuspal radius. Implications in relation to dentistry and evolutionary biology are briefly considered.
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Keywords: Dental enamel; Fracture modes; Margin cracks; Channel cracks; Occlusal loading

1. Introduction

Teeth are brittle, but resilient. Their capacity to withstand high loads over a lifetime of stringent mastication is of particular concern in dentistry and evolutionary biology [1–8]. Tooth enamel provides mechanical protection for the pulp–dentin interior, and limits access of bacterial products to it. Enamel is harder and stiffer than dentin, and thereby shields the tooth interior from external loads. But enamel is also considerably less tough than dentin, meaning that it is relatively susceptible to crack propagation. Anecdotal evidence in the dental and anthropological literature suggests that cracks are a regular occurrence in mature human enamel, generally developing from the cementum–enamel margins and extending longitudinally toward the occlusal surface, as depicted schematically in Fig. 1. There is some suggestion that such ‘‘margin” cracks may evolve within the enamel from ‘‘tuft”-like defects emanating from the dentin–enamel junction (DEJ) [2,9,10]. Margin cracks are also reported to be a source of failure in all-ceramic dental crowns, with the cracking manifested as a spall on the side walls adjacent to the cervical base of the crown [11–13]. Interestingly, attempts in the biomechanics literature to quantify margin failure processes have been restricted to post-mortem examinations of extracted teeth in overload tests [14,15], with little or no effort to identify how the cracks initiate and evolve through the tooth structure *en route* to failure.

In this communication we present results of *in situ* failure tests on extracted molar teeth from human subjects to confirm the importance of margin cracks as a potential source of tooth failure [16]. We mount the teeth roots into an epoxy base and load the cusps with a disk indenter, to simulate an occlusal contact. A layer of Teflon is inserted between indenter and tooth, to simulate biting on soft food. Such a soft contact generally suppresses any competing top-surface fracture modes [11]. A video camera is used

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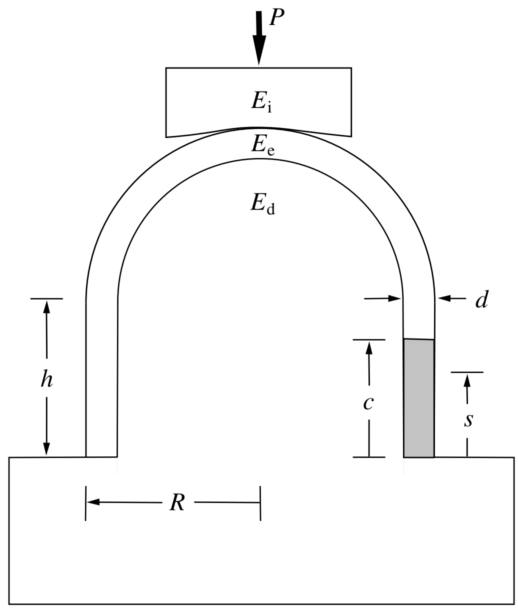

Fig. 1. Margin crack of length c in enamel shell of outer radius R, thickness d, and height h. Coordinate s is measured parallel to the cylindrical wall axis, origin at margin. Modulus E_i, E_e and E_d indicated for indenter, enamel and dentin.

to record the development and propagation of margin cracks as a function of increasing load. Above some threshold, the cracks propagate steadily upward from the base, and subsequently accelerate around the shoulder (suprabulge, in dental notation) to the cuspal contact region. In this study, we arbitrarily denote the configuration where the crack traverses the side wall as "failure". At this stage the oral environment has access to the underlying dentin interior, making it highly susceptible to infection. Up to and including this stage, the cracks remain entirely contained within the enamel thickness. A simple fracture mechanics analysis of the failure condition is then presented, highlighting the roles of tooth size and enamel thickness as key variables.

Further loading ultimately leads to formation of multiple margin cracks, which ultimately link up to delaminate the enamel from the dentin. However, this final stage of tooth degradation lies beyond the scope of the present work.

2. Experiments

2.1. Specimen preparation and testing

We obtained human molar (M2 and M3) and premolar (P4) teeth from the American Dental Association laboratories at the National Institute of Standards and Technology, extracted from 18 to 25 year old patients. The teeth were supplied in aqueous solution, and were kept moist as far as possible through all phases of preparation and testing. The shapes and sizes of the tooth specimens varied, but had an average width 8–10 mm and height 7.5 mm, with four cusps of average diameter 5 mm. Examination of the tooth surfaces with oblique illumination revealed the preexistence of crack-like defects in the molar enamel in most specimens, extending from the cementum–enamel junction toward the cuspal area. Individual teeth were mounted with their roots embedded into cylindrical epoxy moulds 25 mm wide and 10 mm thick. The epoxy was then allowed to cure for one day before testing.

The mounted specimens were set on the platen of a mechanical testing machine. These were loaded normal to the most prominent cusp with an indenter consisting of a tungsten carbide rod with a 3 mm thick Teflon disk glued to the undersurface. The Teflon was inserted to spread the contact at the occlusal surface, thereby diminishing the stress concentration and potentially suppressing any competing sources of top-surface damage [16]. The side wall nearest the loaded cusp was monitored continuously throughout the test with a video camera, using oblique back lighting to highlight any cracks. Transverse sections through selected teeth after indentation (i.e. normal to the load axis) were cut and polished in order to determine the crack geometry.

2.2. Test results

Fig. 2 shows an *in situ* video sequence of margin crack evolution in a molar tooth, at loads $P =$ (a) 250 N and (b) 600 N. The crack tip (arrowed) is observed propagating longitudinally upward from the cervical base. This crack grew gradually above some threshold load, without any apparent unstable pop-in, and with subsequent steady acceleration toward the top-surface beyond the shoulder region. Its geometry was that of a ribbon-like channel crack, nearly normal to the outer enamel surface. Polished sections through such indented teeth revealed these cracks to traverse the width of the enamel without penetration into the dentin sublayer or delamination at the DEJ. No load discontinuities were observed during this phase of the testing. Close inspection of the cusp after completion of the test revealed no local cracking or yield damage in the immediate soft (Teflon) contact region.

Comparative tests on other molars showed a similar trend in fracture evolution, namely appearance of the margin crack above $P \approx 200$ N and steady growth along the side walls toward the occlusal shoulder until $P \approx 400$–600 N. Above this load range the cracks slowed down and did not progress completely to the top surface. We argue that once the crack has reached this point, the enamel has essentially "failed", providing access of the outer environment to the sublayers and marking the first stage of crushing [14,15]. Indeed, at higher loads, the margin cracks began to proliferate, and ultimately, somewhere within the range $P \approx 600$–850 N, began to link up with adjacent arms to produce spalls by delamination of the enamel from the dentin [16]. Such spalls were marked by substantial load drops. In occasional overloaded specimens, the cracks entered into the sublayer to cause a chip in the dentin.

The observed behavior for eight molar cusps is plotted in Fig. 3, as crack size c (measured relative to a baseline 7.5 mm below the cusp) versus occlusal load P. Filled data